A Survey of Glove-Based Systems and Their Applications

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A Survey of Glove-Based Systems and Their Applications

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***Abstract*—Hand movement data acquisition is used in many engineering applications ranging from the analysis of gestures to the biomedical sciences. Glove-based systems represent one of the most important efforts aimed at acquiring hand movement data. While they have been around for over three decades, they keep attracting the interest of researchers from increasingly diverse fields. This paper surveys such glove systems and their applications. It also analyzes the characteristics of the devices, provides a road map of the evolution of the technology, and discusses limitations of current technology and trends at the frontiers of research. A foremost goal of this paper is to provide readers who are new to the area with a basis for understanding glove systems technology and how it can be applied, while offering specialists an updated picture of the breadth of applications in several engineering and biomedical sciences areas.**

***Index Terms*—Gestures recognition, man–machine interfaces, wearable sensors.**

I. Introduction

We use hands for interacting with and manipulating our environment in a huge number of tasks in our everyday life. It is then not surprising that a considerable amount of research effort has been devoted to developing technologies for studying interaction and manipulation and for augmenting our abilities to perform such tasks. The development of the most popular devices for hand movement acquisition, glove-based systems, started about 30 years ago and continues to engage a growing number of researchers.

This paper reviews such glove systems and their applications. Our primary objective is to introduce sensorized gloves to the nonspecialist readers interested in selecting one of these devices for their particular application. Our motivation for writing this paper is the observation that pertinent information on such devices, including measurement performance, is scattered across the engineering and scientific literature and, even when located, can be inaccessible to the nonspecialist. This makes it difficult for a novice to determine whether and how well a particular glove suits a particular application. A thorough study of the literature, especially of the one describing how gloves were applied for different uses, can then help this matching process, at the same time highlighting practical issues that may arise during it.

While aiming at the novice readers who plan to be essentially "users" of sensorized gloves, this paper can, we hope, still inspire the specialists, the "producers" or designers of new devices. Inspiration may not necessarily spur from the specialized literature these readers might be more familiar with. Instead, by glancing outside their area of expertise, they may discover common threads between their research and research in other fields. Thus, this paper aims at helping these readers identify bridges among different areas.

The remainder of this paper is organized as follows. Section II reviews progress in glove technology. After introducing glove characteristics, it guides the reader through a 30 year historical review of the field terminating with current technology. The issue of unipurpose versus general-purpose devices is highlighted. While this has been a central topic in the history of glove devices, it is also one of the most important choices that a user or a producer needs to make early on in the project. The remainder of Section II describes the most recent gloves and gloves accessories. Section III contains an anthological review of applications of glove systems in seven areas: design and manufacturing, information visualization, robotics, art and entertainment, sign language understanding, medicine and health care, and wearable and portable computers. The last comprehensive review of this sort was published by Sturman and Zeltzer in 1994 in an IEEE journal [1]. Back then gloves were starting to gain attention in the first five areas. We chose to summarize the major advances in such fields since the mid 1990s and to describe significant projects in the medical and computers areas. While these two fields have started looking at glove devices only recently, they appear to be the main motivators and leaders behind the innovation in glove technology that has just started taking place. Section IV discusses some key glove characteristics. Also, it aims at giving the reader the means to unveil common threads between different applications from a technical standpoint, discusses limitations of current technology, and offers a perspective on future challenges. Conclusions are reported in Section V.

II. Glove Systems

A. Characteristics

For the purpose of this paper, we define a glove-based system as a system composed of an array of sensors, electronics

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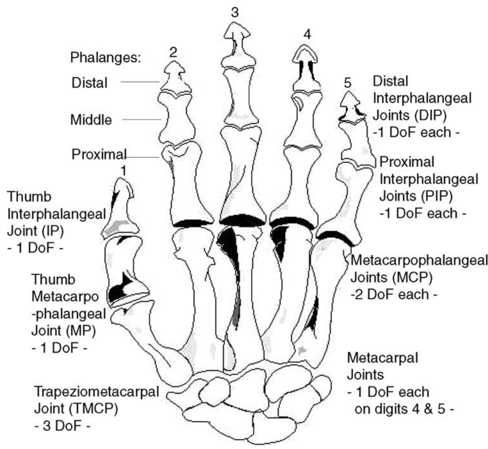


Fig. 1. Hand fingers [thumb (1), index (2), middle (3), ring (4), and little (5)], joints, and related DoFs.

for data acquisition/processing and power supply, and a support for the sensors that can be worn on the user's hand. Typically, it is a cloth glove made of Lycra where sensors are sewn. As worn by the user, it records data related to his/her hand configuration/motion. Fig. 1 shows the hand joints and the degrees of freedom (DoFs) typically used to describe hand motions. The distal interphalangeal (DIP) and proximal interphalangeal (PIP) joints of each finger have 1 DoF each (flexion/extension) while the metacarpophalangeal (MCP) joints have 2 DoFs (flexion/extension and abduction/adduction). The third DoF of the trapeziometacarpal (TMCP) joint allows the thumb to rotate longitudinally as it is brought into opposition with the fingers [2]. While a glove equipped with one sensor per DoF may appear to be the most obvious design choice, a number of gloves with different designs have been proposed over the years: as it will become clearer in the following sections, certain designs may suit specific applications better than others. Fig. 1 also introduces the terminology for hand joints that will be used in this paper.

Table I reports a list of glove characteristics typically reported in the literature for technical comparison purposes, such as sensors specifications (type of information registered by the sensors, sensor technology, number, location, precision, and number of records per seconds), external connections, and data communication interface, as well as a (nonexhaustive) list of their options. Most characteristics are self-explanatory. Some will be discussed in greater detail in Section IV.

B. Evolution of Glove Systems: A Road Map

The first glove-based systems were designed in the 1970s, and since then, a number of different designs have been proposed. Tables II–IV report an extensive list of glove-based systems that have appeared in the literature or marketplace over the past 30 years. This section is meant to serve as a rough guide to the content of Tables II–IV. It sketches a road map of how technology has evolved with time, which will then provide readers with the means to understand current technology and the most recent research efforts.

1) Early Research: The first glove prototypes included the Sayre Glove, the Massachusetts Institute of Technology (MIT)-LED glove, and the Digital Entry Data Glove. The Sayre Glove was developed in 1977 by Thomas de Fanti and Daniel Sandin based on the idea of Rich Sayre. It used flexible tubes with a light source at one end and a photocell at the other, which were mounted along each finger of the glove. As each tube was bent, the amount of light passing between its source and photocell decreased. Thus, voltage from each photocell could be correlated with finger bending [1]. The MIT-LED glove was developed at the MIT Media Laboratory in the early 1980s as part of a camera-based LED system to track body and limb position for real-time computer graphics animation [1]. It used LEDs studded on a cloth. The Digital Entry Data Glove was designed by Gary Grimes and patented in 1983. It used different sensors mounted on a cloth: touch or proximity sensors for determining whether the user's thumb was touching another part of the hand or fingers; four "knuckle-bend sensors" for measuring flexion of the joints in the thumb, index, and little finger; two tilt sensors for measuring the tilt of the hand in the horizontal plane; and two inertial sensors for measuring the twisting of the forearm and the flexing of the wrist [3], [4]. This glove was intended for creating "alphanumeric characters" from hand positions. Recognition of hand signs was performed via a hard-wired circuitry, which mapped 80 unique combinations of sensor readings to a subset of the 96 printable ASCII characters.

These gloves were equipped with a limited number of sensors, were hard wired, and cumbersome. They were developed to serve very specific applications, were used briefly, and were never commercialized.

2) Data Glove-Like Systems: It was the commercialization of the Data Glove in the United States in 1987 that boosted applied research with glove devices and spread their popularity worldwide. First developed by Zimmerman in 1982 [5], the original version of the Data Glove used thin flexible plastic tubes sewn on a cloth and light sources and detectors to record joint angles. A new fiber optics version was developed and commercialized in 1987 by Visual Programming Language Research, Inc. It came equipped with 5 to 15 sensors. Most had ten flex sensors, eight of them measuring the flexion of the MCP and PIP joints of the four fingers and two for the thumb. In some cases, abduction/adduction sensors were used to measure angles between adjacent fingers. Designed to be a multipurpose device, the Data Glove quickly gained the attention of researchers in different fields and a number of devices similar to it were proposed. A low-cost version of the Data Glove, the Power Glove [4], [6], [7], was commercialized by Mattel Intellivision as a control device for the Nintendo video game console in 1989 and became well known among video games players. It used resistive ink printed on flexible plastic bends that followed movements of each finger to measure the overall flexion of the thumb, index, middle, and ring finger. The Super Glove [4] was developed and commercialized by Nissho Electronics in 1995. It came with 10–16 sensors and used resistive ink printed on boards sewn on the glove cloth. An updated version of the Power Glove, the P5 Glove, was commercialized by Essential Reality, LLC, in 2002 [8].

TABLE I
GLOVES CHARACTERISTICS

Sensor information*	continuous; discrete
Sensor number* per finger/thumb	1; >1
Sensor mounting*	cloth support; mechanical structures attached directly to fingers
Sensor location*	hand joints; fingertip positions; exact location not important (see IV.A.1)
External connections	tethered; wireless
Sensor technology	piezoresistive; fiber optic; Hall-effect
Sensor performance low/high	precision; number of records/sec
Interface	serial; parallel; USB
Special requirements yes/no	special users (e.g. motor disabled [99]); special materials (e.g surgery [184], sport [185], fMRI [165])
Calibration*	required; not required

The characteristics indicated with * will be discussed in section IV.

The Data Glove-like systems also include the commercial Space Glove, CyberGlove [see Fig. 2(a)], Humanglove [see Fig. 2(b)], 5DT Data Glove [see Fig. 2(c)], TCAS Glove, and the more recent StrinGlove and Didjiglove [see Fig. 2(e)] as well as prototypes developed by research laboratories around the globe, such as the TUB-Sensor glove [9]–[11]. Although these gloves differed from the original Data Glove in terms of sensor technologies, locations, and mounting, they all shared three basic design concepts with it: they measured finger joint bending, used a cloth for supporting sensors, and were usually meant to be general-purpose devices. As will be reviewed in Section III, by virtue of this last feature, they were indeed used in a variety of projects spanning different fields. Despite their widespread use, they suffered from several drawbacks. Major limitations originated from the cloth support, which acted as a constraint on the user's hand, and from the need for a tedious user-specific calibration procedure. Limitations of this class of gloves will be revisited in greater detail in Section IV.

3) Beyond the Data Glove: Driven by the need to overcome the aforementioned weaknesses, researchers started exploring the viability of different designs. The Fingernail glove was developed by Mascaro and colleagues at MIT [see Fig. 2(f)]. It exploited changes in coloration of the fingernail due to touching, bending/extension, and shear. Infrared LEDs illuminated the nail bed and an array of eight photodiodes mounted on the fingernails measured the intensity of the reflected light (proportional to the blood content under the fingernail). Finger postures (bending angle of the PIP joint) and forces (normal force, shear force, and longitudinal shear force) were predicted from the measured data [12]–[14]. The AcceleGlove proposed by Hernandez and colleagues at George Washington University used five rings to support five accelerometers [15]–[17] [see Fig. 2(g)]. To overcome the problem of constant breaking of wires, a second version of this glove was designed where the accelerometers were attached to a leather glove. The Lightglove, proposed by Howard and Howard was a watch-size wireless device worn underneath the wrist. It used a five-pixel LED scanner/receiver sensor array, and detected finger motion via sensing the disruption of beams of light that fanned out from the wrist. Additional motion was recorded by accelerometers [18], [19]. In the past couple of years, a number of sensorized gloves for alphanumerical character entry in wearable and portable computers have been proposed. They include the Thumbcode, the Fingering, Scurry, Keyboard-Independent Touch-Typing (KITTY), and the Senseboard glove, which will be discussed in more detail in Section III ("Wearable and Portable Computers"). While all these devices stand out for their originality and overcome some of the limitations of the Data Glove-like devices (e.g., most have no cloth), as detailed in Tables II–IV, they have individual limitations. Additionally, they were designed for specific applications rather than for general purpose.

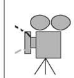
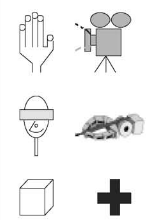
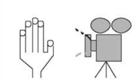
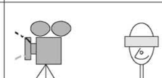
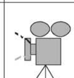
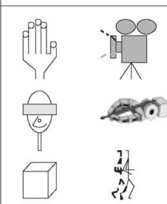
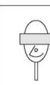
Frontier research in glove technology promises gloves based on textile integrated sensors [see Fig. 2(h)]. We will discuss the most recent research trends in Section IV.

C. Current Technology

While numerous glove designs were proposed over the past 30 years, only a few became commercially available. This section lists design specifications for the most recent commercial technology, roughly in chronological order starting from the early 1990s. We refer the reader to [1] and [4] for an extensive description of the devices developed in the 1970s and 1980s.

1) CyberGlove: Developed by James Kramer at the Virtual Exploration Laboratory of the Center for Design Research

TABLE II
GLOVES COMPARISON

Device	Technology	Sensors	Sensor Precision	Records/sec	Interface	Applications	Advantages/ Disadvantages
Sayre Glove (University of Illinois) [1]	flexible tubes - light source	7 flex C	N/A	N/A	N/A	multidimensional control of sliders and other 2D widgets	legacy equipment
MIT LED Glove (MIT) [1]	LED	N/A C	N/A	N/A	N/A		legacy equipment
Digital Entry Data Glove (AT&T Bell Telephone) [3]	N/A	4 flex C	N/A	N/A	N/A		legacy equipment
Data Glove (MIT, VPL Inc.) [4] [6]	fiber optic	5-15 flex C	12 bit	30-160 Hz	serial		good amount of literature/ non-linear mapping between joint movement and intensity of reflected light, no abduction - adduction sensors (early models), sampling inadequate for time-critical applications (early models), difficult recordings from thumb, calibration required for new users
Power Glove (Mattel Intellivision [4] [7]	piezo-resistive	4 flex C	2 bit	N/A	serial		very low cost/ low precision, calibration required for new users
P5 Glove (Essential Reality Inc) [8]	piezo-resistive	5 flex C	0.5 deg	60 Hz	USB		very low cost/ calibration required for new users
Space Glove (W Industries, Virtuality Entertainment Systems) [2]	fiber optic	6 flex C	12 bit	N/A	works only with W Industries products		fairly responsive/ uncomfortable, scarce literature available
CyberGlove (Stanford University, Virtual Technology) [21] [24]	piezo-resistive	18, 22 flex C	8 bit	150 Hz unfiltered 112 Hz filtered -with 18 sensors	serial		equipped with abduction - adduction sensors, large amount of literature, wireless version available/ 1 size, difficult recordings from thumb, calibration required for new users, very expensive
Super Glove (Nissho Electronics) [4]	piezo-resistive (proprietary technology)	10-16 flex C	0.3 deg	0.2 ms/ sensor	serial		different sizes available wireless version available / abduction -adduction sensors, calibration required for new users, scarce literature

In the column, labeled "sensors," "FLEX" indicates that the glove measures hand joints flexion and "C" the sensors mounted on a cloth. The number refers to the number of sensors per glove. The seventh column, labeled "applications," reports the major applications we found in the literature for each device.

