CHAPTER

HAND EXOSKELETON SYSTEMS—OVERVIEW

8

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8.1 INTRODUCTION

This study is a review of development and state-of-the-art techniques of active hand exoskeletons. There exists a considerable difference between exoskeleton techniques in upper-limb, lower-limb, and hand exoskeletons, based on the motivation as well as the technical difficulties. The authors aim to provide an overview of the applications of hand exoskeletons as assistive, rehabilitative, augmentative, and other devices. Both "rigid" exoskeletons and "soft" gloves are reviewed. For the purpose of this paper, only robotic devices that actively control one or more degrees of freedom (DOF) of at least one digit of the hand, and that are grounded in such a way that attaches to the body of the user are considered. By this definition of an active hand exoskeleton, passive devices such as HandSOME [1] or SCRIPT [2] are not considered even though they may accomplish many of the same tasks. Additionally, end-effector robotic systems that are not grounded at the hand or forearm, such as HandCARE [3] or Reha-Digit (https://reha-stim.com) are not included. Finally, to prevent redundancy with the first chapter of this book (see Chapter 1), combined arm and hand exoskeletons with more independent active DOFs at the shoulder, elbow, and wrist joints than at the digits of the hand are excluded.

Hand exoskeletons are uniquely qualified to perform a variety of useful functions. Unlike end-effector systems that manipulate the hand with respect to a point remote to the body, exoskeletons attach to the human hand and move synchronously with the joints of the digits. This enables more potential applications such as natural teleoperation, strength augmentation, and provision of additional structure and correction of movement similar to an orthosis. Additionally, the potential for hand exoskeleton portability permits their development for assisting and augmentation outside of a stationary setting. However, hand exoskeletons also bring major challenges in mechanism design and control algorithm development. To solve these challenges typically requires interdisciplinary knowledge of hardware design, software development, and human anatomy and physiology among other fields.

The first powered hand exoskeletons were in development since at least the late 1980s [4,5]. These early devices were not meant for standalone use, but rather as force feedback gloves for teleoperation. They developed naturally out of purely sensory data gloves such as [6] and findings that teleoperation was improved with force feedback. However, within a few years, hand exoskeleton

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systems began appearing in the literature for assisting paralyzed individuals [7] and augmenting performance while wearing a space suit [8]. Later, applications extended to rehabilitation, which requires better human-in-the-loop understanding in terms of intention detection and motion control. Lastly, numerous hand exoskeletons have been developed for other purposes such as teleoperation and as haptic devices in VR environments. For all these systems, the historical trend has been for the need for active systems due to the inadequacy of purely passive ones.

This chapter begins with a graphical overview of a sample of existing hand exoskeletons along with a discussion of hand exoskeletons in terms of mechanism design, actuation methods, transmission systems, control algorithms, and intent estimation methods. Afterwards, an overview of a selection of hand exoskeletons for each application is provided.

Hand exoskeleton research is a rapidly growing and evolving field, with many new systems developed and studies published each year. Several publications have previously reviewed hand exoskeletons, and the authors refer interested readers to [9–14] among others for further information on the field.

8.2 OVERVIEW OF HAND EXOSKELETON SYSTEMS

Fig. 8.1 provides a chronological overview of the characteristics of 40 hand exoskeletons found in the literature. The *Y*-axis categorizes systems by the number of independent active DOFs. Mechanically coupled DOFs are commonly found in hand exoskeleton systems and are indicated by thin lines between coupled DOFs.

8.2.1 MECHANISM

8.2.1.1 Degrees of freedom

A simplified model of the hand that is commonly used for discussion of hand exoskeletons in shown in Fig. 8.2. Each of the four fingers, namely the index, middle, ring, and pinky fingers, are widely agreed upon to contain four DOFs. At the knuckle, or metacarpophalangeal (MCP) joint, each of the four fingers is capable of flexion and extension (F/E) as well as abduction and adduction (A/A). The four fingers are capable of two additional F/E motions each, at their respective proximal interphalangeal (PIP) and distal interphalangeal (DIP) joints.

The thumb is generally regarded as a more complex mechanism than the other digits, and kinematic models for its motion are still being refined [15]. Nonetheless, the prevailing model consists of five rotation axes [16,17]. The carpometacarpal (CMC) and MCP joints of the thumb are each considered to be capable of F/E and A/A, whereas the interphalangeal (IP) joint is capable only of F/E. However, it should be noted that one of the most important movements of the thumb is that of opposition and reposition (O/R). O/R consists of rotation of the plane of F/E of the thumb about an axis through the CMC such that the finger pad of the thumb can touch that of the fingers. This motion occurs as a combination of F/E and A/A of the joints of the thumb.

In total, there are 21 DOFs in this simplified model of the hand that ignores motion of the four finger metacarpals. Given the compact size of the hand, the required ability of the exoskeleton to rotate about hand joints without physically overlapping said joints, actuator size and mass, and