(CDR) at Stanford University, it was commercialized by a CDR spin-off, Virtual Technologies, Inc. (Palo Alto, CA) in 1992. It comes equipped with 18 or 22 piezo-resistive sensors. The 18-sensor model features two bend sensors on each finger (MCP and PIP joints—see Fig. 1), and four abduction/adduction sensors, plus sensors measuring thumb crossover, palm arch, wrist flexion, and wrist abduction/adduction. The 22-sensor model features four additional sensors for measuring DIP joints flexion. Calibration is needed to make glove measurements insensitive to differences in users' hands, finger length, and thickness and convert sensor voltages to joint angles. It is performed with the VirtualHand calibration software by having the user flex their hand a few times and editing the gain and offset parameter value for each sensor to best match the motion of the virtual hand to the physical hand. The VirtualHand line of software also includes several packages for manipulation

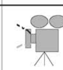
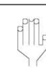
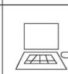
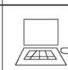
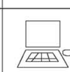
TABLE III
GLOVES COMPARISON (SEE FOOTNOTE OF TABLE II)

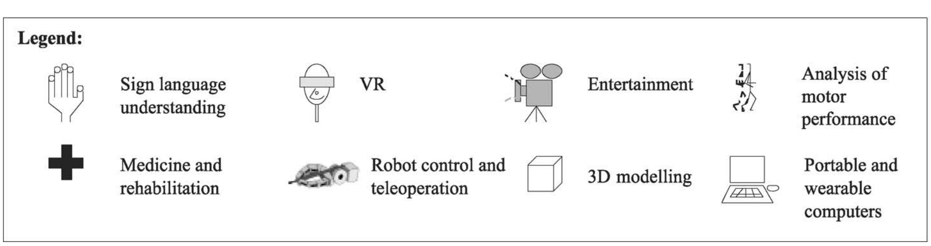
Device	Technology	Sensors	Sensor Precision	Records/sec	Interface	Applications	Advantages/ Disadvantages
5DT, 16DT Glove (5DT) [25]	fiber optic (proprietary technology)	5 (5DT) 14 (16DT) flex C	8 bit	200 Hz (5DT), 100 Hz (16DT)	serial, USB, adapter available		left-right-handed models available, wireless version available, MRI compatible version available, fair amount of recent literature, equipped with abduction -adduction sensors (16DT)/ 1 size, calibration required for new users
Pinch Glove (University of Central Florida, Fakespace Labs Inc) [26]	electrical contacts	7 C	1 bit	N/A	serial		over 1000 postures possible, no calibration, different sizes available/ does not record joint angles
TCAS Glove (T.C.A.S. Effects Ltd) [34]	piezo-resistive (proprietary technology)	8,11,16 flex C	N/A	N/A	N/A		the company produces a range of body sensing products, e.g., sensing jackets and pants to be used with the glove/ scarce literature
TUB-Sensor glove (Technical University of Berlin) [9] [10]	inductive length encoders	12, 22 flex C	8 bit	25 Hz -with 14 sensors	serial		mechanical robustness of sensors, equipped with pressure sensors, available in 3 sizes/ scarce literature
SIGMA glove (Sheffield University) [99]	carbon ink bend sensors	30 flex C	N/A	N/A	parallel		available in 3 sizes, equipped with abduction -adduction sensors, easy donning for disabled users/ scarce literature
Humanglove (Humanware Srl) [96]	Hall-effect sensors	20,22 flex C	0.4 deg	50 Hz	serial		available in 3 sizes, equipped with abduction -adduction sensors, custom design available/ difficult recording from thumb and DIP joints, calibration required for new users
Washington University Glove (Washington University) [127]	pressure sensors and sealed air filled tubes	4 flex C	2.5-3 deg	240 Hz	serial		low cost/ bulky, low precision, leaking air hoses, scare literature
Swedish glove (Swedish Defense Research Establishment, Linkoping University, Orebro University) [11]	air pressure and capacitive sensors	3 pressure, 1 capacitive flex C	N/A	N/A	N/A		low cost/ low precision, scarce literature, not suitable for complex posture recognition, calibration required for new users
Accele Glove (George Washington University) [15]	dual-axis accelerometers	6 C / No C	6.5 deg	100 Hz	serial		no calibration, external tracking system not required, low cost/ cannot recognize horizontal postures

of computer-aided designs (CADs) and character animation [VirtualHand for V5 (CATIA), VirtualHand for MotionBuilder, and VirtualHand SDK]. The CyberGlove is considered one of the most accurate glove systems currently available [2], [4], [20]. A wireless version of the CyberGlove (CyberGlove II) was commercialized in 2005 (Immersion Corporation, San Jose, CA) [see Fig. 2(a)] [21].

2) *Humanglove:* Patented in 1997, it is commercialized by Humanware Srl (Pisa, Italy) [22]. It is equipped with 20 Hall-effect sensors that measure flexion/extension of the four fingers MCP, PIP, and DIP joints and flexion/extension of the thumb TMCP, metacarpal phalangeal (MP), and interphalangeal (IP) joints, as well as fingers and thumb abduction/adduction; two additional sensors measure wrist flexion and abduction/adduction [23].Glove calibration is similar to that of the CyberGlove and is

TABLE IV
GLOVES COMPARISON (SEE FOOTNOTE OF TABLE II)

Device	Technology	Sensors	Sensor Precision	Records/sec	Interface	Applications	Advantages/ Disadvantages
3d Imaging Data Glove (University of Newcastle upon Tyne) [101]	3D electro-magnetic sensors	11 C	0.001 m (position), 0.001 rad*s (orientation)	10 Hz	Ethernet		high precision/ complex system, needs model of the hand, low sampling
Lightglove (Lightglove LLC) [18]	electro-optical, accelerometers	5-pixel LED scanner/ receive sensor array	N/A	N/A	USB		wireless, low cost, no cloth/ sensitivity to lighting conditions, pointing motion has limited range and is difficult to control
Fingernail glove (MIT) [13]	electro-optical	6 LED/ 8 photodiodes per sensor	10 deg	N/A	N/A		no cloth, can also measure force/ simultaneous prediction of position and force data is not possible
Didjiglove (Didjiglove Pty. Ltd) [24]	capacitive sensors	10 flex C	10 bit	200 Hz	serial		deeply integrated with 3D Studio MAX and MAYA, available in left and right models/ calibration required for new users, scarce literature yet (probably due to the fact that the device is quite recent)
Acceleration Sensing Glove (Berkeley University) [174]	accelerometers/ MEMS	6 C	10 bit	34.7 Hz	serial		wireless/ scarce literature
StrinGlove [27]	magnetic	24 flex C	12 bit	30 Hz	serial		washable (sensors are easily detachable), 3 sizes, designed for easy wearing on and off , embedded DSP-based encoding system for hand posture recognition available/ sensors are fragile (although easy to replace), calibration required for new users
Chording Glove [129]	switches	5 C	1 bit	N/A	N/A	 	portability/ non trivial training to learn chords
Thumbcode [131]	switches	12 C	1 bit	N/A	N/A		portability/ non trivial training to learn chords
Fingering [132]	accelerometers	5	N/A	N/A	N/A		portability/ non trivial training to learn chords, little information available
Scurry [133]	gyroscopes	4	N/A	N/A	N/A		portability, no cloth/ user must maintain specific hand posture, little information available
KITTY [136]	printed-circuit wires	5	N/A	N/A	N/A		portability, no cloth, QWERTY keyboard inputs/ little information available
Senseboard [135]	N/A	N/A	N/A	N/A	N/A		portability, no cloth, QWERTY keyboard inputs/ user must maintain specific hand posture, little information available



performed through a software package called Graphical Virtual Hand, which displays an animated hand that mirrors movements of the user's hand [see Fig. 2(b)].

3) 5DT Data Glove: Commercialized by Fifth Dimension Technologies (5DT) (Irvine, CA), it comes in several versions. The 5DT Data Glove 5 uses proprietary optical-fiber flexor sensors. One end of each fiber loop is connected to a LED, while light returning from the other end is sensed by a phototransistor. The glove measures the finger bending indirectly based on the intensity of the returned light [24]. There is one sensor per finger

Fig. 2. Glove systems. (a) CyberGlove II. Reproduced by permission of Immersion Corporation. Copyright © 2008 Immersion Corporation. All rights reserved. (b) Humanglove. Image courtesy Humanware. (c) 5DT Data Glove. Image courtesy www.5dt.com. (d) Pinch Glove. Image courtesy Fakespace Systems. (e) Didjiglove. Image courtesy John Timlin, Didjiglove Pty. Ltd., Melbourne, Australia. (f) Fingernail Sensor [186]. Image courtesy H. H. Asada. (g) AcceleGlove [15]. Copyright © ACM. Reprinted by permission. (h) Upper limb garment prototype [187] and sensing glove [188] by Pisa University: sensors are directly integrated in Lycra fabrics by using conductive elastometers sensors. © 2006 IEEE and © 2005 IEEE.

to measure overall flexion of the four fingers (average of MCP and PIP joint flexion) and thumb (average of MP and IP joint flexion). The 5DT Data Glove 16 [see Fig. 2(c)] is a higher end version of the 5DT Data Glove 5 and has 14 sensors. It measures finger flexion (two sensors per finger, MCP and PIP joints as well as IP and MP joints) and abduction/adduction between fingers. Wireless versions and versions optimized for use in MRI environments (the 5DT Data Glove 5 MRI and the 5DT Data Glove 16 MRI) are available [25]. These gloves require calibration, which is similar to that of the Cyberglove. The 5DT Data Glove software interprets the glove readings as gestures. The current gesture library uses binary open/close configurations for the fingers, excluding the thumb, so that $2^4 = 16$ possible gestures can be generated. Gesture "0" is defined as all the fingers closed and gesture "15" as all the fingers open. In the 5DT Data Glove 5, a finger is considered unflexed/flexed if the sensor reading is smaller/greater than a predetermined lower/upper threshold. In the 5DT Data Glove 16, the maximum of the individual joint sensor values is taken to obtain a closed gesture, and the minimum to obtain an open gesture [24], [25].

4) Pinch Glove: The first prototype, originally called the Chord Glove, was developed by Mapes at the University of Central Florida. Commercialized by Fakespace Laboratories (Mountain View, CA) [26] [see Fig. 2(d)], it uses electrical contacts at the fingertips, on the back of fingers, or in the palm. When two or more electrical contacts meet, a conductive path is completed and a posture can be made. The PinchGlove interface detects whether a posture has been made and keeps a record of the posture duration. Postures can be programmed, and no additional posture recognition techniques are required. This makes the PinchGlove excellent for posture recognition with over 1000 postures theoretically possible [4]. A salient feature of this glove is that it does not require calibration.

5) Didjiglove: Recently commercialized by Didjiglove Pty, Ltd., the Didjiglove [see Fig. 2(e)] uses ten capacitive bend sensors to record finger flexion (fingers MCP and PIP, and thumb TCMP and MP). The sensors consist of two layers of conductive polymer separated by a dieletric. Each layer is comb-shaped; a change in the amount of sensor bending results in a change in the overlapping electrode surface, and ultimately in a change in capacitance. The Didjiglove requires calibration: to calibrate the glove, the user makes hand shapes and records these by pressing the appropriate buttons. It is designed for computer animation, and specifically to function as an advanced programming interface for toolkits such as 3-D Studio Max and Maya [24], for which software drivers are provided.

6) StrinGlove: Recently proposed by a group of Japanese researchers and commercialized by Teiken Limited in Japan, it uses 24 inductcoders to record MCP, PIP, DIP angles of fingers and MP and IP angles of thumb, abduction/adduction angles of fingers and thumb, as well as wrist motion. It is also equipped with nine contact (magnetic) sensors, placed one in the thumb and two on each finger (tip and PIP phalanx). It requires calibration. A salient feature of this glove is the cloth design: the glove is washable and the sensors are easily detachable [27], [28].

D. Glove Accessories

1) 3-D Trackers: A complete description of hand movement requires knowledge of both hand configuration (amount of joint bending or joint relative positions) and hand position in space (location and orientation of the hand, for a total of 6 DoFs—3 for translations and 3 for rotations). While sensorized gloves record the former type of data, trackers record the latter. Usually, gloves and trackers are used in conjunction. Commercial systems typically contain both.

Over the years, several trackers have been proposed that differ in their key performance parameters (accuracy, jitter, drift, and latency). Most of the trackers currently used are noncontact position measurement devices (typically magnetic, ultrasonic, or optical). Noncontact trackers have largely replaced the earlier mechanical trackers, kinematic structures composed of links interconnected using sensorized links: they are less cumbersome and do not hinder the user's freedom of motion. In this section, we chose to focus on the technology basics and refer the reader elsewhere [24], [29] for further details.

a) *Magnetic*: A magnetic tracker uses a magnetic field produced by a stationary transmitter to determine the position of a moving receiver element [24]. Advantages include the low cost, reasonable accuracy, and no requirement of direct line of sight transmitter–receiver. Disadvantages include sensitivity to magnetic fields and ferromagnetic materials that may be in the workspace. Metallic objects need to be removed from the area close to the transmitter or receiver.

b) *Ultrasonic*: A ultrasound tracker uses an ultrasonic signal produced by a stationary transmitter to determine the position of a moving receiver [24]. Unlike magnetic trackers, ultrasonic trackers do not suffer from metallic interference. However, they suffer from echoes from hard surfaces and require direct line of sight from transmitter to receiver. If an object obstructs the line of sight between an ultrasound transmitter and receiver, the tracker signal is lost. Update rate is approximately 50 datasets/s, less than half that of magnetic trackers.

c) *Optical*: An optical tracker uses optical sensing to determine the real-time position/orientation of an object [24]. Similar to acoustic trackers, optical trackers require direct line of sight and are insensitive to metallic interference. However, when compared with acoustic trackers, optical trackers have significantly higher update rates and are capable of much larger work envelopes. Disadvantages include sensitivity to reflection of light from surfaces in the environment.

d) *Inertial*: An inertial tracker is a self-contained sensor that measures the rate of change of an object's orientation or the rate of change of an object's translation velocity [24]. Advantages include sourceless operation with theoretically unlimited range, no line-of-sight constraints, and very low sensor noise. A major disadvantage is that to derive position or orientation, the output of inertial trackers must be integrated and the result is sensitive to drift and bias of the sensors.

2) Actuators: Gloves equipped with actuators can provide force-feedback to the user's fingers, i.e., when worn these gloves can convey touch sensations to the user's hand. Several gloves of this sort, sometimes called "haptic", were proposed over the years. Features include number of actuators, maximum force, weight, and bandwidth. An important design choice is whether they use separate sensing gloves. Some devices are exoskeletons worn on the fingers and hand that do not use sensing gloves. For instance, the Dexterous Hand Master developed in 1987 as a master device for the four-digit dexterous robot Utah/MIT hand was an exoskeleton attached directly to the fingers with Velcro straps [30], [31]. Hall-effect sensors at the joints measured the bending of the three joints of each finger as well as abduction/adduction of the fingers and motions of the thumb. Similarly, the Rutgers Master II developed by Burdea and colleagues at Rutgers University was composed of an exoskeleton that functioned as both a force-feedback structure and a measuring device [32]. Other devices use separate sensing gloves. For example, the Rutgers Master I was an exoskeleton designed to retrofit a Data Glove [33]. Similarly, the commercial CyberGrasp (Immersion Corporation, San Jose, CA) is an exoskeleton that fits over a CyberGlove [21]. In this paper, we chose to focus on nonactuated gloves. The reader is referred to [34] and [35] for a more complete description of actuated gloves.

III. Applications

This section surveys applications of glove-based systems in seven areas. It is divided into two parts, which describe classical and recent applications. The first part describes applications in design and manufacturing, information visualization, robotics, art and entertainment, and sign language understanding. These applications were explored since early research on glove systems. We chose to focus on the work from the mid 1990s onwards and refer the reader to Sturman and Zeltzer's paper [1] for earlier work. The second part describes applications in medicine and health care and in portable and wearable computers. While these areas have just started looking at glove systems, they are already demanding a shift-of-gears in glove technology. The material presented in each area has no pretense of being exhaustive. Rather, it focuses on representative projects and the rationale for using glove systems (see Table V for a summary).

A. Classical Applications

1) Design and Manufacturing: In this area, glove-based systems are used to interact with computer-generated (typically virtual reality) environments. Using a computer screen or a head-mounted display, the user, who can be located either on site or remotely over the Internet [36], [37], can visualize environments or artifacts that are being designed before their actual construction or manufacturing eliminating the need for expensive mock-ups. Compared to traditional interfaces such as keyboards and mice, glove-based systems allow a more natural interaction with the environment; for example, the user can grasp virtual objects or issue commands via gestures. Typical commands include the "flying" gesture (pointing with the index finger changes the users' viewpoint through the virtual world as if they were flying through that space [38]–[40]) or the "pinching" gesture (pinching between the fingers and thumb selects an option from a menu [41]).

Following the Virtual Environment Display System, a National Aeronautics and Space Administration (NASA) virtual reality pioneering project of the mid 1980s [42], a variety of similar systems were proposed over the years. Tinmith was developed at the University of South Australia for assisting in the design of outdoor and indoor environments. The user could capture and view on-site 3-D graphical models for existing outdoor environments, for example, a building, and integrate them with virtual reality models of indoor environments. Pinch Gloves were used to control the menu system allowing the user to select options [see Fig. 3(a)] [41]. Interactive synthesis of spherical mechanisms (ISIS) and VRSpatial were developed

TABLE V
SUMMARY OF APPLICATIONS

Category	Application	Rationale	Alternative	Purpose
Classical Applications	Design/manufacturing	interact with computer-generated environments in a more natural way	keyboard, mouse	virtual architecture: test environments before their contruction virtual prototypes: test artifacts before their production 3D modelling virtual training
Classical Applications	Information visualization	interact with data in a more natural way	keyboard, mouse	scientific visualization: manipulate scientific data audio-visual presentations: manipulate data
Classical Applications	Robotics	control and program robots in a more natural way	keyboard, mouse	mobile robots: control a robot or a team of robots multi-DoF robots: control many DoFs simultaneously programming by demonstration: teach skills to robots in a natural way
Classical Applications	Arts/entertainment	interact with computer-generated environments in a more natural way	keyboard, mouse	computer-animated characters: control many DoFs simultaneously musical performance: control acoustic parameters videogames
Classical Applications	Sign language understanding	automatic translations	camera-based device	communication systems for the deaf
Recent Applications	Medicine/ Health care	easy/quick measurement of hand motion	motion analysis system, goniometer, keyboard, mouse	motor rehabilitation: diagnosis, treatment human motion analysis ergonomics medical education and training
Recent Applications	Computers	enhance computers' portability	keyboard and mouse	wearable computers

at Iowa State University. They were systems for assisting in the design of spherical mechanisms. Users could walk into a 3-D space, synthesize a mechanism, and then, move around the space to evaluate the mechanism's motion. Interaction with the systems was performed through a combination of gestures recorded with Pinch Gloves and selections from 3-D menus [see Fig. 3(b)] [43]–[45]. In the industrial world, Daimler-Benz and Boeing were among the first to develop virtual reality systems for design. Daimler-Benz's testers could select between different furnishing options and models for Mercedes interiors using Data Gloves. Boeing's designers and maintainers could evaluate and test the military aircraft Joint Strike Fighter using CyberGloves. Designers could "walk" around a virtual aircraft as if they were on a carrier deck and simulate maintenance tasks (e.g., loading a weapon or removing a part). In both projects, gloves were used to select options from menus [46]. Related applications also include virtual reality systems for training of skilled personnel, such as pilots (cockpit familiarization [47]), soldiers [48] [see Fig. 3(c)], and astronauts [49] [see Fig. 3(d)].

3-D modeling is another application of glove-based systems in the design and manufacturing area. Software for 3-D modeling is typically used by architects, industrial designers, and fine artists to visualize 3-D shapes, often at a late stage of design after pencil sketches have been drawn. Gloves allow creation of 3-D shapes directly using hands, which may make the design process more natural and easier since its earlier stages [50]. Weiner and Ganapathy first implemented this concept. They used hand gestures captured by a Data Glove to create B-spline-based 3-D models. Fingertips were used to specify the position of a series of control points for the curve [1], [51]. A similar system was Surface Drawing. As the user moved the hand wearing a CyberGlove, the trail of its motion was recorded by a computer as a stroke. The strokes could be combined to construct complex shapes. Different configurations of the hand resulted in strokes with different features. For example, drawing with the fingertip allowed very small details to be added; this mode was activated by putting the hand in a pointing posture; bending the hand changed the curvature of the strokes. The user could also move

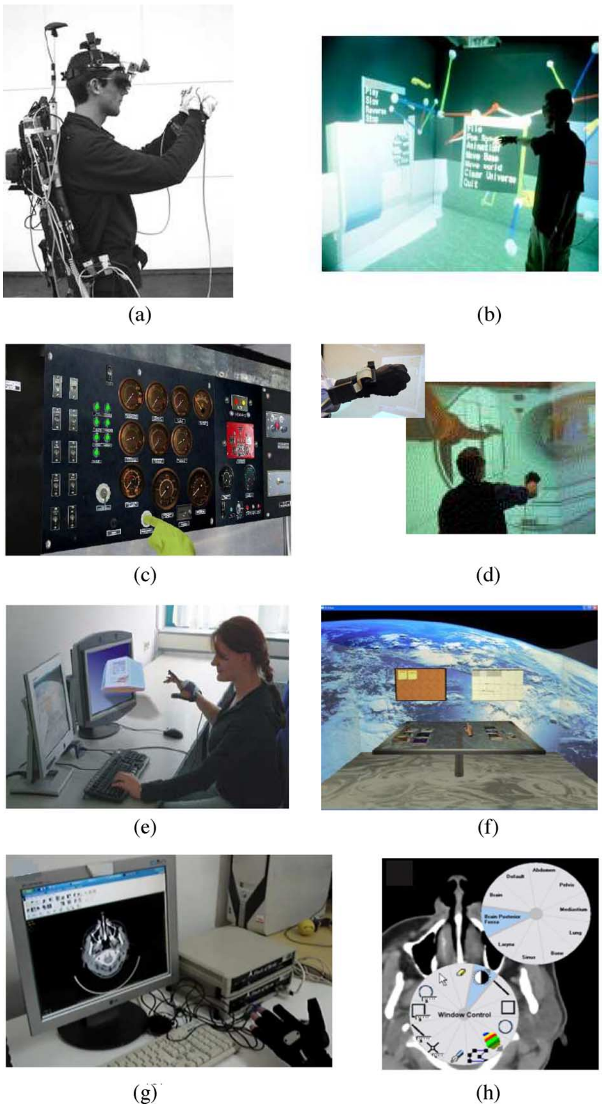


Fig. 3. Glove applications based on gesture recognition. (a) Tinmith wearable computer with glove device [41]. © 2001 IEEE. (b) VRSpatial main menu [45]. Copyright © ASME. Reprinted by permission. (c) Simulator to train drivers of artillery self-propelled gun: the user is performing a "point" gesture during virtual training [48]. © 2006 IEEE. (d) Simulator to train astronauts to perform tasks in microgravity: an object can be selected and grabbed by clenching fingers into a fist gesture. Reprinted from [49], Copyright (2006), with permission from Elsevier. (e) and (f) Virtual desktop: the user can grab a document by making a fist, and release it by opening the fist [58]. © 2006 IEEE. A gesture interface for radiological workstations: (g) by making predefined gestures, (h) the user can call the database browser or tools for analyzing images [57]. © 2007 IEEE.

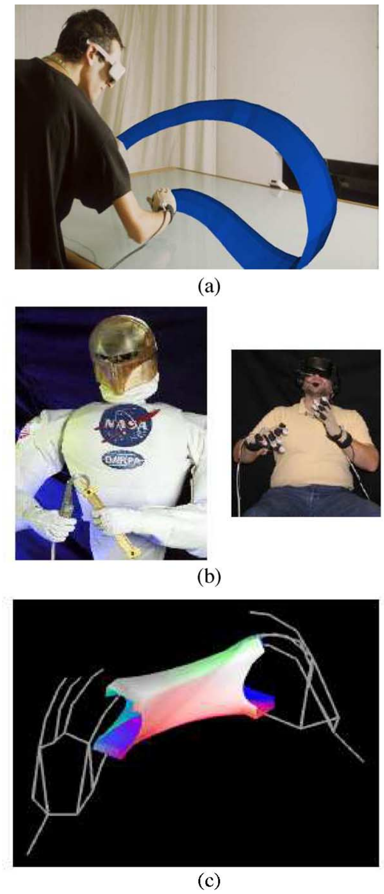


Fig. 4. Glove applications based on continuous data recording. (a) Hand movements create shapes that float above the Responsive Workbench [52]. Copyright © ACM. Reprinted by permission. (b) NASA/DARPA Robonaut and telepresence gear: the Robonaut mimics the operator's hand motions [189]. © 2003 IEEE. (c) Sound sculpting: a sheet clamped to the index and thumb tips of the two hands [20]. Image courtesy A. Mulder.

and scale the shapes using tools such as tongs and erasers. Surface Drawing was implemented on the Responsive Workbench, a virtual reality system developed in the 1990s comparable to a large drawing board and operated by projecting a computer-generated stereoscopic image off a mirror and through a table surface. Using stereoscopic shuttered glasses, the user could observe a 3-D image displayed above the tabletop [52], [53] [see Fig. 4(a)].

2) Information Visualization: Computer graphics is often used to create visual representations to aid in the understanding of data. Good data visualization techniques are especially useful when data are complex numerical representations of scientific concepts or results, e.g., the outputs of simulations [29]. Glove-based systems can potentially improve the naturalness of the user's interaction with the data, thereby potentially enhancing the effectiveness of traditional data visualization techniques.

Bryson and Levit from NASA showed the feasibility of this concept with the virtual wind tunnel in the late 1980s. Users could visualize a simulated airflow around an aircraft. Using a Data Glove, they could "grab" onto one or more streamlines of the fluid flow, move them, and observe the changes in the flow, which were calculated and visualized by supercomputers in real time [1], [42]. Malkawi and colleagues proposed a similar system for interacting with indoor thermal computational fluid dynamic data. Wearing a CyberGlove users could issue commands to the system via mimicking predefined postures such as "closed fist" and "open flat palm." Such postures encoded commands of precise or approximate data positioning (e.g., create an isosurface in a precise position in space or move an isosurface in a certain area) [54]. The Responsive Workbench, which was described earlier, was a platform for many data visualization systems that were developed in the past years (see [55] for a review). Recent data visualization applications also include systems for manipulating massive geospatial [56] and medical data [57] [see Fig. 3(g) and (h)] or generic computer files [58] [see Figs. 3(e) and (f)].

3) Robotics: Glove-based systems can potentially make robot programming—a central issue in robotics—more natural and easier, particularly when methods based on teleoperation or automatic programming are used. This is particularly true for multi-DoF systems that require the control of a large number of joints, which is difficult to accomplish with standard control techniques. In automatic programming, the robot learns its behavior automatically, for example, "observing" a demonstration performed by a human [59]. This method is receiving growing attention as robots are increasingly used in nonstructured environments, in tasks unpredictable *a priori*, and by nonspecialized personnel.

After Sturman's seminal work showed the feasibility of using gestures as interfaces for robot control [2], several researchers pursued this approach. For instance, Iba and colleagues at Carnegie Mellon implemented a system to control a mobile robot via a CyberGlove. The user communicated with the robot using six gestures (opening, opened, closing, pointing, waiving left/right) that corresponded to commands: for instance, "closing" decelerated and stopped the robot, "waiving left/right" directed the robot toward the direction in which the hand was waiving [60]. Several researchers used glove-based systems to teleoperate multifingered robotic hands [1], [61], [62]. One of the most impressive recent applications was implemented on the NASA/Defense Advanced Research Projects Agency (DARPA) Robonaut [see Fig. 4(b)], an anthropomorphic human scale robot designed to reduce the extravehicular activities burden on astronauts. Wearing a helmet equipped with a stereo screen, stereo phones, a microphone, and two CyberGloves linked directly to the robot's stereo cameras, stereo microphones, speaker, and five-finger dextrous hands, respectively, the user could teleoperate the robot to perform maintenance tasks such as threading nuts into bolts and tying knots [63].

Other researchers used gloves to teach robots manipulation skills from demonstration [64], [65]. Ogawara and colleagues implemented this concept on an anthropomorphic robot that was equipped with a stereo vision system, dual 7 DoF arms, and multifingered hands. The robot observed the human instructor perform the task while wearing two CyberGloves and constructed a task model in two steps. First, using the information recorded from the gloves, it constructed a rough model of the task as a sequence of discrete hand actions (power grasp, precision grasp, release, pour, hand over) and its attributes (start and stop time, absolute position in space, left or right hand). Processing the images recorded with the vision system, it then refined the model of the task adding information about the type of objects that were being manipulated. At the end of this process, the robot was able to perform the task demonstrated by the instructor (pouring the content on a container held in one hand into another container held in the other hand) even in environments different from those used for training [66]–[68].

4) Art and Entertainment: Attraction between glove-based systems and the entertainment industry has been long-standing. Gloves have been used for video games and animation of computer-generated characters [1], [2], [24], [69]–[71] as well as movie productions [72]. These applications, like robotics, often require the control of many DoFs, a problem that can be easily addressed with glove systems. Glove devices have also been used in musical performance, typically to control acoustic parameters [2], [73]–[76]. In this context, not only gloves allow simultaneous control of many DoFs but they also give the musician the freedom to move expressively, transmitting that expression to music [2].

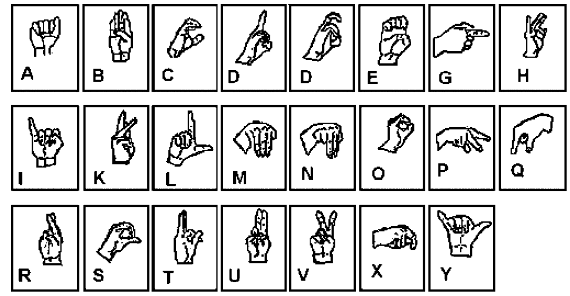


Fig. 5. Vietnamese sign language [151]. © 2007 IEEE.