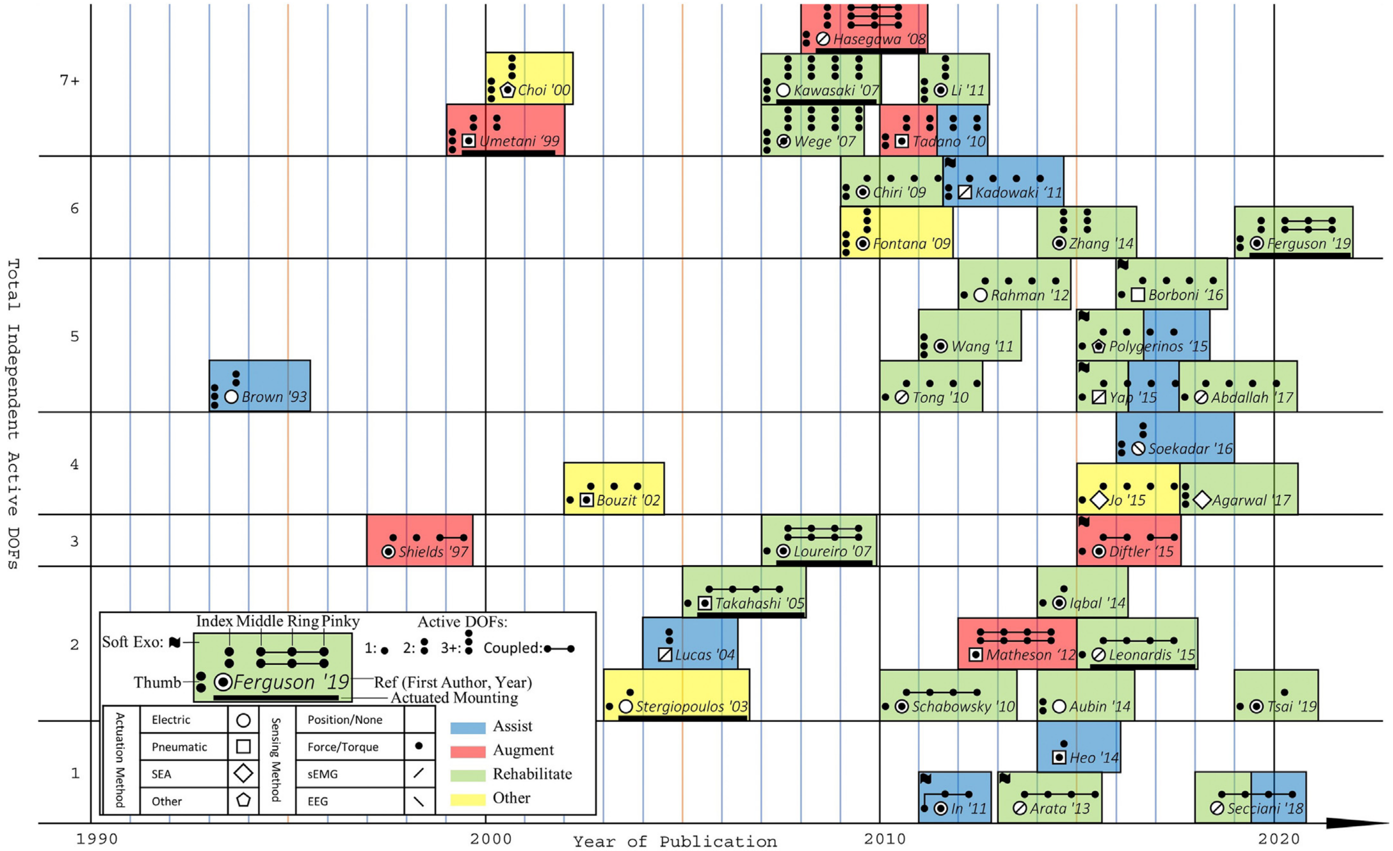

FIGURE 8.1

A graphic summary of hand exoskeletons in the literature.

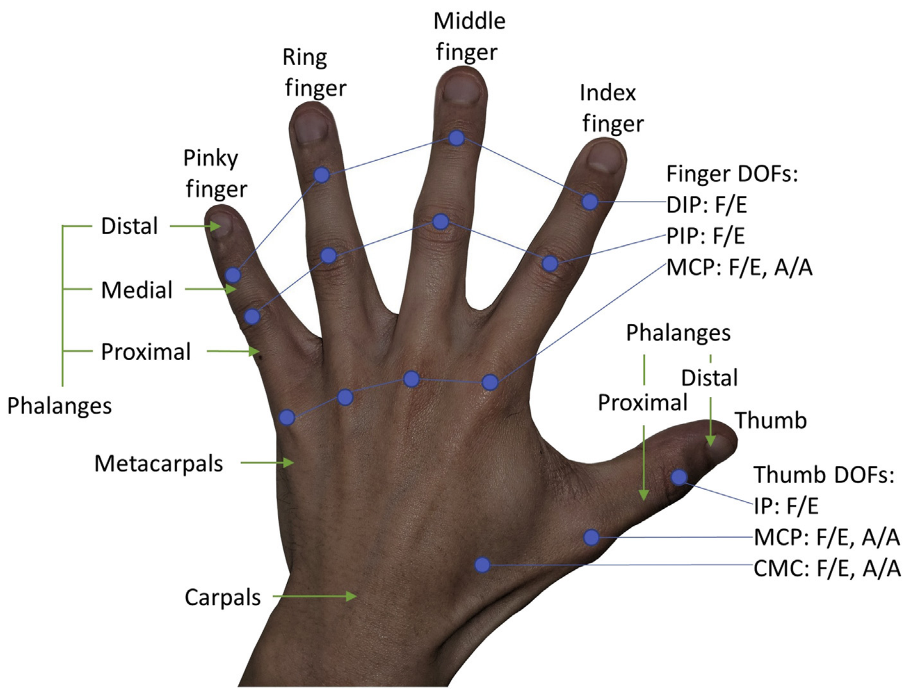

FIGURE 8.2

Simplified model of the hand. Bones are indicated by green, and joints in blue.

increasing complexity of intent estimation and control algorithms with more DOFs, it is frequently impractical to actively control every joint. Instead, it is common practice to include passive DOFs. As such, it is necessary when designing a hand exoskeleton to identify which motions must be actuated and which can be left passive. This choice depends largely on application, however even within applications there is not a unanimous consensus as can be seen in the varying designs shown in Fig. 8.1.

In addition to passive joints, most hand exoskeletons also feature either underactuated or coupled joints. This occurs when multiple DOF's are actuated by a single actuator. In hand exoskeletons, this commonly occurs in three ways. The first consists of placing rigid connections between fingers at specific attachment locations such that separate fingers move together. The second method requires a differential or some other mechanism such that multiple DOFs are driven by a single actuator but without a set ratio between joint angles velocities. This method enables some devices to conform grasp shape to a variety of different objects even with a single actuator. These first two methods are indicated on Fig. 8.1 by thin lines between DOFs. The final method involves the use of gears, pulleys, or links such that separate DOFs actuate together with a fixed ratio of joint angle velocities. This last method is frequently used to control multiple F/E DOFs with a single actuator, and is not indicated in Fig. 8.1.

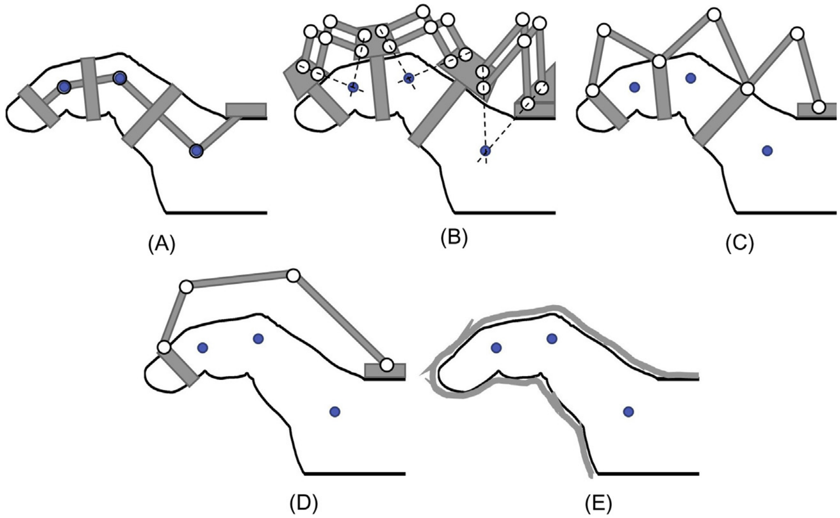

FIGURE 8.3

Example schematics of hand exoskeletons in each category. (A) Matched axes, (B) remote center of motion, (C) redundant linkage, (D) base-to-distal, and (E) compliant.