After MIT Media Laboratory composer Tod Machover pioneered this application in the early 1990s [1], several groups proposed similar systems. Sound Sculpting, prototyped by Mulder and Fels, was among the most original projects. Wearing two CyberGloves, the user manipulated 3-D virtual objects, such as a rubber balloon or a rubber sheet. Position, orientation, and shape of the objects could be modified via hand gestures. Changes of the objects were mapped to changes in acoustic parameters. For example, fingertips of both hands could be clamped to the corners of the rubber sheet; a change in the distance between index and thumb caused a visual change in the width of the rubber sheet and an acoustic change in the chorus depth [77] [see Fig. 4(c)]. The reader is referred to [75] and [76] for extensive reviews of application of glove-based systems in musical performance.

5) Sign Language Understanding: After the pioneering project of Grimes with the Digital Entry Data Glove (Section II), many projects used glove-based systems for automatic understanding of gestural languages used by the deaf community [1] (see Fig. 5 for an example). The systems developed in these projects differed in characteristics such as number of classifiable signs, which could range from a few dozen to several thousand, types of signs, which could be either static or dynamic, and percentage of signs correctly classified. The simplest systems were limited to understanding of finger spelling or manual alphabets (a series of hand and finger *static* configurations that indicate letters). Takashi and Kishino [78] and Murakami and Taguchi [79] used a Data Glove for recognition of the Japanese alphabets. For recognition of the American alphabet, Medhui and Kahn used a Data Glove [80] whereas Hernadez-Herbollar used an AcceleGlove [16]. The more complex systems aimed at understanding sign languages, a series of *dynamic* hand and finger configurations that indicate words and grammatical structures. For instance, Kim and colleagues used a Data Glove for recognition of the Korean language [81], Kadous a Power Glove for the Australian language [82], Vamplew a CyberGlove for the Australian language [83], Gao and colleagues a CyberGlove for the Chinese language [84], [85], and Liang and Ouyoung a Data Glove for the Taiwanese language [86]–[88]. The reader is referred to [89] and [90] for a detailed comparison.

Some systems embedded interfaces for translating sign languages into text or vocal outputs [91]–[93]. For instance, the Talking Glove used a CyberGlove and recorded, recognized, and translated American sign language into text or spoken English [94].

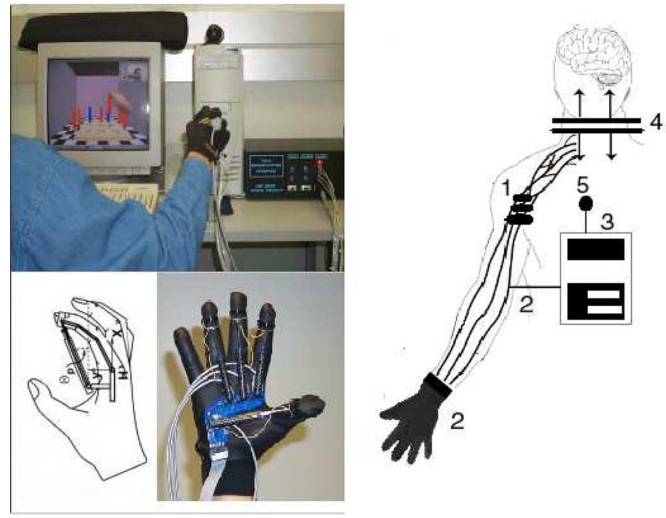
B. Recent Applications

1) Medicine and Health Care: While originally glove systems were not intended for being applied in medicine and health care, they have increasingly been attracting attention of researchers in these areas. Early research was limited to automatic sign language recognition (described earlier). Current research is exploring the suitability of these systems for a greater range of applications, as described later.

a) *Motor Rehabilitation:* In this area, most projects have explored the viability of using glove-based systems as tools for hand functional assessment. Clinical assessment of hand function requires acquisition of a number of data, including pinch and grip strength, sensitivity to temperature, and most importantly, the range of motion of hand joints. Quantitative measurements of range of motion are usually performed using mechanical or electronic goniometers, but the process is time-consuming and can have limited accuracy and repeatability, even when performed by a skilled therapist [95]. As glove systems can measure the range of motion of all hand joints simultaneously during dynamic tasks, they can potentially speed up the measurement process.

While some researchers explored the feasibility of using commercial gloves as goniometric devices [96]–[98], others developed *ad hoc* sensorized gloves so as to take into account the specific needs of disabled users [99], [100] or to obtain greater measurement performance [101]. A few groups used sensorized gloves as part of more complex systems for hand functional assessment/motor rehabilitation (see [24] and [102] for a summary). Among them, Greenleaf Medical Systems developed the Wrist System, a tool for quantitative dynamic assessment of the upper extremity function. It used a Data Glove with specially fitted sensors to record wrist flexion/extension and radial/ulnar motions [92].

Several virtual reality workstations for motor therapy that employed glove-based systems have been proposed [24], [103]–[105]. Patients undergoing such therapies first have their hand motion measured with a glove device. The recorded data are then transmitted to a computer that assesses the patients' hand capability and plans the treatment. During a treatment session, the patients perform hand exercises with a haptic glove, which, for example, generates forces that resist their grasping movements [106]. The workstation proposed by Burdea and colleagues was composed of two subsystems. The diagnostic subsystem consisted of an electronic goniometer, a pinchmeter, a dynamometer, and a 16-sensor Data Glove-like device modified to contain 16 force sensors. The therapy subsystem used a Rutgers Master I haptic glove [33] to provide the user's fingers with force-feedback. The user could perform virtual exercises, such as squeezing a virtual ball or the peg-in-hole exercise [32], [33], [107]–[110] [see Fig. 6(a)]. While most therapy virtual reality workstations were designed for stroke survivors, clinical studies on other patient populations such as postsurgical patients (e.g., carpal tunnel syndrome) are ongoing [102], [111].



(a) (b)

Fig. 6. Applications in motor rehabilitation. (a) Rutgers University virtual rehabilitation system [107]. © 2000 IEEE (top figure). The haptic glove reads gestures and applies forces to the user's hand in real time [32]. © 2002 IEEE (bottom figure). (b) Scheme of the GRIP system: (1) neural electrodes, implantable stimulator, and telemetry system; (2) artificial sensors (position, contact); (3) control system; (4) system for high-level control, (5) system to provide cognitive feedback.

Functional restoration is another application of glove systems in motor rehabilitation. At Advanced Robotics Technology and Systems (ARTS) Laboratory, we used a sensorized glove for this purpose in the framework of the European project GRIP (ESPRIT Long Term Research Programme No. 26322). GRIP aimed at building a closed-loop control system for functional electrical stimulation to restore grasping in hemiplegic patients. Disabled subjects wore a Humanglove modified with eight force sensors whose signals were used in the sensory-feedback loop [see Fig. 6(b)].

b) *Analysis of Motor Performance:* In this area, glove systems are mainly used as alternatives to motion analysis systems. In the latter, markers are typically attached to subjects' hands and the marker's positions are recorded by video cameras. While providing accurate measurements, they require long and tedious calibration procedures and suffer from several limitations, including occlusion of markers and sensitivity to reflected light (see also Section II, "Glove

Accessories"). Glove-based systems are cheaper and easier to set up; for these reasons, they are being increasingly used in this area.

Gloves have been used in numerous experiments aimed at investigating grasping movements during which subjects are typically asked to grasp real [112]–[115], imaginary [116], or computer-generated [117] objects. Features are extracted from the recorded data to quantitatively describe and infer information about the movement. For example, angles spanned by fingers were used to infer hand shapes [112], [116], [118]. Several groups used glove-based systems to investigate grasping in zero-gravity conditions. In 1998, during the NASA NeuroLab Mission, astronauts used a custom-made glove equipped with LEDs on the fingertips to study changes induced by microgravity in eye–hand coordination [119]. More recently in a project funded by the Italian Space Agency, ARTS Laboratory and Kayser Italia Srl developed the Hand Posture Analyzer, a system that included a reengineered version of the Humanglove, a handgrip dynamometer and a pinchmeter to study changes induced by microgravity in hand motor control [120]–[123].

c) *Ergonomics*: Another area where gloves are used as alternatives to traditional motion analysis systems is ergonomics. Here, hand movement recordings are used to perfect the design of products, tasks, or environments. Protomic of the Netherlands used data recorded with a CyberGlove to tune the design of the DataStealth keyboard, an ergonomic keyboard for improved user's comfort and reduced risk of repeated strain injury. The movement of the users' fingers while typing on the DataStealth, on a classic flat keyboard, and on a range of alternative keyboards were recorded. The collected data were then fed to a biomechanical model of stresses and strains in the soft tissues of the hand, so to identify which designs minimized users' efforts [21]. In a Philips factory, a data glove equipped with force sensors and a video camera were used to record hand motions of workers performing assembly tasks. The data were used to redesign the assembly tasks to avoid awkward physiological strains or postures and ultimately to prevent upper limb disorders [124]. At the University of Sheffield, U.K., the SIGMA Glove was used to study causes of failure of prosthetic joint implants. During the performance of simple tasks, such as opening a door or a jar, the rotations of MCP joints were measured and the relative stress patterns were displayed on a monitor in real time [99].

d) *Medical Education and Training*: Virtual reality has introduced new ways of visualizing and manipulating 3-D anatomical data obtained by techniques such as MRI or computerized tomography. This has brought several advantages to the medical community, including methods for medical training with unprecedented features (modeling of rare cases, errors made on virtual rather than real patients) [24], [125].

In the early 1990s, Delp and Rosen created a tendon transplant simulator, which was one of the first virtual reality simulators for medical personnel. Using a head-mounted display and a Data Glove, surgeons could explore a mechanical and anatomic model of the skeleton of the lower limbs. The limbs had mechanical properties and the kinematics of the legs could be animated to simulate walking. To plan a surgery to correct patients with a gait disorder, surgeons could study the effect of modifying the insertion points of tendons. The gait of the patients could then be predicted with the simulator [126]. At the Advanced Research Project Agency, Arlington, VA, a similar system, the virtual abdomen, was developed. It was an abdominal simulator with simple graphic representations of the liver, stomach, colon, pancreas, gall bladder, and biliary tree. Using a head-mounted display and a Data Glove, it was possible to fly around, pick up, and move the organs [40]. Krapichler and colleagues described a virtual reality system for visualizing, processing, and manipulating 3-D tomographic data. The user wore a 5DT Data Glove and interacted with the system using predefined hand gestures, such as pointing, navigation, grasping, and release. For example, a "pointing" gesture enabled selection of segmented objects within the virtual reality scene, e.g., an arterial occlusion inside the abdomen. With the "flying" gesture, hand orientation was transformed into a change of viewing position and orientation evoking an impression of flying through the scene [39].

2) Wearable and Portable Computers: The introduction of gloves as controllers for consumer electronics, and in particular, as text entry and pointing devices for portable and wearable computers is one of the most recent developments in glove-based systems applications. In the search for more portable peripherals, computer makers first pursued the idea of making traditional peripherals smaller. Such solutions had a major limitation: peripherals cannot be miniaturized beyond a certain limit, as they need to be big enough to be seen and easily operated upon with our hands. A new approach based on replacing traditional peripherals with wearable ones was then pursued. Glove-based systems appeared like the perfect solution: postures could be captured and translated into keystrokes or commands, thereby eliminating the need for a physical traditional keyboard.

Early projects attempted to use Data Glove-like devices [127], [128]. Many looked at chord gloves, i.e., gloves that detect data patterns corresponding to hand configurations. The Chording Glove designed by Rosenberg and Slater [129] was equipped with five sensors located at the tips of each finger that detected when a finger was pressed against something. The glove proposed by Cho *et al.* used 14 keys (seven per glove) and chording methods that resembled those for Braille keyboards [130]. The Thumbcode [see Fig. 7(a)] mounted 12 discrete keys (three for each finger). Touch of the thumb onto the keys generated a key stroke. Holding some fingers together and some apart expanded the character set from 12 characters to 96 [131]. Drawbacks of these designs included the constraint placed by the cloth on the user's hand [127], [129], [130] and the nontrivial training required for the user to learn the chords [129], [130].

Fig. 7. Gloves for portable/wearable computers. (a) Thumbcode. Image courtesy V. Pratt. (b) Scurry [134]. © 2005 IEEE. (c) Senseboard. Image courtesy Senseboard Technologies. (d) Design study of KITTY glove. Image courtesy C. Mehring.

Gloves with a number of completely different designs were proposed after this early phase. The Fingering by Fukumoto and colleagues consisted of five finger rings equipped with accelerometers [132]. The rings were connected with a wrist-mounted data processing unit. Chords were generated via sequences of typing actions against a hard surface like in piano playing. Scurry by Samsung [133], [134] [see Fig. 7(b)] used four rings equipped with gyroscopes and a wrist-mounted unit that processed the data. When used as a virtual keyboard, software displayed a keyboard and a pointer on the screen of the computing system. The user could select characters by moving the pointer, whose position was controlled by the user's fingers motions. Senseboard [see Fig. 7(c)] by Senseboard Technologies [135] was composed of two hand straps that slipped onto the user's hands. KITTY by the University of California, Irvine used spiral-shaped printed-circuit wires that wrapped around each finger and the thumb and connected to a "watch-like" unit carrying wireless transmission electronics [see Fig. 7(d)] [136], [137]. All these devices put minimal constraint in the user's hands (no cloth); some (Senseboard and KITTY) were also able to recognize the user's motions as if he/she was typing on a traditional QWERTY keyboard. While their commercialization has been announced several times, to the best of our knowledge, these gloves are not commercially available.

"Projection keyboards" were proposed in the last year. They represent the ultimate attempt to eliminate any constraint to the user's hand. The image of a keyboard is projected via laser beams on a surface, and the motions of the user's fingers over the "keyboard" are detected via optical sensing. The user's hand is bare, and the "keyboard" vanishes when the power is switched OFF. For a detailed description of these devices, the reader is referred to [131].

IV. Discussion of Design Issues and Challenges

This section highlights some important issues that arise when attempting to match a glove device to an application. We focus on unifying ideas that are scattered throughout the vast literature on glove applications. We note that Sturman and Zeltzer have addressed theoretical aspects, independent of the application, of this matching process in [138]. Instead, we chose to focus on the practical aspects, which we accomplish by explicitly highlighting the constraints placed by the application and illustrating the relevant issues with examples taken from the literature. The examples will, we hope, provide the reader with a starting point for further exploration on how the challenges discussed might have since been addressed.

A. *Selecting a Glove With Appropriate Technical Specifications*

Table I lists the various characteristics of glove devices that we examined while surveying existing glove-based systems. Lessons that can be learned from the literature when matching the characteristics of a glove device, either to be designed or to be selected from a pool of existing devices, are discussed in what follows.

1) Sensor Information and Number/Placement: The first decision that a user or producer must make is what information the sensors will provide, their number, and their placement. As indicated in Table I, one can either choose sensors that measure discrete data (e.g., created via electrical contacts like in the PinchGlove or pressing of switches like in the Chording Glove) or continuous data (e.g., Data Glove-like devices).

In applications where hand configurations need to be encoded into different patterns to be classified, the first type of devices may be a natural choice. These are the simplest gloves to design from both a hardware and a signal processing perspective (which shall be discussed in a later section). Generally, the number and placement of sensors in these devices explicitly determines the "dictionary" of the patterns that can be formed/detected, and sensors can be placed anywhere on the glove. Data Glove-like devices that record continuous finger flexion information are better suited for the bulk of applications that involve modeling of the hand, such as representation of the hand in a virtual environment, and monitoring of its DoFs for medical purposes, such as motor rehabilitation. When used for gesture-based applications, they may require complex signal processing algorithms to extract information on hand configurations from the recorded data. The issue of sensor mounting becomes particularly relevant in such devices: cloth supports [see, for example, Fig. 2(a)–(c)] not only result in movement constraints on the user's hand but also affect measurement repeatability (which we discuss in a later section).