8.2.1.2 Topology

Various studies have classified the topology of hand exoskeleton mechanisms in different ways [10,14]. This chapter classifies topology by categorizing as matched axes, remote center of motion, redundant linkage, base-to-distal, or compliant. Similar categories have been proposed in the literature, although terminology differs. Fig. 8.3 contains example diagrams of each category.

In order for a hand exoskeleton to properly control the desired DOFs of the digits of the hand, it is necessary for actuation of the exoskeleton joints to cause predictable rotations of the joints of the human hand.

The most direct way to cause hand exoskeleton motion to predictably control DOFs of the hand is to place the axis of rotation of the exoskeleton joint coincident with that of the human joint as shown in Fig. 8.3A. Exoskeletons that do so are referred to here as matched axes exoskeletons. Although such a topology may initially present as simple, they are in practice difficult to achieve as placing the exoskeleton F/E joints coincident to those of the fingers requires the structure of the exoskeleton to be laterally adjacent to said fingers. Given that many grasps place the fingers in contact with each other, this topology is usually not feasible for multiple finger systems. It should be noted that, in all systems studied, A/A motions of the four fingers were achieved with a matched axes topology.

An alternative method is for the mechanism of the exoskeleton to cause each link to rotate about remote centers of motion aligned with those of the finger joints as shown in Fig. 8.3B. There are several possible mechanisms to do this, and the problem has been analyzed in Ref. [18]. For hand exoskeletons, common mechanisms in this category include parallelogram mechanisms and circular-prismatic joints. These mechanisms can be low-profile depending on design. Exoskeletons that feature this topology generally connect to the segments of the hand immediately proximal and distal to each joint such that each exoskeleton joint is coupled to a biological joint.

A redundant linkage topology is another option to couple motion of a specific exoskeleton joint to a single hand joint. These systems also attach to the digit before and after each actuated hand joint, but feature additional linkages and joints between each attachment point as shown in Fig. 8.3C. These extra joints and linkages serve to turn the combined digit-exoskeleton system between adjacent attachment points into four-bar or other mechanisms with well-defined relations between exoskeleton and hand joint motions. The resulting mechanism is typically slightly larger than those that use a remote center of motion topology.

Base-to-distal topology exoskeletons relax the recommendation of coupling specific exoskeleton joints to specific hand joints. Instead, these systems connect a serial linkage from the exoskeleton base, typically the dorsum, to distal to the last actuated joint as shown in Fig. 8.3D. The connecting serial linkage effectively actuates the entire digit together, as opposed to at each joint. Although there is some variability between individuals, it has been shown that F/E of the PIP and DIP joints are in general coupled [19], and multiple studies have reported accurate estimation of finger joint angles based on this coupling. Foremost among the advantages of this topology are simplified design and the removal of required adjustment mechanisms for varying user digit segment lengths with proper selection of link lengths. However, this comes at the costs of larger mechanism size and, despite joint coupling, reduced controllability of the hand.

Compliant topology exoskeletons can appear similar to gloves, and do away with rigid joints altogether, as shown in Fig. 8.3E. The actuation method or transmission is built into the exoskeleton such that there is minimal rigid structure. The structure of the exoskeleton bends with the actuated digits. These exoskeletons bring all the advantages and challenges of soft robots. Extra care must be taken such that forces are not applied inappropriately, as there are not rigid joints to guide torques and forces and thus the user's skeleton becomes the guiding structure.

A common requirement for the topologies of nearly all hand exoskeletons is an open palm. This requirement has a threefold purpose. First, occupying the palm with the mechanism prevents grasp of, and interaction with, most objects. Second, placing the mechanism on the palm prevents full closure of the hand. Lastly, the ability to obtain tactile feedback is an instrumental part of the human hand. Any obstruction of the palmar side of the hand will reduce this ability, and thus have a negative impact on the user.

8.2.2 ACTUATION

All active exoskeleton systems, by definition, require at least one actuator. Requirements for these actuators differ by system and application, but common desirable characteristics are high force/torque, high actuation bandwidth, low mass, backdrivability, and easy and precise control. Fig. 8.1 includes information on actuation method for each exoskeleton.

8.2.2.1 Electric motors

Electric motors are the most common actuator used, and come in several varieties. While standard rotary motors make up the bulk of these systems, a significant number also use linear actuators. Electric motors provide the notable advantages of easy, precise, and high bandwidth actuation, but they in general have a lower power-to-mass ratio than their main competitor. Via use of gears, the torque provided by electric motors can be easily increased, but at the expense of speed.

8.2.2.2 Pneumatic actuators

Pneumatic actuators account for nearly all other hand exoskeleton systems. Different systems have incorporated pneumatics in different methods, including pneumatic cylinders, pneumatic muscle actuators, and soft elastomeric actuators. Pneumatics are characterized by high power-to-mass ratio, yet also create challenges in control. Additionally, pumps and/or compressed gas containers are required for their use.

8.2.2.3 Series elastic actuators

A relatively small minority of hand exoskeletons feature series elastic actuators (SEAs). This method of actuation typically features an electric motor driving a transmission ending in springs. Despite using electric motors, the addition of springs changes the characteristics of SEAs enough that they can be considered in a different category. By nature, SEAs provided advantages in safety and impact resistance. Additionally, the springs allow the implementation of highly accurate force-control. However, SEAs also suffer from high power requirements, increased mechanical complexity, low actuation bandwidth, and low stiffness. A discussion of the use of SEAs in rehabilitation robotics is provided in Ref. [20].

8.2.2.4 Other actuators

Other actuation methods have been implemented in the remaining few hand exoskeletons. These include hydraulic actuators, ultrasonic motors, and shape memory alloys among others.

8.2.3 TRANSMISSION

8.2.3.1 Direct drive, gear, or linkage

The simplest and most direct way to transfer force/torque from the actuator to the joints of the hand is through direct drive, gears, or rigid links. With this type of transmission, the motor is typically placed on the dorsum or on the finger linkages themselves. While this reduces complexity, it also increases mass at the hand which is undesirable for many systems. Due to limitations in permissible motor size or mass, these systems usually have fewer actuators unless the structure of the exoskeleton is supported externally.

8.2.3.2 Bowden cable

Bowden cable transmission systems offer an attractive alternative to direct drive, gear, or linkage transmission systems due to the ability to place the motor remotely. This option is particularly attractive for nonportable hand exoskeletons, as the motors can be moved to a stationary location to reduce inertia while still permitting the arm to be moved. However, Bowden cable transmissions suffer from friction, backlash, comparatively lower maximum force before breaking, and the sheathes exerting forces on the exoskeleton when moved. Nevertheless, they are a popular choice to reduce inertia of hand exoskeletons.

8.2.3.3 Tendon driven

Another option is to use cables to mimic the functionality of the tendons of the hand. By attaching them at a distal point beyond a joint, and applying tension, they can cause joints to move in a way that closely matches biology. However, tendon transmissions are, in general, unidirectional. In order to achieve bidirectional actuation, a second cable, often from another actuator, must be attached to apply force in the opposite direction. Additionally, tendon transmissions can suffer from cable breakage and sometimes require complex routing. Nonetheless, as they apply force/torque across a digit and not just a joint, they are frequently used in soft exoskeleton gloves. They are often coupled with restorative springs.

8.2.3.4 Compliant

Several other compliant transmissions have been proposed for hand exoskeletons, and theoretically any of the methods used in soft robotics [21] could be applied. Various methods using electric motors, pneumatics, and hydraulics have been tried. These transmissions simultaneously increase safety by absorbing impacts, and can reduce safety if unsafe forces are routed through the hand due to the lack of exoskeleton structure.

8.2.3.5 Restorative springs

Although a passive element, springs are used in most hand exoskeletons with otherwise unidirectional actuation. Frequently, they are coupled with either tendons or pneumatic cylinders that control only flexion or only extension in order to passively provide the other.

8.2.4 SENSING METHOD

In order for a hand exoskeleton to properly accomplish a task, it is necessary to prescribe an overarching strategy for how it is to be controlled. The inputs to this control strategy are the desired actions to perform. The desired action, in turn, is dictated by the state of the system and estimated intention of the user. There are a variety of sensors used to acquire this information, and some of the more common strategies are discussed.

8.2.4.1 Position sensors

The vast majority of hand exoskeletons have some method of detecting the joint angles and/or the position of the various links with respect to the exoskeleton base. There are a variety of different choices to establish this information including encoders on the motors, encoders or potentiometers placed at joints, flex sensors, and linear variable differential transducers among others. Position sensors are required to obtain the physical configuration of the exoskeleton, and are therefore critical to many control strategies.

8.2.4.2 Force/torque sensors

Numerous applications require knowledge of the forces/torques experienced by the hand exoskeleton. This information can be used to enable admittance or force control, provide information on rehabilitation progress to a physical therapist, and for interactive use as a teleoperation or virtual reality haptic device. Inclusion of force/torque sensors are varied, with some systems omitting them, others building them into the fundamental structure of the device, and others placing them at human–robot interface locations.

8.2.4.3 Electromyogram

Surface electromyogram (sEMG) is a method for detecting the electrical activity in muscle [22]. In healthy individuals, these electrical signals accompany all movements. With sEMG used to detect these signals, a hand exoskeleton can generate trajectories with complementary movements. This ideally enables real-time control of an exoskeleton without requiring the user to exert forces or torques on the system, creating greater transparency. However, sEMG faces a variety of challenges as a method for intent estimation. Every time the system is donned/doffed, electrodes must be reattached, and changes in position will result in changes in detected electrical activity requiring recalibration. Additionally, there are challenges with using electrodes with hairy, dirty, or wet skin. Finally, the resolution of sEMG is relatively low and the number of electrodes used may be less than the number of active DOFs, and thus it is challenging to use to control a high DOF system.

8.2.4.4 Electroencephalogram

Similar to sEMG, electroencephalogram (EEG) is used to detect electrical biosignals. However, EEG is used to noninvasively detect brain signals, in the form of electrical activity, through the scalp. As with sEMG, EEG could be used to control a hand exoskeleton without applying forces/torques. Additionally, it can be used with users that do not have proper muscle functioning, such as victims of stroke or spinal cord injury. It has also been shown to be capable of controlling a variety of complex robotic systems, such as mobile or humanoid robots [23,24]. EEG suffers from many of the same challenges as sEMG, as well as low signal-to-noise ratios, significant required processing, and long reaction times.

8.2.5 CONTROL

There exist several control strategies used by hand exoskeletons to correctly actuate the hand to accomplish tasks. A brief summary of some of the more common strategies are detailed below.

8.2.5.1 Passive motion

Passive motion ignores the intention of the user entirely, and attempts to control the hand exoskeleton along a trajectory as if the user was not there. This strategy typically uses a position or velocity low-level controller. The passive motion can be used to test functionality of a device, or to bring the exoskeleton to a specific state, such as a neutral position for donning/doffing. However, the most significant application is as continuous passive motion (CPM) [25]. Applied in the initial stages after an injury or surgery, CPM can be effective in preventing the development of stiffness. However, it has been shown that interactive treatment with a rehabilitation robot can provide benefits that CPM cannot [26]. For this reason, as well as for applications outside of rehabilitation, active intent estimation is necessary.

8.2.5.2 Master/slave system

The first active hand exoskeletons were developed as haptic devices and data gloves to control other robotic systems. It is therefore logical that one strategy for controlling a hand exoskeleton is to use it as the slave of a master/slave system. Of particular interest is the use of two hand gloves, one a master system and one a slave hand exoskeleton system, where the movements of the hand in the master system are mirrored to the other by the hand exoskeleton. This is a commonly proposed technique for bimanual rehabilitation of stroke, and has been shown to be effective [27–29].

8.2.5.3 Biosignal control

This category consists of strategies for controlling the exoskeleton based upon biological signals measured from the body through EMG, EEG, electrooculogram (EOG), or other methods. Depending on the sensing method, the biological signals can be obtained even from users who have impaired motor functioning. As such, biological control strategies are primary candidates for real-time control of assistive exoskeletal devices, although they are also not uncommon for rehabilitation exoskeletons. The challenge of biosignal control strategies is how to convert the biological signals to control inputs, as there is rarely unambiguous or independent mapping between the measured signals and the DOFs to be controlled. There are also options of whether the signals are used as binary switches [30] or for proportional control [31].

8.2.5.4 Force-based strategies

Force-based control strategies are those that control the hand exoskeleton based upon the interaction forces and torques applied between the human hand and exoskeleton. These include low-level control of impedance, admittance, and force. Further, these strategies can be divided into assistive strategies that help the user move, and resistive strategies that hinder movement. Assistive force-based control strategies are common across all hand exoskeleton applications. Resistive strategies are found primarily in systems made as haptic devices (to simulate virtual objects it is necessary to resist movements of the hand that would penetrate said objects), as well as rehabilitation devices for the latter stages of physical therapy.

8.3 ASSISTIVE HAND EXOSKELETONS

Assistive hand exoskeletons are a popular area of research in academia and have even begun to be commercialized. One of the primary design requirements of these systems is portability. A consequence of this is that systems are heavily limited in the number and size of actuators. It is not at present a viable strategy to attempt to independently control all, or even most of, the DOFs of the hand, as the required motor mass would be prohibitive for use by the intended functionally impaired audience.