A theoretical approach for addressing the problem of choosing the most appropriate number and locations of sensors for glove devices was proposed by Sturman and Zeltzer [138]. It was based on the analysis of the DoFs of the application and their match to the DoFs of the device. We highlight the experimental approach, taken by many, that brings into sharp focus the requirements of the specific application. For instance, in an application where the glove was being used as a keyboard, Edmison and colleagues at Virginia Tech determined the location (and hence number) of sensors by recording and analyzing typing motions of subjects wearing the glove. Data suggested that (piezo-resistive) sensors placed at the PIP finger joints, fingertips, and at the exterior side of the index finger would fully capture the flexion of the vertical fingers, keystrokes, and hand lateral movements. The experiments revealed that the sensors thus placed would fully describe the movements that allow typing [128]. At the ARTS Laboratory, in an application where the glove was being used to control a neuroprosthesis (GRIP project, see Section III), we performed the following experiment: unimpaired subjects, wearing a Humanglove equipped with additional force sensors, were asked to grasp different everyday objects. We recorded the force information for individual sensor placements for the subjects over three trials per grip for each object. The location (and hence number) of sensors was determined by classifying sensor locations based on the quality of their outputs measured in terms of reproducibility and usefulness of the force information produced during the subjects grasping. The sensors outputs were labeled as "not useful" when the sensor was not able to give information about the force produced in at least one of the trials, "useful and reproducible" when the sensor was able to give information about the force produced in all the trials, and "useful but not reproducible" when the outputs of the sensors displayed excessive variability from trial to trial [139], [140]. The experiments revealed the (experimentally) optimal placement of sensors that guaranteed that the outputs produced were useful and reproducible for each of the grips considered.

In short, the experimental approach consists of using actual data to identify and retain those sensor locations that produce the greatest useful yet reproducible information and eliminate those that do not.

2) Glove Measurement Performance: Literature on sensorized gloves typically reports information on the performance of sensors mounted on the glove (summarized in Tables II–IV). One seldom finds information about the measurement performance of the overall glove system (sensors + support + electronics) in terms of repeatability and accuracy. Some exceptions include [141] (CyberGlove), [100] (SigmaGlove), [96] (Humanglove), [97], [142] (DataGlove), and [143] (TUB-Sensor glove). A partial explanation appears to be the lack of a standard methodology for facilitating such broad application-independent comparisons. The community stands to benefit from the development of such standards and by authors including it in their published work in the context of their application. The recent survey paper on gloves used as portable keyboards [131] does just that.

Measurement performance of the overall glove system can help assess whether a glove is suitable for an application and impacts the design requirements of the software that will ultimately be used to decipher the "signal" from the "noisy" sensor outputs [141]. For the Data Glove-like devices, several studies have identified the following factors as potential sources of noise in the sensor outputs (and hence error in the deciphered signal): poor calibration (see [141] for a description of detailed testing on the CyberGlove), flexion/extension movements of the wrist [96], [142], force of the hand grip [142], and wear and tear [144].

Perhaps to a novice user's surprise, it has been well documented that the overall measurement performance for these devices is most influenced by the sensor support and the quality of its fit to the user's hand [27], [96], [97], [100], [141]–[143]. This highlights the main problem with the one-glove-size-fits-all approach when using glove devices where the sensors are mounted on a cloth support. Some commercial gloves are sold in several hand sizes, which may partially mitigate this problem. Depending on the application requirements, the engineering and assembly effort for mounting the sensors on mechanical structures attached directly to the fingers might be worth the resulting improved glove performance.

3) Calibration: Different people may have different hand sizes, finger length, and thickness. As a consequence, glove sensors may overlap different finger locations for different users, which may affect glove measurements. To reduce inaccuracies, most gloves need to be calibrated for a particular user. Calibration is typically performed by asking the user to place their hands in specified gestures (e.g., flat hand, fist, flex the hand a few times). Editing of gain and offset parameters for each sensor may be required to best match the motion of the physical hand with the sensor readings.

Calibration is a time-consuming, tedious process and its results are often not ideal. A source of inaccuracy particularly evident for gloves with many sensors (e.g., Cyberglove) is cross-coupling between sensors. Depending on the level of accuracy required by the application, different calibration approaches can be pursued. Applications that require recognition of a few gestures seem to reach satisfactory levels of precision with the calibration procedure described earlier [145]. More complex calibration procedures are typically needed for applications that require high levels of accuracy, such as those in the area of robotic telemanipulation [145]–[149]. In certain applications, it may even be possible to use uncalibrated gloves. For classification of hand shapes, Heumer and colleagues [150] showed that uncalibrated data can still lead to recognition rates of about 80%, which may be acceptable for applications where occasional misclassifications are not critical. Commercial systems often come with calibration software, but data regarding the dependance of the sensitivity of measurements on calibration are rarely provided.

B. Signal Processing Requirements

While commercial devices are sold with basic software for data acquisition from the sensors, the researcher is often left with the application-specific task of designing the data processing algorithms that operates on the raw (noisy) sensor outputs. While algorithms are dependent on the specific glove application, they also share a common structure that we discuss next.

Glove applications can be divided into two main classes: applications where the gloves are used as monitoring devices and applications where gloves are used to communicate a command, a character, or a word. In the former class, continuous data are recorded. Analysis of motor performance is a typical application of this class. In the latter class, the recorded data (either continuous or discrete) are typically processed to extract the command, character, or word. Gesture-based applications are a typical example. As discussed in Section III, such applications span fields such as robotics, sign language understanding, etc.

Processing algorithms for the first class of applications typically require just a single step of processing to extract the "signal"/feature being monitored from the raw sensor output. Occasionally, a second step for feature classification or recognition is needed. The feature extraction procedure of the first step is usually obvious from context. For instance, Jack and colleagues used a glove device to record continuous joint angle movements' data from stroke patients undergoing virtual reality motor therapy to assess their progress during treatment. The first (and only) processing step simply involved extraction of a feature, the range of motion of the fingers [110], whose values were compared across different treatment sessions. At ARTS Laboratory, we used a glove device to record continuous joint angle movements' data from orthopedic and unimpaired subjects to develop a tool for hand functional assessment. The feature extraction step was performed using the method of principal components. The features thus extracted were then subsequently classified. This involved clustering the data that led to the identification of three different groups: unimpaired, patients who had undergone surgery, and patients who were still waiting for surgery [98]. Generically speaking, feature extraction and classification techniques for the first class of applications tend to be simple and can usually be found in standard numerical/statistical analysis software such as MATLAB.

Processing algorithms for the second class of applications typically involve extraction and classification of a larger number of features. Consequently, the choice and/or refining of the feature extraction algorithm itself can be the subject of vigorous activity. The development of robust statistical techniques that are able to extract a greater number of increasingly weaker features from nonstationary noisy data is an ongoing endeavor that is a fertile area of research. Nonetheless, a researcher has a range of techniques to choose from which we spotlight next.

From a signal processing standpoint, classification of postures (static hand configuration) is easier than classification of gestures (dynamic hand configurations), as it does not need to take motion history into account. Artificial neural networks (ANNs) have been used for both (static) postural classification [48], [69], [79], [80] and gesture classification [57], [81], [83], [84]. The methods of template matching and fuzzy rule-based classification have been applied to posture classification in [86] and [151], respectively, whereas hidden Markov models (HMMs) and Bayesian classifiers have been applied in gesture classification in [87] and [152], respectively. Specialized toolboxes for ANN-, fuzzy rule-, and HMM-based classifications are often available in numerical analysis software such as MATLAB and might hence be easier for a researcher to implement. The literature on data classification continues to grow with Open Source software implementations often available for download on user forums such as [153]. The reader is referred to [89], [90] for a detailed description of methods for data classification and to [150] for a comparison.

Ultimately, for both classes of applications, glove measurement performance determines how powerful the processing techniques for feature extraction/classification need to be. The usability and repeatability mantra is applicable because it directly impacts the amount of statistical variability in the unprocessed sensor outputs. For example, in an application where a certain joint angle is being measured, a reduced variability will increase our confidence that the hand is actually in the classified posture. The amount of variability affects how distinct the postures need to be to ensure reliable recognition and influences the number of clusters needed [141], [154]. A reduced variability will increase the size of the "dictionary" of reliable detectable postures and reduce the computational complexity of the algorithms needed for classification. Standard techniques to reduce variability and facilitate recognition include filtering data, accrediting postures as recorded only when held longer than a predefined time, and adding constraints (e.g., posture A can only be followed by posture B) [58], [151]. It is worth noting that choosing gloves that allow recordings of discrete (versus continuous) data drastically simplifies the design of the data processing algorithm, as these gloves do not need complex algorithms for pattern classification.

We refer the readers interested in the aforementioned second class of application to Sturman and Zeltzer's seminal work [2], [138]. They propose the concept that an application is a mapping between hand actions (continuous such as DoFs, fingertips motions, joint velocities, and directions of motion, or discrete such as hand postures) and their interpretations (direct, mapped, symbolic). Identifying what mapping is implemented by a certain application may be useful for a twofold purpose: identify similar applications, which can act as sources of inspiration, and aid in the design of the signal processing software, by identifying the variables to be manipulated by the signal processing algorithm.

C. Complementary Inputs

Measurements taken with sensorized gloves can be complemented with other types of measurements. It has been shown that this strategy brings advantages in several contexts. One of the main motivations for using glove-based systems is that they potentially allow a more natural man–machine interaction compared to traditional keyboards and mice. However, in some cases, interaction based only on gestures may be difficult; augmenting gestures with additional (complementary) inputs may make it easier. While many concepts, e.g., notions of space, are best communicated gesturally rather than verbally, many others, e.g., notions of time, are best communicated verbally. Thus, fusion of gestures and speech has been used to build more effective and user-friendly interfaces [4], [51], [54], [155]–[160]. Besides speech, video cameras have also been widely used to generate complementary inputs. A typical field of application where data recorded with gloves and video cameras are fused is robotics, and specifically, the studies that aimed to teach robots manipulation skills, where these data are employed to build models of the environment to be used by the robot [66], [161], [162]. Other applications employed glove recordings fused with data recorded from video cameras [163], [164] and tactile data to solve ambiguity issues in sign languages recognition [86], improve realism of manipulation tasks [165], improve reliability, and speed up training of users performing tasks under teleoperation [166].

In the aforementioned examples, complementary inputs were generated by sources external to the glove. Complementary inputs can also be generated internally, i.e., by sensors mounted on the glove itself. Typical internal inputs for gloves equipped with sensors that measure motions come from force sensors [139], [140], [167]–[169]. Such inputs were used in the context of medicine or health care studies for the purpose of better characterizing hand function. For instance, when studying a patient's grasping ability, it is usually important to monitor the motion as well as the forces that the patient can generate [108], [139], [140]. An original example was provided by LaViola and Zeleznik, who proposed Flex and Pinch, a glove equipped with both electrical contacts and bend sensors [170].

D. Appropriateness of Glove Devices Versus More Conventional Devices

Whenever a traditional device can be used in place of a glove, for a given application, a reasonable question to ask is whether the quality of the user experience provided by the two devices is comparable. For example, in some of the applications described in Section III, gloves function as little more than 3-D joysticks [42]–[44], [171]. This prompts the question: does the application benefit from the use of a glove or should a traditional device be used instead?

Most articles found in the literature ignore this vital question. Sturman and Zeltzer examined the issue of the appropriateness of using whole-hand inputs as methods of interaction and suggested that a decision can be made at an early stage of the project based on the answers to a series of questions [138], some of which we include next.

1) Are there "natural" ways to use the hand in the application?
2) Are there many different tasks to switch between?
3) Do the tasks require coordination of many DoFs?

An affirmative answer to these questions justifies the use of whole-hand inputs versus conventional devices.

In contrast to the theoretical early-stage approach advocated by Sturman and Zeltzer, other researchers assessed appropriateness of specific glove devices experimentally at the final stage of their project. The latter choice can be justified by the credo that the ultimate test of the appropriateness of the glove is the quality of the user experience. Experimental protocols that aim to do just that typically require that subjects try different devices, namely the glove under assessment and traditional alternatives. In some cases, subjects were asked to describe their preferences, typically by scoring factors such as ease of use and comfort. In other cases, their performance was measured with objective metrics such as speed of interaction and number of successful trials. While there appears to be no general, golden standard protocol for conducting experimental trials of the type described earlier, nor do most recent articles make such a comparison, the literature on wearable and portable computers provides an exception. Metrics such as number of characters the user can input per minute, number of discrete keys, and time interval for key press are commonly accepted and usually reported by researchers and manufacturers; this is helpful when comparing new devices and traditional ones, e.g., QWERTY keyboards [131].

In comparative studies of the kind discussed, it is perhaps not surprising that a few experimental studies found that traditional interfaces outperformed glove devices. For example, a study performed at Iowa State University compared two versions of a system for assisting in the design of spherical mechanisms, one using a virtual reality system with a Pinch Glove, the other using a traditional computer workstation with a 2-D mouse. Users preferred the latter to the former [43], [44]. Bowman and Wingrave reported a similar result for TULIP, a menu system for virtual reality environments. Pinch Gloves and traditional pen and tablet menus were compared. The latter allowed users to perform a significantly faster interaction [172]. Some glove-based interfaces, e.g., those based on chord gloves, may require a nontrivial user training period. In this case, assessment may consider user's performance before and after training as well as the time needed for a user to reach a level of performance comparable to that obtainable with a traditional interface and to relearn use after a long absence [129], [131].

These user preferences need not discourage the enthusiastic glove device researcher. We believe there is an opportunity to combine cutting edge interface design with the latest in glove devices. Our viewpoint is that improved user interface software should be able to flip the user preference. However, we remain open to the possibility that there is something more fundamental about certain modes of interaction that make users prefer traditional devices. The full resolution of this issue remains outside the scope of this paper though it might constitute an area of creative interdisciplinary research.

E. Limitations of Current Technology

The Data Glove-like systems are still the most widely used glove-based systems. They allow continuous recording of hand joint angles. These data are important for a large number of the applications described in Section III. Applications that require virtual reality construction of graphical representations of the user's hand are easier when starting from the hand flexion data [170]. Such data can be processed to extract hand postures. The richness of information that can be derived from hand joints appears to be at the root of the success of these gloves in many research areas.

A major limitation appears to be limited portability, primarily due to tethering and presence of cloth support, which limits the user's haptic sense and naturalness of movement, and makes the glove cumbersome. The cloth support has also been found to affect measurement performance [96], [97], which, in turn, may limit the ability of the glove measurement to perform fine discrimination, and therefore, the number of patterns a glove can generate when used for gesture-based applications [141]. Other limitations include poor robustness, poor durability, need for calibration for new users (a tedious, nonautomatic process), and high cost (several commercial devices are currently priced between U.S. $2000 and U.S. $5000, e.g., 5DT Data Glove 16, or beyond U.S. $10 000, e.g., CyberGlove).