Hand exoskeletons in this category include:

8.3.1 BROWN ET AL

The assistive hand exoskeleton by Brown et al. [7] dates back to 1993 and consists of rigid joints placed between aluminum blocks with bands that wrap around the fingers between joints. The overall mechanism falls under the redundant linkage topology category. It uses a motor and tendon actuation system to control unidirectional actuation of three DOFs of the thumb and two DOFs of the index finger, and restoring actuation occurring due to passive springs connecting between the aluminum blocks.

8.3.2 LUCAS ET AL

Lucas et al. [30] developed a two active DOF exoskeleton for actuation of the index finger. It features pneumatic linear actuators controlled using sEMG using either binary or variable control algorithms. One of the actuators controlled MCP joint F/E, while passive MCP A/A movements were allowed. The other pneumatic actuator controlled coupled F/E of the DIP and PIP joints. The actuators are directly connected to the redundant linkage topology to actuate the system.

8.3.3 IN ET AL

In et al. [32] developed a soft exoskeleton glove to actuate the thumb, index, and middle fingers with a single motor. Flexion is achieved with a unidirectional motor and tendon actuation system combined with a differential mechanism to compliantly enable different grasps of the index and middle fingers. Extension is passively achieved with springs.

8.3.4 KADOWAKI ET AL

Kadowaki et al. [33] published on a power-assist soft exoskeleton glove for hand grasping in daily life by the elderly or disabled. The system compliantly actuates F/E of all five full digits using five pneumatic sheet-like curved rubber muscles and O/R of the thumb with a pneumatic spiral rubber muscle. The hand module consists entirely of cloth and rubber, and consequently weighs just 135 g, not including remotely located valves and air pressure source. Control is demonstrated both as a master/slave system with a data glove, and with EMG.

8.3.5 OFX

Heo and Kim [34] created the Open Fingerpad eXoskeleton, OFX, with a single active DOF of the index finger. The OFX, as the name describes, is distinct in that the finger pad is unobscured due to use of cantilever load cells on either side of the index finger, allowing the user to naturally interact with and feel surfaces. A pneumatic cylinder directly actuates rotation of the entire index finger about the MCP F/E joint with a rigid finger module designed with a matched axes topology. A thumb module with a locking mechanism enables pinching.

8.3.6 EXOGLOVE

The fabric-based ExoGlove [35,36] features interchangeable pneumatically actuated soft elastomeric actuators. These actuators, which attach with Velcro dorsally to each finger and thumb, each produce specific motions depending on the distributed stiffness within the actuator. The actuators are customizable for different grasps and can be manufactured in an hour. The ExoGlove uses a combination of EMG and radio frequency identification (RFID) for intent detection. The ExoGlove is also intended for use as a rehabilitation hand exoskeleton.

8.3.7 POLYGERINOS ET AL

Polygerinos et al. [37,38] developed a hydraulically actuated, compliant, portable hand exoskeleton glove for assistance and at-home rehabilitation. The system is low-profile (<2 cm), lightweight (<500 g), and capable of 2 hours of continuous use powered by a waist pack weighing less than 3 kg. Each of the five digits is driven by a separate hydraulic soft actuator made of molded elastomeric chambers with fiber reinforcements. These actuators are designed to actuate F/E motions of the four fingers and combined F/E and O/R motions of the thumb along natural trajectories. Different actuators can be made for different sized hands and different motion profiles. Fluidic pressure sensors are placed in line with the actuators to regulate pressure with a sliding-mode controller.

8.3.8 HX

The HX hand exoskeleton published in Ref. [39] is a rigid, underactuated, cable-driven exoskeleton for the index finger and thumb. Each digit has one actuated DOF controlling all F/E motion, the index finger possesses an actuated MCP A/A joint, and the thumb has an active joint for CMC O/R. The exoskeleton features a combination of matched axes and remote center of motion mechanism topologies for different joint axes. The HX was shown in Ref. [40] to be controllable with intent estimation based upon a combination of EEG and EOG.

8.3.9 SECCIANI ET AL

Secciani et al. [41] present their work on several generations of light, low-cost, 3D-printed, portable assistive and rehabilitation hand exoskeletons. The most recent design is compact, entirely portable, and customizable for different users. A single servomotor, combined with a transmission system with varying pulley diameters, enables actuation of all four fingers with natural grasping patterns using a base-to-distal topology that attaches to the medial phalanges. Intention detection is enabled via EMG.

8.4 REHABILITATION HAND EXOSKELETONS

Hand exoskeletons have also been developed for rehabilitation, and a wide variety of them have been presented in the literature. As opposed to assistive hand exoskeletons, rehabilitation hand exoskeletons do not, by nature, need to be portable. Instead, the most important requirement is the ability to enable the exercises required for physical therapy. This has enabled the development of extremely complex hand exoskeletons to enable independent control of many movements, although this complexity is not ubiquitous. Indeed, the two hand exoskeletons with greater than 15 active DOFs, as seen in Fig. 8.1, were developed more than a decade ago. Although these systems can reproduce almost any hand motion, the complexity also equates to bulkiness and introduces greater challenges for control and intent estimation. Many recent designs have instead limited the number of independent active DOFs, and therefore enable smaller, sleeker, and potentially less expensive designs that still permit the majority of motions required for rehabilitation. Rehabilitation exoskeletons are also generally designed not to be used by a single patient, but by a variety of users. As such, ability to accommodate hands of different sizes and impairments is a common requirement.

The goal of hand rehabilitation exoskeletons is to restore, or at least improve, the ability of the patient to use the hand without the exoskeleton. This is done to enable the patient to resume normal activities of daily living (ADL) without the need to constantly wear an assistive device. Many ADL involving the hand are reach-and-grasp tasks that also require movement of the arms. As it is not uncommon for patients with hand impairments to also have impairments in the arm, it is a logical step to design a single exoskeleton combining both a multi-DOF hand exoskeleton and a full arm exoskeleton. However, there are relatively few examples of this in the literature. Instead, many upper-limb exoskeletons with hand modules actuate just one DOF to permit a single simple grasp.

There are several challenges limiting the development of arm exoskeletons with multi-DOF hand modules. Typically, the more DOFs a hand exoskeleton can actuate, the more complex and heavier the system becomes. This creates problems if the hand exoskeleton is attached to the distal end of an upper-limb system, as it increases mass and inertia. Additionally, power and control signals for the hand must be routed in such a way that does not interfere with motion of the arm. Though feasible, this becomes more difficult with more hand DOFs. Furthermore, the combined human arm and hand system possesses dozens of DOFs. As the number of DOFs of the combined exoskeleton system increases, questions of intent estimation and redundancy resolution become more difficult to answer.

A common addition to rehabilitation robotic systems is a virtual reality or computer game environment [1,3,42–45]. These games are intended to engage the patient and keep them motivated to perform greater repetitions of tasks, increase possible training session durations, and potentially reduce the need for supervision by a physical therapist. The tasks are designed to require motions similar to those normally performed during physical therapy sessions. They have been proven as effective strategies for rehabilitation in multiple studies.

Numerous rehabilitative hand exoskeletons exist in the literature, and a sample are shown in Fig. 8.1.

8.4.1 HWARD

HWARD [46,47], the Hand-Wrist Assisting Robotic Device, is a three active DOF pneumatically actuated and backdriveable exoskeleton designed for repetitive grasp and release movements. One of the actuators controls a mechanically coupled grouping of all F/E motions of the four fingers, another the F/E motions of the thumb, and the final controls F/E of the wrist. The coupling of the four fingers permits the mechanism to use a matched axes topology without placement of exoskeleton structure between the fingers.

8.4.2 GENTLE/G

Gentle/G [48] consists of a three active DOF hand exoskeleton combined with the active three DOF HapticMaster [49] system and a passive three DOF Connection Mechanism. The HapticMaster and Connection Mechanism together serve to enable active positioning and passive orienting of the hand exoskeleton module. Similar to the HWARD, the Gentle/G has a single actuator for controlling thumb F/E, and groups the F/E of the four fingers with a matched axes topology. However, the Gentle/G uses two actuators to flex/extend the MCP and PIP joints independently.

8.4.3 WEGE ET AL

Wege et al. [50,51] developed a rehabilitation hand exoskeleton with 20 independent active DOFs. To the authors' knowledge, no other existing hand exoskeleton has as many active DOFs of the hand. The exoskeleton estimates user intention with force sensors and 10 EMG electrodes placed along the forearm. Each digit is controlled in A/A at the most proximal joint and all three F/E motions with a motor and Bowden cable transmission combined with a redundant linkage topology.

8.4.4 KAWASAKI ET AL

Kawasaki et al. [52,53] created an 18 active DOF hand and wrist exoskeleton. Two of these DOFs are located at the wrist. The thumb is controlled in CMC A/A and all F/E, whereas each of the four fingers are controlled in MPC A/A, MPC F/E, and PIP F/E. The mechanism uses matched axes for the A/A motions and redundant linkages with motors placed on the links for F/E motions. The device is controlled as a master/slave system using "mirror therapy" with a Cyber Glove (Virtual Technologies Co.).

8.4.5 HANDEXOS

HANDEXOS [54,55] is a multiphalanges device intended for poststroke rehabilitation. The device is designed to minimize human/exoskeleton rotational axes misalignment. For each digit, flexion is passively accomplished with three springs and cables, while extension is controlled for all MCP, PIP, and DIP joints by a single motor and cable. The thumb features one additional active DOF for CMC O/R driven by an on dorsum motor directly actuating a slider-crank mechanism. The system features a remote center of motion topology for each of the four finger MCP joints, and a matched axes topology for each DIP, PIP, and IP joint. The O/R joint is approximated and slightly offset dorsally. It should be noted that despite being comparatively compact, the matched axes topology inherently prevents fully adducting the fingers together.

8.4.6 TONG ET AL

Tong et al. [56,57] developed the hand exoskeleton that was later commercialized as the Hand of Hope (http://www.rehab-robotics.com/). It is intended for use with stroke rehabilitation. F/E of each of the digits is controlled independently by five linear actuators that directly drive linkages to move about remote centers of rotation aligned with the finger joints. User intent is estimated from EMG signals.

8.4.7 HEXORR

HEXORR [58] consists of two modules, one for the thumb and one for the fingers. Each module possesses one independent active DOF. The thumb mechanism can be passively adjusted to enable active control of different motions. The finger mechanism mechanically couples all fingers at attachment points, and causes F/E using a four-bar linkage system with link lengths chosen to maximize backdrivability. The mechanism uses a matched axes topology.

8.4.8 ATX

The ATX [59] is a thumb exoskeleton with five independent active DOF. The five DOFs were chosen to match a model of the thumb consisting of DOFs for CMC F/E and A/A, MCP F/E and A/A, and IP joint F/E. The ATX uses a matched axes for CMC F/E, but redundant linkages for MCP and IP F/E.

8.4.9 IHANDREHAB

iHandRehab [60] is a cable-driven rehabilitation hand exoskeleton with eight independent active DOF. The index finger modules have the same overall design, enabling each of the three F/E and the A/A motion of the respective digit. The mechanism is based on a parallelogram structure that adds a redundant link topology but places joints at matched axes locations. Range of motion (ROM) of each joint can be mechanically adjusted to prevent injuring patients.

8.4.10 RAHMAN ET AL

Rahman et al. [61] presented a five digit hand exoskeleton for stroke rehabilitation by mirroring motions from a custom control glove worn on the unaffected hand. This device features an independent linear actuator controlling a novel L-shaped sliding bar mechanism for F/E of each digit. This sliding mechanism effectively creates a remote center of motion topology through the combination of active rotation and passive translations.

8.4.11 ARATA ET AL

Arata et al. [62] created a compliant hand exoskeleton based on a sliding spring mechanism. Coupled F/E of the three DOFs of all fingers are controlled by sliding a spring blade with respect to two others and rigid connection points on each finger, causing the blades to bend.

8.4.12 IOTA

The IOTA [63], or Isolated Orthosis for Thumb Actuation, is a thumb exoskeleton designed for rehabilitation of pediatric patients with thumb-in-palm deformity. It is capable of independently actuating CMC A/A and MCP F/E with a matched axes topology. Five control modes were proposed, including manual control, teach & learn, cyclic control, wrist control, and functional assistance modes.

8.4.13 HEXOSYS-I

Iqbal et al. [64,65] developed HEXOSYS-I, a portable index finger and thumb exoskeleton device designed to facilitate therapy exercises. It features underactuated base-to-distal topology that is directly driven by a single motor for each joint and is able to apply up to 45*N* of bidirectional force in F/E. The link lengths were selected via a multiparametric optimization procedure that considered isotropy, dexterity, and the ability to exert force perpendicular to the finger phalanges.

8.4.14 ZHANG ET AL

Zhang et al. [66] made a portable rehabilitation hand exoskeleton featuring a novel "circuitous joint" that functions as a remote center of motion mechanism. The six active DOF device independently controls each of the three F/E joints of the index and middle fingers using a Bowden cable transmission system with a motor pack that mounts to the forearm.

8.4.15 BRAVO

The BRAVO hand exoskeleton [67] was developed for rehabilitation exercises involving cylindrical grasps. The four fingers are rigidly mechanically coupled at a shared driving shaft, are driven by a single motor that causes coupled F/E of all finger joints. The thumb features a spatial four-bar linkage mechanism, the plane of actuation is passively adjustable in six DOFs, and actuates coupled F/E of the distal two joints. The entire mechanism uses the redundant linkage topology. The BRAVO is specifically designed to be integrated with the L-Exos upper-limb exoskeleton [68,69].