F. Research Trends and Lingering Issues

A number of different designs were explored in the last few years with the stated objective of overcoming such drawbacks. Gloves that do not use a cloth to support sensors (e.g., [15] and [132]), do not require calibration for new users (e.g., [15] and [26]) have improved portability (e.g., they can be interfaced to handheld devices like PDAs [173] or are wireless [21], [25], [174]), and are low cost (a few hundreds U.S. dollars, e.g., [8] and [18]) were developed. Among these new devices, most have specific limitations, others are still at a preliminary stage. In the last couple of years, many devices were specifically designed for being used as virtual keyboards in wearable and portable computers [133], [135], [136]. While they may be suitable for gesture-based applications outside the wearable and portable computer area, they appear to be unsuitable for applications that require high measurement performance and continuous recording of hand joints.

The most recent literature envisions glove-based systems where sensors are directly deposed or woven into textiles [128], [175]–[177] and that could function as dual-purpose devices, i.e., as the clothing being worn and as recording/control devices. Such instrumental clothing is gaining increasing attention in the medical/health care and wearable/portable computers areas. It could monitor user's motion as well as vital and behavioral parameters [178]–[180]. The recorded data could be used to study movements or physiological and emotional states during daily activities, or simply to control the "digital world" around us.

Several groups have started working on this new generation of gloves [see Fig. 2(h)], including De Rossi's group at University of Pisa [175]–[177], [181], [182]. Preliminary results are promising but a number of technical issues still need to be solved. Fabrication techniques need to be perfected and properties of materials need to be characterized. Technical challenges include solving problems such as how to make e-textile able to bend and bunch just like any other article of clothing, optimize energy usage when both power sources and power consumers are distributed throughout the system, and allocate tasks to processing and sensing elements located on the body based upon the motion of a user and of objects in the user's environment. How to reduce cost and improve robustness and durability are also major problems that will need to be faced. Gloves that need to be worn while performing standard everyday activities will need to be almost "disposable" so that the subject's behavior is not restricted in an attempt to protect an expensive device [183]–[185]. If successful, this new technology can not only potentially improve gloves portability, but also their capability to generate patterns and to perform fine discrimination among similar hand configurations.

V. Conclusion

While future research directions remain open to discussion, this paper has made it clear that the breadth of research in glove devices has expanded and grown over the past three decades. This area of research remains very active and it is evident that technological advances in computing, sensor devices, materials and processing/classification techniques will make the next generation of glove devices cheaper, more powerful, versatile and, we hope, more ubiquitous.

The role of software in making glove devices more ubiquitous in our daily lives cannot be overemphasized. Recent history has shown that when the underlying software is intuitive and seamless, then mass adoption of the device is a consequence (e.g., iPod). We suspect that this moment is not far away for glove devices—the time frame will continue to be shortened as researchers from different areas of academia and industry work toward resolving the technological challenges discussed herein.

References

[1] D. J. Sturman and D. Zeltzer, "A survey of glove-based input," *IEEE Comput. Graph. Appl.*, vol. 14, no. 1, pp. 30–39, Jan. 1994.

[2] D. J. Sturman. (1992). Whole-hand input, Ph.D. dissertation, Massachusetts Inst. Technol., Cambridge [Online]. Available: http://xenia.media.mit.edu/djs/thesis.pix.pdf

[3] G. Grimes, "Digital data entry glove interface device," U.S. Patent 4 414 537, AT&T Bell Lab., Murray Hill, NJ, Nov. 1983.

[4] J. J. LaViola, "A survey of hand posture and gesture recognition techniques and technology," Brown Univ., Providence, RI, Tech. Rep. CS-99-11, Jun. 1999.

[5] T. G. Zimmerman, "Optical flex sensor," U.S. Patent 4 542 291, Sep. 29, 1982.

[6] H. Eglowstein, "Reach out and touch your data," *Byte*, vol. 15, no. 7, pp. 283–290, Jul. 1990.

[7] D. L. Gardner, "The Power Glove," *Des. News*, vol. 45, pp. 63–68, Dec. 1989.

[8] [Online].Available: http://www.essentialreality.com

[9] F. Hofmann and J. Henz, "The TU-Berlin SensorGlove," Tech. Univ. Berlin, Berlin, Germany, Tech. Rep., 1995.

[10] F. Hofmann, "Der TU-Berlin Sensorhandschuh, technische Beschreibung und aktueller Stand," Tech. Univ. Berlin, Berlin, Germany, Tech. Rep., Nov. 1998.

[11] N. Karlsson, B. Karlsson, and P. Wide, "A glove equipped with finger flexion sensors as a command generator used in fuzzy control system," *IEEE Trans. Instrum. Meas.*, vol. 47, no. 5, pp. 1330–1334, Oct. 1998.

[12] S. Mascaro and H. H. Asada, "Fingernail touch sensors: Spatially distributed measurements and hemodynamic modeling," in *Proc. IEEE Int. Conf. Robot. Autom.*, 2000, vol. 4, pp. 3422–3427.

[13] S. Mascaro and H. H. Asada, "Photoplethysmograph fingernail sensors for measuring finger forces without haptic obstruction," *IEEE Trans. Robot. Autom.*, vol. 17, no. 2, pp. 698–708, Oct. 2001.

[14] S. Mascaro and H. H. Asada, "Finger posture and shear force measurement using fingernail sensors: Initial experimentation," in *Proc. IEEE Int. Conf. Robot. Autom.*, 2001, vol. 2, pp. 1857–1862.

[15] J. L. Hernandez-Rebollar, N. Kyriakopoulos, and R. W. Lindeman, "The AcceleGlove: A whole-hand input device for virtual reality," in *Proc. SIGGRAPH*, 2002, p. 259.

[16] J. L. Hernandez-Rebollar, R. W. Lindeman, and N. Kyriakopoulos, "A multi-class pattern recognition system for practical finger spelling translation," in *Proc. IEEE Int. Conf. Multimodal Interfaces*, 2002, pp. 185–190.

[17] J. L. Hernandez-Rebollar, N. Kyriakopoulos, and R. W. Lindeman, "A new instrumented approach for translating American Sign Language into sound and text," in *Proc. IEEE Int. Conf. Autom. Face Gesture Recognit.*, 2004, pp. 547–552.

[18] [Online]. Available: http://www.lightglove.com

[19] B. Howard and S. Howard, "Lightglove: Wrist-worn virtual typing and pointing," in *Proc. IEEE Int. Symp. Wearable Comput.*, 2001, pp. 172–173.

[20] A. Mulder and S. Fels, "Sound sculpting: Manipulating sound through virtual sculpting," in *Proc. Western Comput. Graph. Symp.*, 1998, pp. 15–23.

[21] [Online]. Available: http://www.immersion.com

[22] [Online]. Available: http://www.hmw.it

[23] *Humanglove Developers Manual*, Humanware, Pisa, Italy, 1998.

[24] P. Coiffet and G. C. Burdea, *Virtual Reality Technology*. New York: Wiley, 2003.
[25] [Online]. Available: http://www.5dt.com
[26] [Online]. Available: http://www.fakespacelabs.com
[27] T. Kuroda, Y. Tabata, A. Goto, H. Ikuta, and M. Murakami, "Consumer price data-glove for sign language recognition," in *Proc. Int. Conf. Disabil., Virtual Reality Associated Technol.*, 2004, pp. 253–258.
[28] [Online]. Available: http://www.kk-teiken.co.jp.
[29] N. Durlach and A. Mavor, *Virtual Reality: Scientific and Technological Challenges*. Washington, DC: Nat. Acad. Press, 1995.
[30] S. C. Jacobsen, J. E. Wood, D. F. Knutti, and K. B. Biggers, "The Utah/MIT hand: Work in progress," *Int. J. Robot. Res.*, vol. 3, no. 4, pp. 21–50, 1984.
[31] B. A. Marcus, B. An, and B. Eberman, "EXOS research on master controllers for robotic devices," in *Proc. SOARP Conf.*, 1991, pp. 238–245.
[32] M. Bouzit, G. C. Burdea, G. Popescu, and R. Boian, "The Rutgers Master II—New design force-feedback glove," *IEEE/ASME Trans. Mechatron.*, vol. 7, no. 2, pp. 256–263, Jun. 2002.
[33] G. C. Burdea, J. Zhuang, E. Roskos, D. Silver, and N. Langrana, "A portable dextrous master with force feedback," *Presence: Teleop. Virtual Environ.*, vol. 1, no. 1, pp. 18–28, 1992.
[34] C. Youngblut, R. E. Johnson, S. H. Nash, R. A. Wienclaw, and C. A. Will, "Review of virtual environment interface technology," Inst. Defense Anal. (IDA), Alexandria, VA, Tech. Rep. IDA Paper P-3186 Log: H96-001239, 1996.
[35] G. C. Burdea, *Force and Touch Feedback for Virtual Reality*. New York: Wiley, 1996.
[36] M. W. Krueger, *Artificial Reality*. New York: Addison-Wesley, 1991.
[37] F. W. B. Li, R. W. H. Lau, and F. F. C. Ng, "VSculpt: A distributed virtual sculpting environment for collaborative design," *IEEE Trans. Multimedia*, vol. 5, no. 4, pp. 570–580, Dec. 2003.
[38] K. Boehm, W. Huebner, and K. Vaaenaenen, "GIVEN: Gesture driven interactions in virtual environments: A toolkit approach to 3D interactions," in *Proc. Conf. Interface Real Virtual Worlds*, 1992, pp. 243–254.
[39] C. Krapichler, M. Haubner, A. Loesch, and K. H. Englmeier, "A human–machine interface for medical image analysis and visualization in virtual environments," in *Proc. IEEE Int. Conf. Acoust., Speech, Signal Process.*, 1997, vol. 4, pp. 2613–2616.
[40] J. Moline, "Virtual reality for health care: A survey," in *Virtual Reality in Neuro-Psycho-Physiology*. Amsterdam, The Netherlands: IOS Press, 1998.
[41] W. Piekarski and B. H. Thomas, "Tinmith-Metro: New outdoor techniques for creating city models with an augmented reality wearable computer," in *Proc. Int. Symp. Wearable Comput.*, 2001, pp. 8–9.
[42] S. Bryson and C. Levit, "The virtual wind tunnel," *IEEE Comput. Graph. Appl.*, vol. 12, no. 4, pp. 25–34, Jul. 1992.
[43] T. J. Furlong, J. M. Vance, and P. Larochelle, "Spherical mechanism synthesis in virtual reality," in *Proc. ASME Des. Autom. Conf.*, 1998, pp. 13–16.
[44] P. T. Evans, J. M. Vance, and V. J. Dark, "Assessing the effectiveness of traditional and virtual reality interfaces in spherical mechanism design," *ASME J. Mech. Des.*, vol. 121, no. 4, pp. 507–514, Dec. 1999.
[45] J. N. Kihonge, J. M. Vance, and P. M. Larochelle, "Spatial mechanism design in virtual reality with networking," *ASME J. Mech. Des.*, vol. 124, no. 3, pp. 435–440, Sep. 2002.
[46] R. Steffan, U. Schull, and T. Kuhlen, "Integration of virtual reality based assembly simulation into CAD/CAM environments," in *Proc. Annu. Conf. IEEE Ind. Electron. Soc.*, 1998, vol. 4, pp. 2535–2537.
[47] K. U. Doerr, H. Rademacher, S. Huesgen, and W. Kubbat, "Evaluation of a low-cost 3D sound system for immersive virtual reality training systems," *IEEE Trans. Vis. Comput. Graph.*, vol. 13, no. 2, pp. 204–212, Mar./Apr. 2007.
[48] D. Xu, W. Yao, and Y. Zhang, "Hand gesture interaction for virtual training of SPG," in *Proc. Int. Conf. Artif. Reality Telexistence*, 2006, pp. 672–676.
[49] J. Rönkkö, J. Markkanen, R. Launonen, M. Ferrino, E. Gaia, V. Basso, H. Patel, M. D'Cruz, and S. Laukkanen, "Multimodal astronaut virtual training prototype," *Int. J. Human–Comput. Stud.*, vol. 64, no. 3, pp. 182–191, 2006.
[50] D. F. Keefe, D. A. Feliz, T. Moscovich, D. H. Laidlaw, and J. J. LaViola, "Cave painting: A fully immersive 3D artistic medium and interactive experience," in *Proc. Symp. Interactive 3D Graph.*, Mar. 2001, pp. 85–93.
[51] D. Weimer and S. K. Ganapathy, "A synthetic visual environment with hand gesturing and voice input," in *Proc. Human Factors Comput. Syst.*, 1989, pp. 235–240.
[52] S. Schkolne, M. Pruett, and P. Schroder, "Surface drawing: Creating organic 3D shapes with the hand and tangible tools," in *Proc. SIGCHI Conf. Human Factors Comput. Syst.*, 2001, pp. 261–268.
[53] S. Schkolne and P. Schroder, "Surface drawing," Dept. Comput. Sci., California Inst. Technol., Pasadena, Tech. Rep. CS-TR-99-03, 1999.
[54] A. Malkawi and R. Srinivasan, "Multimodal human–computer interaction for immersive visualization: Integrating speech–gesture recognitions and augmented reality for indoor environments," in *Proc. IASTED Int. Conf. Comput. Graph. Imag.*, 2004, pp. 171–176.
[55] G. Wesche, J. Wind, M. Gobel, L. Rosemblum, J. Durbin, R. Doyle, D. Tate, R. King, B. Frohlich, M. Fischer, M. Agrawala, M. Beers, P. Hanrahan, and S. Bryson, "Applications of the responsive workbench," *IEEE Comput. Graph. Appl.*, vol. 17, no. 4, pp. 10–15, Jul./Aug. 1997.
[56] C. Shahabi, Y. Y. C. K. Chung, K.-C. Huang, J. Khoshgozaran-Haghighi, C. Knoblock, S. C. Lee, U. Neumann, R. Nevatia, A. Rihan, S. Thakkar, and S. You, "Geodec: Enabling geospatial decision making," in *Proc. Int. Conf. Multimedia Expo*, 2006, pp. 93–96.
[57] B. Tani, R. F. Maia, and A. von Wangenheim, "A gesture interface for radiological workstations," in *Proc. Int. Symp. Conf. Comput.-Based Med. Syst.*, 2007, pp. 27–32.
[58] M. Deller, A. Ebert, M. Bender, and H. Hagen, "Flexible gesture recognition for immersive virtual environments," in *Proc. Inf. Vis. Conf.*, 2006, pp. 563–568.
[59] G. Biggs and B. MacDonald, "A survey of robotic programming systems," presented at the Australas. Conf. Robot. Autom., Brisbane, Australia, 2003.
[60] S. Iba, J. M. V. Weghe, C. J. J. Paredis, and P. K. Khosla, "An architecture for gesture-based control of mobile robots," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 1999, vol. 2, pp. 851–857.
[61] L. Pao and T. H. Speeter, "Transformation of human hand positions for robotic hand control," in *Proc. IEEE Int. Conf. Robot. Autom.*, 1989, vol. 3, pp. 1758–1763.
[62] J. Hong and X. Tan, "Calibrating a VPL Data Glove for teleoperating the Utah/MIT hand," in *Proc. IEEE Int. Conf. Robot. Autom.*, 1989, vol. 3, pp. 1752–1757.
[63] M. A. Diftler, C. J. Culbert, R. Platt, and W. J. Bluethmann, "Evolution of the NASA/DARPA robonaut control system," in *Proc. IEEE Int. Conf. Robot. Autom.*, 2003, vol. 2, pp. 2543–2548.
[64] C. P. Tung and A. C. Kak, "Automatic learning of assembly tasks using a dataglove system," in *Proc. IEEE/RSJ Conf. Intell. Robots Syst.*, 1995, vol. 1, pp. 1–8.
[65] P. C. Lam, Y. H. Liu, D. Li, and M. Y. Y. Leung, "Generating dexterous manipulation for multifingered robot hands by combining motion planning and teaching," in *Proc. IEEE Can. Conf. Electr. Comput. Eng.*, 1999, vol. 3, pp. 1419–1424.
[66] K. Ogawara, J. Takamatsu, S. Iba, T. Tanuki, H. Kimura, and K. Ikeuchi, "Acquiring hand-action models in task and behavior levels by a learning robot through observing human demonstrations," in *Proc. IEEE-RAS Int. Conf. Humanoid Robots*, Cambridge, MA, 2000.
[67] K. Ogawara, J. Takamatsu, H. Kimura, and K. Ikeuchi, "Generation of a task model by integrating multiple observation of human demonstrations," in *Proc. IEEE Int. Conf. Robot. Autom.*, 2002, pp. 1545–1550.
[68] K. Ogawara, J. Takamatsu, H. Kimura, and K. Ikeuchi, "Extraction of essential interactions through multiple observations of human demonstrations," *IEEE Trans. Ind. Electron.*, vol. 50, no. 4, pp. 667–675, Aug. 2003.
[69] F. W. Damasio and S. R. Musse, "Animating virtual humans using hand postures," in *Proc. Brazilian Symp. Comput. Graph. Image Process.*, 2002, p. 437.
[70] N. Adamo-Villani and R. Wilbur, "An immersive game for K-5 math and science education," in *Proc. Conf. Inf. Vis.*, 2007, pp. 921–924.
[71] N. Rezzoug, P. Gorce, A. Heloir, S. Gibet, N. Courty, J. F. Kamp, F. Multon, and C. Pelachaud, "Virtual humanoids endowed with expressive communication gestures: The Hugex project," in *Proc. IEEE Int. Conf. Syst., Man Cybern.*, 2006, pp. 8–11.
[72] M. Minoh, H. Obara, T. Funtatomi, M. Toyura, and K. Kakusho, "Direct manipulation of 3D virtual objects by actors for recording live video content," in *Proc. Conf. Inf. Res. Dev. Knowl. Soc. Infrastracture*, 2007, pp. 11–18.
[73] G. Singh, "Surrendering control," *IEEE Comput. Graph. Appl.*, vol. 22, no. 4, pp. 4–5, Jul./Aug. 2002.
[74] H. Morita, S. Hashimoto, and S. Ohteru, "A computer music system that follows a human conductor," *Computer*, vol. 24, no. 7, pp. 44–53, Jul. 1991.