8.4.16 SINFONIA

The Gloreha Sinfonia (https://www.gloreha.com) soft exoskeleton glove developed from [70] is a commercialized device for stroke rehabilitation. The glove independently controls F/E of the five digits via linear actuation by five pneumatic cylinders of flexible rods routed dorsally along the digits and attached to the fingertips. The Sinfonia can be purchased with an optional arm module for passive gravity compensation called the Gloreha Aria. The glove is controlled for either CPM or with mirror therapy with a sensorized glove on the other hand.

8.4.17 AGARWAL ET AL

Agarwal et al. [71,72] published prototypes of thumb and index finger exoskeletons that feature similar designs with redundant linkage topologies. Each of these devices independently actuate each F/E and an A/A motion of their respective digit using SEAs with Bowden cable transmission systems. The devices are highly transparent to the user, and accurate torque control is demonstrated.

8.4.18 ABDALLAH ET AL

An EMG controlled, portable, low-cost, hand exoskeleton is presented by Abdallah et al. in Ref. [73]. The design is 3D-printed, and all actuators and electronics are contained within a forearm splint module that attaches to the dorsal side of the palm, wrist, and forearm. The mechanism topology is that of the redundant linkage type, but with additional links added to couple F/E motions. The joints of each of the five digits of the hand are controlled in coupled F/E motions by a servomotor each, while A/A is passively permitted.

8.4.19 FERGUSON ET AL

In Ref. [74], Ferguson et al. created a three finger hand exoskeleton with reconfigurable mechanical coupling to actuate all five digits. Each exoskeleton finger consists of a base-to-distal mechanism that independently controls two DOF F/E motions using an electric motor and Bowden cable transmission system. The device was designed to be integrated with the EXO-UL8 [75,76] and BLUE SABINO [77] upper-limb exoskeletons. A second-generation hand exoskeleton with an active thumb O/R is under development.

8.4.20 DEXOHAND

The DexoHand [78] was developed and tested for use with stroke patients with spasticity. It was used to actuate F/E of the MCP, PIP, and DIP of the middle finger, as well as of the MCP and IP joints of the thumb with a remote center of motion mechanism driven by one actuator for each digit. The device was tested by a group of healthy and impaired individuals who reported high usability and satisfaction.

8.5 AUGMENTATION HAND EXOSKELETONS

Compared to other categories, few hand exoskeletons for augmentation were found in the literature. There are a number of significant obstacles to the development of an ideal augmentation hand exoskeleton for general use by healthy individuals. Foremost among these obstacles is low mass. In order for a hand exoskeleton to truly augment a healthy individual in tasks without unusual burdens, it is necessary for the mechanism to be of low enough mass to be mostly ignored. To the authors' knowledge, no existing combination of mechanical structure, materials, actuator, and power supply can fulfill this requirement while providing meaningful augmenting force. Power supply and actuators may be placed remotely to reduce mass at the hand, but this necessarily introduces at least some restriction of arm motion due to the resulting connector routing. The requirement can be relaxed if the mass of the hand exoskeleton can be offset to the environment through a supporting device.

Another significant challenge is for the augmentation hand exoskeleton to permit all the motions of a healthy hand. Even the most simplified kinematic models of the hand assume more than 20 DOFs. Although not all DOFs must be actively controlled to achieve augmentation, relatively few designs even passively permit all motions.

Additional challenges for augmentation hand exoskeletons come in the forms of intent estimation and control. Given the high number of DOFs and compact size it is difficult to accurately estimate the desired motion of all joints. Additionally, the exoskeleton must be capable of being extremely transparent.

In addition to general power augmentation hand exoskeletons, augmentation exoskeletons for specific challenging tasks can be found in the literature. A commonly stated application for these exoskeletons is for use in extravehicular activity (EVA) gloves in space. EVA gloves can be bulky and stiff, particularly at the MCP joint, and are fatiguing when used for extended periods of time. The augmentation hand exoskeletons for EVA gloves are intended to reduce the strain of hand activities on astronauts while wearing the gloves. It is important to note that the EVA gloves are already somewhat restrictive, and thus the hand exoskeletons that reduce the required effort to use the glove would not necessarily purely augment a user that is not wearing such a glove.

8.5.1 SHIELDS ET AL

Shields et al. [8] presented a three finger hand exoskeleton for use with EVA gloves. The exoskeleton features a rigid body that extends over the dorsal side of the hand, and encloses the four fingers in protective brackets with the ring and pinky fingers grouped together. The mechanism is based on a remote center of motion topology, and uses motors with cable transmissions.

8.5.2 SKIL MATE

Skil Mate [79] is a combination elbow–wrist–hand augmentation exoskeleton for use in hostile environments with seven independent active DOFs at the hand. Index and middle finger MCP and PIP joints, as well as F/E of thumb CMC, MCP, and IP joints are actuated in flexion by pneumatic cylinder actuators and restored in extension by coil springs. The wrist module passively allows two DOFs while the elbow is controlled in F/E by McKibben artificial muscles.

8.5.3 HASEGAWA ET AL

Hasegawa et al. [80] published their work on a portable wrist-hand augmentation exoskeleton with 11 DOFs and a matched axes topology. Three DOFs were dedicated to actuate a wrist five-parallel-link mechanism in all rotations. The hand module is capable of simulating variable compliance at the fingertips for grasping stability using a polyarticular tendon-driven transmission. The thumb is actuated in O/R as well as in biarticular MCP and IP F/E. The little, ring, and middle fingers are mechanically coupled at the attachment points. The index finger and the grouped three fingers are driven by three motors and tendon pairs each. For each finger grouping, one motor and tendon drives MCP flexion, one motor and tendon drives biarticular MCP and PIP flexion, and the last motor and tendon pair drives polyarticular flexion of all three finger joints. The system is force controlled based on detected sEMG signals.

8.5.4 TADANO ET AL

Tadano et al. [81] created a 10 DOF hand exoskeleton for power amplification driven by pneumatic artificial rubber muscles (PARM). On each of the four fingers, one PARM is used to control MCP F/E, another causes biarticular F/E of the PIP and DIP joints. The thumb features a cable and pulley system for CMC A/A, as well as a PARM for biarticular F/E of MCP and IP joints. Despite use of (mostly) compliant actuators, the system features rigid joints and thus is not a soft glove. The device does not easily fall into one of the discussed topologies, as the joint rotations are misaligned with those of the finger but the attachment points have passive tolerances to accommodate. The PARMs, cable and pulley, as well as "balloon type" force sensors contain no electronics at the hand, enabling the system (excluding remotely located pressure sensors and servo valves) to be waterproof. The system can also be used as an assistive exoskeleton.