[75] J. A. Paradiso, "Electronic music: New ways to play," *IEEE Spectr.*, vol. 34, no. 12, pp. 18–30, Dec. 1997.

[76] A. Mulder, "Towards a choice of gestural constraints for instrumental performers," in *Trends in Gestural Control of Music*. Paris, France: IRCAM, 2000.

[77] A. Mulder, S. Fels, and K. Mase, "Empty-handed gesture analysis in MAX/FTS," in *Proc. AIMI Int. Workshop Kansei—Technol. Emotion*, 1997, pp. 87–90.

[78] T. Takahashi and F. Kishino, "Hand gesture coding based on experiments using a hand gesture interface device," *SIGCHI Bull.*, vol. 23, no. 2, pp. 67–74, Apr. 1991.

[79] K. Murakami and H. Taguchi, "Gesture recognition using recurrent neural networks," in *Proc. Conf. Human Factors Comput. Syst.*, 1991, pp. 237–242.

[80] S. A. Mehdi and Y. N. Khan, "Sign language recognition using sensor gloves," in *Proc. Int. Conf. Neural Inf. Process.*, 2002, vol. 5, pp. 2204–2206.

[81] J. S. Kim, W. Jang, and Z. Bien, "A dynamic gesture recognition system for the Korean sign language (KSL)," *IEEE Trans. Syst., Man, Cybern. B, Cybern.*, vol. 26, no. 2, pp. 354–359, Apr. 1996.

[82] W. Kadous, "GRASP: Recognition of Australian sign language using instrumented gloves," Bachelor's thesis, Univ. New South Wales, Sydney, Australia, 1995.

[83] P. Vamplew, "Recognition of sign language gestures using neural networks," presented at the Eur. Conf. Disabilities, Virtual Reality Associated Technol., Maidenhead, U.K., 1996.

[84] W. Gao, J. Ma, J. Wu, and C. Wang, "Sign language recognition based on HMM/ANN/DP," *Int. J. Pattern Recognit. Artif. Intell.*, vol. 14, no. 5, pp. 587–602, 2000.

[85] C. Wang, W. Gao, and S. Shan, "An approach based on phonemes to large vocabulary Chinese sign language recognition," in *Proc. IEEE Int. Conf. Autom. Face Gesture Recognit.*, 2002, pp. 393–398.

[86] R. H. Liang and M. Ouhyoung, "A real-time continuous alphabetic sign language to speech conversion VR system," *Comput. Graph. Forum*, vol. 14, no. 3, pp. 67–76, 1995.

[87] R. H. Liang and M. Ouhyoung, "A sign language recognition system using hidden Markov Model and context sensitive search," in *Proc. ACM Symp. Virtual Reality Softw. Technol.*, 1996, pp. 59–66.

[88] R. H. Liang and M. Ouhyoung, "A real-time continuous gesture recognition system for sign language," in *Proc. IEEE Int. Conf. Autom. Face Gesture Recognit.*, 1998, pp. 558–567.

[89] R. Watson, "A survey of gesture recognition techniques," Dept. Comput. Sci., Trinity College, Hartford, CT, Tech. Rep. TCD-CS-93-11, Jul. 1993.

[90] S. Ong and S. Ranganath, "Automatic sign language analysis: A survey on the future beyond lexical meaning," *IEEE Trans. Pattern Anal. Mach. Intell.*, vol. 27, no. 6, pp. 873–891, Jun. 2005.

[91] S. Fels and G. E. Hinton, "Glove Talk 2: A neural network interface which maps gestures to parallel formant speech synthesizer controls," *IEEE Trans. Neural Netw.*, vol. 9, no. 1, pp. 205–212, Jan. 1998.

[92] W. J. Greenleaf, "Developing the tools for pratical VR applications," *IEEE Eng. Med. Biol. Mag.*, vol. 15, no. 2, pp. 23–30, Mar./Apr. 1996.

[93] W. Gao, J. Ma, S. Shan, X. Chen, W. Zeng, H. Zhang, J. Yan, and J. Wu, "Handtalker: A multimodal dialog system using sign language and 3-d virtual human," in *Proc. Int. Conf. Adv. Multimodal Interfaces*, 2000, pp. 564–571.

[94] J. Kramer and L. Leifer, "The talking glove: An expressive and receptive verbal communication aid for deaf, deaf-blind and non-vocal," Stanford Univ., Uninc Santa Clara County, CA, Tech. Rep., 1989.

[95] F. A. Hellebrandt, E. N. Duvall, and M. L. Moore, "The measurement of joint motion. Part 3—Reliability of goniometry," *Phys. Therapy Rev.*, vol. 29, pp. 302–307, 1949.

[96] L. Dipietro, A. M. Sabatini, and P. Dario, "Evaluation of an instrumented glove for hand-movement acquisition," *J. Rehabil. Res. Dev.*, vol. 40, no. 2, pp. 179–190, Mar./Apr. 2003.

[97] D. Quam, G. Williams, J. Agnew, and P. Browne, "An experimental determination of human hand accuracy with a data glove," in *Proc. Annu. Meeting Human Factors Soc.*, 1989, pp. 22–30.

[98] S. Micera, E. Cavallaro, R. Belli, F. Zaccone, E. Guglielmelli, P. Dario, D. Collarini, B. Martinelli, C. Santin, and R. Marcovich, "Functional assessment of hand orthopedic disorders using a sensorized glove: Preliminary results," in *Proc. IEEE Int. Conf. Robot. Autom.*, 2003, vol. 2, pp. 2212–2217.

[99] N. W. Williams, "The virtual hand," *J. Hand Surg.*, vol. 22B, no. 5, pp. 560–567, 1997.

[100] N. W. Williams, J. M. T. Penrose, C. M. Caddy, E. Barnes, D. R. Hose, and P. Harley, "A goniometric glove for clinical hand assessment," *J. Hand Surg.*, vol. 25B, no. 2, pp. 200–207, 2000.

[101] Y. Su, C. R. Allen, D. Geng, D. Burn, U. Brechany, G. D. Bell, and R. Rowland, "3D motion system ("data-gloves"): Application for Parkinson's disease," *IEEE Trans. Instrum. Meas.*, vol. 52, no. 3, pp. 662–674, Jun. 2003.

[102] G. C. Burdea, P. L. T. Weiss, and D. Thalmann, "Guest editorial special theme on virtual rehabilitation," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 15, no. 1, p. 1, Mar. 2007.

[103] G. M. Prisco, C. A. Avizzano, M. Calcara, S. Ciancio, S. Pinna, and M. Bergamasco, "A virtual environment with haptic feedback for the treatment of motor dexterity disabilities," in *Proc. IEEE Int. Conf. Robot. Autom.*, 1998, vol. 4, pp. 3721–3726.

[104] C.-Y. Shing, C.-P. Fung, T.-Y. Chuang, I.-W. Penn, and J.-L. Doong, "The study of auditory and haptic signals in a virtual reality-based hand rehabilitation system," *Robotica*, vol. 21, pp. 211–218, 2003.

[105] K. Morrow, C. Docan, and G. Burdea, "Low-cost virtual rehabilitation of the hand for patients post-stroke," in *Proc. Int. Workshop Virtual Rehabil.*, 2006, pp. 6–10.

[106] W. Greenleaf and T. Piantanida, "Medical applications of virtual reality technology," in *The Biomedical Engineering Handbook*, Boca Raton, FL: CRC Press, 2000.

[107] V. G. Popescu, G. C. Burdea, M. Bouzit, and V. R. Hentz, "A virtual-reality-based telerehabilitation system with force feedback," *IEEE Trans. Inf. Technol. Biomed.*, vol. 4, no. 1, pp. 45–51, Mar. 2000.

[108] D. Jack, R. Boian, A. S. Merians, M. Tremaine, G. C. Burdea, S. V. Adamovich, M. Recce, and H. Poizner, "Virtual reality-enhanced stroke rehabilitation," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 9, no. 3, pp. 308–318, Sep. 2001.

[109] S. V. Adamovich, A. S. Merians, R. Boian, M. Tremaine, G. C. Burdea, M. Recce, and H. Poizner, "Virtual reality based exercise system for hand rehabilitation post-stroke: Transfer to function," in *Proc. IEEE Conf. EMBS*, 2004, pp. 4936–4939.

[110] D. Jack, R. Boian, A. Merians, S. V. Adamovich, M. Tremaine, M. Recce, G. C. Burdea, and H. Poizner, "A virtual reality-based exercise program for stroke rehabilitation," in *Proc. 4th Int. ACM Conf. Assistive Technol.*, 2000, pp. 56–63.

[111] A. Heuser, H. Kourtev, S. Winter, D. Fensterheim, G. Burdea, V. Hentz, and P. Forducey, "Telerehabilitation using the Rutgers Master II glove following carpal tunnel release surgery: Proof-of-concept," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 15, no. 1, pp. 43–49, Mar. 2007.

[112] M. Santello and J. F. Soetching, "Gradual molding of the hand to object contours," *J. Neurophysiol.*, vol. 79, pp. 1307–1320, 1998.

[113] C. Ansuini, V. Tognin, L. Turella, and U. Castiello, "Distractor objects affect fingers' angular distances but not fingers' shaping during grasping," *Exp. Brain Res.*, vol. 178, no. 2, pp. 194–205, 2007.

[114] C. Ansuini, M. Santello, F. Tubaldi, S. Massaccesi, and U. Castiello, "Control of hand shaping in response to object shape perturbation," *Exp. Brain Res.*, vol. 180, no. 1, pp. 85–96, 2007.

[115] C. Ansuini, L. Giosa, L. Turella, G. Altoe, and U. Castiello, "An object for an action, the same object for other actions: Effects on hand shaping," *Exp. Brain Res.*, vol. 185, no. 1, pp. 111–119, Feb. 2008.

[116] M. Santello, M. Flanders, and J. F. Soetching, "Postural hand synergies for tool use," *J. Neurosci.*, vol. 18, no. 23, pp. 10105–10115, Dec. 1998.

[117] M. Carrozzo and F. Lacquaniti, "Virtual reality: A tutorial," *Electroencephalogr. Clin. Neurophysiol.*, vol. 109, pp. 1–9, 1998.

[118] C. Ansuini, M. Santello, S. Massaccesi, and U. Castiello, "Effects of end-goal on hand shaping," *J. Neurophysiol.*, vol. 95, no. 4, pp. 2456–2465, 2006.

[119] O. Bock, "Grasping of virtual objects in changed gravity," *Aviation, Space, Environ. Med.*, vol. 67, no. 12, pp. 1185–1189, Dec. 1996.

[120] P. Dario, S. Micera, F. Posteraro, V. Zolesi, G. Neri, and S. Baldacci, "Hand Posture Analyzer (HPA): Methods and instruments for the study of upper limb biomechanics in weightlessness," in *Microgravity and Space Station Utilization*, vol. 2, no. 2/3/4, R. Monti, Ed. MO: Liguori, 2002.

[121] S. Baldacci, G. Neri, V. Zolesi, and V. Cotronei, "Hand posture analyzer (HPA): Portable instruments for upper limb posture analysis," presented at the Conf. Exhibit Int. Space Station Utilization, Cape Canaveral, FL, Oct. 15–18, 2001.

[122] S. Micera, P. Dario, and F. Posteraro, "On the analysis of hand synergies during grasping in weightlessness," in *Proc. Life Space Life Earth, Eur. Symp. Life Sci. Res. Space, Annu. Int. Gravitational Physiol. Meeting*, 2002, pp. 233–234.

[123] V. Zolesi, L. Serafini, S. Baldacci, G. Neri, L. Liuni, F. Flore, F. Posteraro, P. Pastacaldi, P. Dario, M. Zago, and F. Lacquaniti, "New protocols for the analysis of the performance of the upper limb on the International Space Station," presented at the AIAA Conf. Space, Long Beach, CA, 2003.

[124] C. Allen, K. Z. Karam, P. Cam, M. Hill, and T. Tindle, "Application of virtual reality devices to the quantitative assessment of manual assembly forces in a factory environment," in *Proc. IEEE Int. Conf. Ind. Electron., Control, Instrum.*, 1995, vol. 2, pp. 1048–1053.

[125] R. M. Satava and S. B. Jones, "Current and future applications of virtual reality for medicine," *Proc. IEEE*, vol. 86, no. 3, pp. 484–489, Mar. 1998.

[126] S. L. Delp and F. R. Zajac, "Force and moment generating capacity of lower limb muscles before and after lengthening," *Clin. Orthop. Related Res.*, vol. 284, pp. 247–259, 1992.

[127] A. Toney, "A novel method for joint motion sensing on a wearable computer," in *Proc. IEEE Int. Symp. Wearable Comput.*, 1998, pp. 158–159.

[128] J. Edmison, M. Jones, Z. Nakad, and T. Martin, "Using piezoelectric materials for wearable electronic textiles," in *Proc. IEEE Int. Symp. Wearable Comput.*, 2002, pp. 41–48.

[129] R. Rosenberg and M. Slater, "The chording glove: A glove-based text input device," *IEEE Trans. Syst., Man, Cybern. C, Appl. Rev.*, vol. 29, no. 2, pp. 186–191, May 1999.

[130] M.-C. Cho, K.-H. Park, S.-H. Hong, J. W. Jeon, S. I. Lee, H. Choi, and H.-G. Choi, "A pair of Braille-based chord gloves," in *Proc. Int. Symp. Wearable Comput.*, 2002, pp. 154–155.

[131] M. Kolsch and M. Turk, "Keyboards without keyboards: A survey of virtual keyboards," Univ. California, Berkeley, Tech. Rep. 2002-21, 2002.

[132] M. Fukumoto and Y. Tonomura, "'Body coupled fingering': Wireless wearable keyboard," in *Proc. Conf. Human Factors Comput. Syst.*, 1997, pp. 147–154.

[133] B. S. Soh, Y. S. Kim, and S. G. Lee, "Improving the usability of a wearable input device SCURRY," presented at the Int. Conf. Ubiquitous Comput., Nottingham, U.K., 2004.

[134] Y. S. Kim, B. S. Soh, and S. G. Lee, "A new wearable input device: SCURRY," *IEEE Trans. Ind. Electron.*, vol. 52, no. 6, pp. 1490–1499, Dec. 2005.

[135] [Online]. Available: http://www.senseboard.com

[136] C. Mehring, F. Kuester, K. D. Singh, and M. Chen, "KITTY: Keyboard independent touch typing in VR," in *Proc. IEEE Virtual Reality*, 2004, pp. 243–244.

[137] F. Kuester, M. Chen, M. E. Phair, and C. Mehring, "Towards keyboard independent touch typing in VR," in *Proc. ACM Symp. Virtual Reality Softw. Technol.*, 2005, pp. 86–95.

[138] D. J. Sturman and D. Zeltzer, "A design method for "whole-hand" human–computer interaction," *ACM Trans. Inf. Syst.*, vol. 11, no. 3, pp. 219–238, 1993.

[139] F. Vecchi, S. Micera, F. Zaccone, M. C. Carrozza, A. M. Sabatini, and P. Dario, "A sensorized glove for applications in biomechanics and motor control," presented at the Annu. Conf. Int. Functional Electr. Stimulation Soc., Cleveland, OH, 2001.

[140] F. Vecchi, C. Freschi, S. Micera, A. M. Sabatini, P. Dario, and R. Sacchetti, "Experimental evaluation of two commercial force sensors for applications in biomechanics and motor control," presented at the Annu. Conf. Int. Functional Electr. Stimulation Soc., Aalborg, Denmark, 2000.

[141] G. D. Kessler, L. Hodges, and N. Walker, "Evaluation of the Cyber glove as a whole hand input device," *ACM Trans. Comput.–Human Interaction*, vol. 2, no. 4, pp. 263–283, Dec. 1995.

[142] S. Wise, W. Gardner, E. Sabelman, E. Valainis, Y. Wong, K. Glassand, J. Drace, and J. Rosen, "Evaluation of a fiber optic glove for semi-automated goniometric measurements," *J. Rehabil. Res. Dev.*, vol. 27, no. 4, pp. 411–424, 1990.

[143] M. Mentzel, F. Hofmann, T. Ebinger, B. Jaetzold, L. Kinzl, and N. J. Wachter, "Reproduzierbarkeit von Fingergelenkwinkelmessungen mit einem Sensorhandschuh," *Handchirurgie, Mikrochirurgie, Plastische Chirurgie*, vol. 33, pp. 59–64, 2001.

[144] C.-S. Fahn and H. Sun, "Development of a data glove with reducing sensors based on magnetic induction," *IEEE Trans. Ind. Electron.*, vol. 25, no. 2, pp. 585–594, Apr. 2005.

[145] F. Kahlesz, G. Zachmann, and R. Klein, "'Visual-fidelity' dataglove calibration," in *Proc. Comput. Graph. Int.*, 2004, pp. 403–410.

[146] M. Fischer, P. van der Smagt, and G. Hirzinger, "Learning techniques in a dataglove based telemanipulation system for the DLR hand," in *Proc. Int. Conf. Robot. Autom.*, 1998, pp. 1603–1608.

[147] T. S. Chou, A. Gadd, and D. Knott, "Hand-eye: A vision based approach to data glove calibration," in *Proc. Human Interface Technol.*, 2000, pp. 2–7.

[148] W. B. Griffin, R. P. Findley, M. L. Turner, and M. R. Cutkosky, "Learning techniques in a dataglove based telemanipulation system for the DLR hand," presented at the Symp. Haptic Interfaces Virtual Environ. Teleoperator Syst., Chicago, IL, 2000.

[149] A. S. Menon, B. Barnes, R. Mills, C. D. Bruyns, A. Twombly, J. Smith, K. Montgomery, and R. Boyle, "Using registration, calibration, and robotics to build a more accurate virtual reality simulation for astronaut training and telemedicine," presented at the Int. Conf. Comp. Graph., Vis. Comp. Vision, Plzen-Bory, Czech Republic, 2003.

[150] G. Heumer, H. B. Amor, M. Weber, and J. Bernhard, "Grasp recognition with uncalibrated data gloves—A comparison of classification methods," in *Proc. IEEE Virtual Reality Conf.*, 2007, pp. 19–26.

[151] T. D. Bui and L. T. Nguyen, "Recognizing postures in Vietnamese sign language with MEMS accelerometers," *IEEE Sensors J.*, vol. 7, no. 5, pp. 707–712, May 2007.

[152] J. Wong, R. Lau, and L. Ma, "Engineering design with a virtual hand surface," in *Proc. IEEE Int. Conf. Multi-Media Eng. Educ.*, 1998.

[153] [Online]. Available: http://www.mathforum.net

[154] M. Deller, A. Ebert, M. Bender, and H. Hagen, "Flexible gesture recognition for immersive virtual environments," in *Proc. Inf. Vis.*, 2006, pp. 563–568.

[155] J. Bers, S. Elo, S. Lessiter, and D. Tames, "CyberBELT: Multi-modal interaction with a multi-threaded documentary," in *Proc. Conf. Human Factors Comput. Syst.*, May 1995, pp. 322–323.

[156] I. Wachsmuth, "Communicative rhythm in gesture and speech," in *Proc. Int. Gesture Workshop Gesture-Based Commun. Human–Comput. Interaction*. Lecture Notes in Artificial Intelligence, vol. 1739. New York: Springer-Verlag, Mar. 1999, pp. 277–289.

[157] S. Iba, C. J. J. Paredis, and P. K. Khosla, "Intention aware interactive multi-modal robot programming," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2003, vol. 4, pp. 3479–3484.

[158] A. Forsberg, J. J. LaViola, and R. Zeleznik, "Incorporating speech input into gesture-based graphics applications at the Brown University Graphics Lab," in *Proc. CHI Workshop Des. User Interface Pen Speech Multimedia Appl.*, Pittsburgh, PA, USA, 1999.

[159] T. Yoshikawa, S. Uchino, N. Abe, K. Tanaka, H. Taki, T. Yagi, and S. He, "Voice and gesture recognition system facilitating communication between man and virtual agent," in *Proc. Int. Conf. Adv. Inf. Netw. Appl.*, 2006, pp. 673–677.

[160] A. M. F. Burlamaqui, A. A. S. Souza, J. P. A. Bezerra, R. R. Dantas, C. A. Schneider, J. Xavier, and L. M. G. Goncalves, "A multimedia framework for collaborative interaction of people and robots through the Web," in *Proc. Int. Conf. Virtual Environ., Human–Comput. Interfaces Meas. Syst.*, 2006, pp. 2–7.

[161] R. Zollner, O. Rogalla, R. Dillmann, and M. Zollner, "Understanding users intention: Programming fine manipulation tasks by demonstration," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2002, vol. 2, pp. 1114–1119.

[162] K. Bernardin, K. Ogawara, K. Ikeuchi, and R. Dillmann, "A sensor fusion approach for recognizing continuous human grasping sequences using hidden Markov Models," *IEEE Trans. Robot.*, vol. 21, no. 1, pp. 47–57, Feb. 2005.

[163] V. R. Culver, "A hybrid sign language recognition system," in *Proc. IEEE Int. Symp. Wearable Comput.*, 2004, pp. 30–33.

[164] H. Brashear, T. Starner, P. Lukowicz, and H. Junker, "Using multiple sensors for mobile sign language recognition," in *Proc. IEEE Int. Symp. Wearable Comput.*, 2003, pp. 45–52.

[165] J. Ku, R. Mraz, N. Baker, K. K. Karkzanis, J. H. Lee, I. Kim, S. I. Kim, and S. J. Graham, "A data glove with tactile feedback for fMRI of virtual reality experiments," *CyberPsychol. Behav.*, vol. 6, no. 5, pp. 497–508, 2003.

[166] Y. Shen, Y. Liu, and K. Li, "Haptic tactile feedback in teleoperation of a multifingered robot hand," in *Proc. World Congr. Intell. Control Autom.*, 2000, vol. 1, pp. 85–90.

[167] K. N. Tarchanidis and J. N. Lygouras, "Data glove with a force sensor," *IEEE Trans. Instrum. Meas.*, vol. 52, no. 3, pp. 984–989, Jun. 2003.

[168] M. H. Yun, D. Cannon, A. Freivalds, and G. Thomas, "An instrumented glove for grasp specification in virtual-reality-based point-and-direct telerobotics," *IEEE Trans. Syst., Man, Cybern. B, Cybern.*, vol. 27, no. 5, pp. 835–846, Oct. 1997.

[169] S. Shimizu, M. Shimojo, S. Sato, Y. Seki, A. Takahashi, Y. Inukai, and M. Yoshioka, "The relationship between human grip types and force distribution pattern in grasping," in *Proc. Int. Conf. Adv. Robot.*, 1997, pp. 299–304.

[170] J. LaViola and R. C. Zeleznik, "Flex and pinch: A case study of whole hand input design for vitual environment interaction," in *Proc. IASTED Int. Conf. Comput. Graph. Imag.*, 1999, pp. 221–225.

[171] K. Korida, H. Nishino, and K. Utsumiya, "An interactive 3D interface for a virtual ceramic art work environment," in *Proc. Int. Conf. Virtual Syst. MultiMedia*, 1997, pp. 227–234.

[172] D. A. Bowman and C. A. Wingrave, "Design and evaluation of menu systems for immersive virtual environments," in *Proc. IEEE Virtual Reality*, 2001, pp. 149–156.

[173] J. Hooker, C. Barhost, J. Brausen, J. Devlin, E. Ford, and D. B.-V. Kuren, "System design for a pediatric physical therapy strength testing glove," in *Proc. IEEE Conf. EMBS*, 2004, pp. 2470–2475.

[174] J. K. Perng, B. Fisher, S. Hollar, and K. S. J. Pister, "Acceleration sensing glove (ASG)," in *Proc. IEEE Int. Symp. Wearable Comput.*, 1999, pp. 178–180.

[175] E. P. Scilingo, F. Lorussi, A. Mazzoldi, and D. De Rossi, "Strain-sensing fabrics for wearable kinesthetic-like systems," *IEEE Sensors J.*, vol. 3, no. 4, pp. 460–467, Aug. 2003.

[176] P. S. Stanley-Marbell, D. Marculescu, R. Masculescu, and P. K. Khosla, "Modeling, analysis, and self-management of electronic textiles," *IEEE Comput.*, vol. 52, no. 8, pp. 996–1010, Aug. 2003.

[177] J. Edmison, D. Lehn, M. Jones, and T. Martin, "E-textile based automatic activity diary for medical annotation and analysis," in *Proc. BSN 2006 Int. Workshop Wearable Implantable Body Sensor Netw.*, Apr. 3–5, pp. 131–134.

[178] F. Axisa, C. Gehin, G. Delhomme, C. Collet, O. Robin, and A. Dittmar, "Wrist ambulatory monitoring system and smart glove for real time emotional, sensorial and physiological analysis," in *Proc. 26th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. 2004 (IEMBS'04)*, pp. 2161–2164.

[179] Y. B. Lee, S. W. Yoon, C. K. Lee, and M. H. Lee, "Wearable EDA sensor gloves using conducting fabric and embedded system," in *Proc. IEEE Conf. EMBS*, 2006, pp. 6785–6788.

[180] Y. Lee, B. Lee, C. Lee, and M. Lee, "Implementation of wearable sensor glove using pulse-wave sensor, conducting fabric and embedded system," in *Proc. Int. Summer School Med. Devices Biosensors*, 2006, pp. 94–97.

[181] A. Tognetti, F. Lorussi, M. Tesconi, R. Bartalesi, G. Zupone, and D. De Rossi, "Wearable kinesthetic systems for capturing and classifying body posture and gesture," in *Proc. IEEE EMBS*, 2005, pp. 1012–1015.

[182] A. Tognetti, N. Carbonaro, G. Zupone, and D. De Rossi, "Characterization of a novel data glove based on textile integrated sensors," in *Proc. IEEE Conf. EMBS*, 2006, pp. 2510–2513.

[183] L. K. Simone, E. Elovic, U. Kalambur, and D. Kamper, "A low-cost method to measure finger flexion in individuals with reduced hand and finger range of motion," in *Proc. IEEE Conf. EMBS*, 2004, pp. 4791–4794.

[184] S. Oda, M. Kyoso, A. Uchiyama, A. Takatsu, A. Hattori, and N. Suzuki, "Development of a glove-type interface for data manipulation of the virtual environment in the operating room," in *Proc. IEEE Int. Annu. Conf. Eng. Med. Biol. Soc.*, 1998, vol. 20, pp. 1258–1259.

[185] F. Iredale, T. Farrington, and M. Jaques, "Global, fine and hidden sports data: Applications of 3D vision analysis and a specialised data glove for an athlete biomechanical analysis system," in *Proc. Annu. Conf. Mechatron. Mach. Vis. Practice*, 1997, pp. 260–264.

[186] H. H. Asada and M. Barbagelata, "Wireless fingernail sensor for continuous long term health monitoring," MIT Home Automation and Healthcare Consortium, Cambridge, MA, Phase 3, Progr. Rep. 3-1, 2001.

[187] R. Paradiso and D. De Rossi, "Advances in textile technologies for unobtrusive monitoring of vital parameters and movements," in *Proc. IEEE EMBS*, 2006, pp. 392–395.

[188] F. Lorussi, E. Scilingo, M. Tesconi, A. Tognetti, and D. De Rossi, "Strain sensing fabric for hand posture and gesture monitoring," *IEEE Trans. Inf. Technol. Biomed.*, vol. 9, no. 3, pp. 372–381, Sep. 2005.

[189] M. A. Diftler, C. J. Culbert, R. O. Ambrose, R. Platt, Jr., and W. J. Bluethmann, "Evolution of the NASA/DARPA robonaut control system," in *Proc. IEEE Int. Conf. Robot. Autom.*, 2003, vol. 2, pp. 2543–2548.

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