8.5.5 MATHESON ET AL

Matheson and Brooker [82] developed two augmentation hand exoskeletons for use with EVA gloves based on the same design principle. Each exoskeleton powered extension of the four fingers by pneumatic muscle actuators. For the first prototype, flexion was obtained due to the initial state of the elastic composite material that composed the structure of the compliant exoskeleton. However, material fatigue and poor ROM were observed in testing. The second prototype used torsion springs, coupled F/E of the PIP and DIP, decreased coupling of extension via use of a second pneumatic muscle actuator, and had slightly offset joint axes with the hand. For both prototypes, all four fingers were coupled together.

8.5.6 ROBOGLOVE

The RoboGlove [83] is a spinoff of the Robonaut 2 system developed by General Motors and NASA. It is a soft exoskeleton glove capable of providing steady-state grasp force of 15–20 Lbs. Three electric motors drive ball screws to linearly actuate tendons that together drive F/E of all five digits, with index and middle fingers and pinky and little fingers coupled. Actuators, drive electronics, and microprocessor are contained within a forearm module. At the time of publication, the system had not yet been integrated into an EVA glove.

8.6 OTHERS

In addition to hand exoskeletons for assistance, rehabilitation, and augmentation, there exist a number of systems in the literature that are classified in this chapter as "other" hand exoskeletons. Whereas assistive, rehabilitative, and augmentative hand exoskeletons are primarily intended to move the user for the user's sake, hand exoskeletons that fall in the "other" category are primarily intended to simulate interaction. Applications for these exoskeletons vary, but a significant subset of them are used as virtual reality haptic devices or for teleoperation of other systems. Although these devices were typically developed for industry and academia, the recent boom in consumer virtual reality systems has sparked the creation of a number of commercial systems intended for consumers. It should be noted that these commercial systems are not usually accompanied by publications providing information on specifications, and thus some of them are excluded from Fig. 8.1.

8.6.1 SKK HAND MASTER

The SKK Hand Master [84] is a seven DOF exoskeletal haptic device with a redundant linkage topology driven by ultrasonic motors. These actuators were selected for their light weight, quiet operation, high power-to-weight ratio, high transparency, and no electromagnetic noise. However, they also have disadvantages of hysteresis and temperature rise with operation that were addressed with a PWM/PS driving method. The presented design features two modules, a four DOF index finger and a three DOF thumb, though it is noted that it could be expanded to include the other digits.

8.6.2 RUTGERS MASTER II-ND

The Rutgers Master II-New Design [85] force-feedback glove is a haptic interface designed for virtual environments. Although it may be considered a base-to-distal system, it is unique in the reviewed hand exoskeletons in that the mechanism is placed on the palm. Pneumatic cylinder actuators attach between universal joints at the palm and the fingertips of the thumb, index, middle, and ring fingers. Although this design does prevent interaction with most physical objects, it creates a very compact and lightweight design; the glove exoskeleton structure is just 80 g while the electric wires and pneumatic tubing connecting to the glove is 105 g.

8.6.3 STERGIOPOULOS ET AL

Stergiopoulos et al. [86] developed a base-to-distal hand exoskeleton for VR grasping simulation. The system underactuates the three F/E DOFs of each digit with a single actuator each, and the thumb passively permits A/A. The device is used with the Virtuose 6D commercial six DOF haptic arm to allow simulation of external forces and compensate for mechanism weight.

8.6.4 FONTANA ET AL

Fontana et al. [87,88] presented a portable haptic hand exoskeleton for accurate force displaying and precision grasp simulation. The system has "quasianthropomorphic" kinematics in that it uses a remote center of motion topology such that the exoskeleton moves about axes aligned with those of the hand, but it is also a base-to-distal topology as the linkages only attach at the base and distal phalanges. The thumb and index finger are each actuated in A/A and two F/E motions by three motors mounted on their respective first links to simplify cable routing.

8.6.5 JO ET AL

Jo et al. [89] created a five DOF redundant linkage hand exoskeleton for interaction with virtual reality. Each digit is controlled in F/E by a separate compact SEA featuring a linear electric motor. Linear potentiometers were used with the SEAs to estimate force and implement accurate force-control.

8.7 CONCLUSION

Despite the many advancements made and systems developed over recent decades, active hand exoskeletons still primarily exist in the realm of academia. Functionality for various applications has been demonstrated in lab settings, yet only a few hand exoskeletons have been commercialized. This is speculated to be due to limitations not only in the state-of-the-art of hand exoskeleton design, but also in related fields. It is likely that significant breakthroughs will require or accompany innovations in actuator technology, material science, transmission methods, sensor technology, and control algorithms.

Perhaps the greatest challenges for development and commercialization of hand exoskeletons stem from the many DOF in a relatively compact area. In lower-limb and arm exoskeletons, mechanical designs have tended to converge toward actuation capabilities for similar DOFs, with further improvements still being made in control, actuation method, materials, and power supply. However, for hand exoskeletons, no such trend is immediately apparent and very few systems even approach independent actuation of every motion of the hand.

A popular and growing area is that of using soft robotics for hand exoskeletons, as the systems are often lighter, lower profile, and feature inherent safety. However, existing systems typically have five or fewer independent DOFs and therefore couple motions. Although compliance permits the generated motions to adapt to grab a variety of objects, not all desirable motions can be actuated. Additionally, actuator design and precise control of soft robotic hand exoskeletons have not been refined to the same extent as their rigid counterparts.

Despite the potential for hand exoskeletons to be built onto full arm exoskeletons to improve functionality, few systems have been developed that enable active control of multiple DOF of both the hand and arm. This can be attributed to multiple factors including physical constraints, high required complexity, challenges with intent estimation, and potentially opposing design requirements. However, it should be noted that synthesis of combined arm and hand exoskeleton systems is an active area of research with significant future potential [42,68,74,90].

Another area with room for improvement is that of portability. Numerous portable systems have been developed, yet various systems face issues with operation time, system weight, low number of independently controlled motions, and low torque capabilities. A significant limiting factor is actuator mass, and therefore alternative actuation methods may provide improvements to the state of the art.

There is reason for the increasing call for the application of hand exoskeleton systems. As the global society ages, the need arises for assistive technologies to keep the elderly mobile and functional. Similarly, as medicine improves, the number of patients that survive stroke, spinal cord injuries, and other conditions that require rehabilitation, potentially from robotic systems, increases. Further, augmenting exoskeletons have the potential to improve strength of laborers, resulting in higher worker output, as well as endurance of astronauts, potentially improving mission capabilities even as space flight is entering a new phase with the private sector. Lastly, future and emerging markets such as virtual reality entertainment may create demand for hand exoskeletons that cannot currently be predicted.

This chapter was intended to review the literature on hand exoskeleton systems by providing a summary of the state-of-the-art, and by discussing techniques and challenges related to these devices.

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