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CLINICAL REPORT

Evolution of mechanical fingerspelling hands for people who are deaf-blind

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Abstract—People who are both deaf and blind can experience extreme social and informational isolation due to their inability to converse easily with others. To communicate, many of these individuals employ a tactile version of fingerspelling and/or sign language, gesture systems representing letters or words, respectively. These methods are far from ideal, however, as they permit interaction only with others who are in physical proximity, knowledgeable in sign language or fingerspelling, and willing to engage in one of these "hands-on-hands" communication techniques. The problem is further exacerbated by the fatigue of the fingers, hands, and arms during prolonged conversations.

Mechanical hands that fingerspell may offer a solution to this communication situation. These devices can translate messages typed at a keyboard in person-to-person communication, receive TDD (Telecommunication Devices for the Deaf) telephone calls, and gain access to local and remote computers and the information they contain.

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INTRODUCTION

Communication is such a natural and integral part of one's daily activities that it is taken for granted. Today instantaneous international communication is an affordable reality. For example, it is not uncommon for a person with access to the Information Superhighway (Internet) to retrieve information and post messages from/to a dozen different countries during a single on-line session. Cellular telephones and telephones in airplanes are the latest advances in mobile communication technology. These systems, which permit communication with anyone, at any time, and from any location, suggest that being without communication is unnatural and personally limiting. Yet there are many people for whom interpersonal isolation is a way of life. These are the estimated fifteen thousand deaf-blind men, women, and children in this country who cannot even communicate with another person on the opposite side of the same room, let alone with someone on the other side of the world. There are veterans who incurred deaf/blindness as a result of a service-connected injury.

Usher's Syndrome

The majority of adults who live with the dual sensory loss of deafness and blindness have a disease

called Usher's syndrome. It manifests itself as deafness at birth, followed by a gradual loss of vision commencing in the late teens or early twenties. Although Usher's syndrome accounts for 15 percent of congenital deafness, it is usually not diagnosed until the onset of the visual impairment, or even later. Unaware that special education preparatory to visual loss may be in order, these children are usually enrolled in programs for the deaf where they learn fingerspelling and sign language (and/or lip reading and speech) in addition to reading print. Because they are identified as deaf, Braille skills are not taught.

When loss of vision is superimposed on deafness (as happens with Usher's syndrome), a major channel of receptive communication is lost, usually resulting in an enormous social and informational void.

Alternate Methods of Communication

Braille is a potential tool for relieving some of this isolation. In addition to providing a system for reading, a mechanical representation of Braille has been incorporated in electronic aids such as the Telebraille (a TDD with a 20-character mechanical Braille display), to enable deaf-blind individuals to receive information in both face-to-face and remote communication situations. Learning Braille as an adult, however, is difficult. The very act of learning to read Braille may be considered a final admission of blindness.

Many deaf people use sign language which incorporates more global movements and configurations of the hands and arms, as well as facial expressions, to represent words and phrases. They supplement sign language with "fingerspelling," a gesture system in which there is a specific hand and finger orientation for each letter of the alphabet, to communicate words for which there is no signed equivalent (such as proper names).

Tactile Fingerspelling and Sign Language

A common communication technique used with and among deaf-blind people is simply a hands-on version of fingerspelling and/or sign language (**Figure 1**). Instead of receiving communication visually as deaf people do, the deaf-blind person's hand (or hands) remain in contact with the hand (or hands) of the person who is fingerspelling or signing. The full richness of the motions present in sign language can not be conveyed in the tactile mode required by a deaf-blind individual. Instead, each word of a message is typically spelled out, one letter at a time with the fingerspelling technique. (Although many Usher's Syndrome patients can speak intelligibly or use sign language, others use fingerspelling for expressive communication as well.)

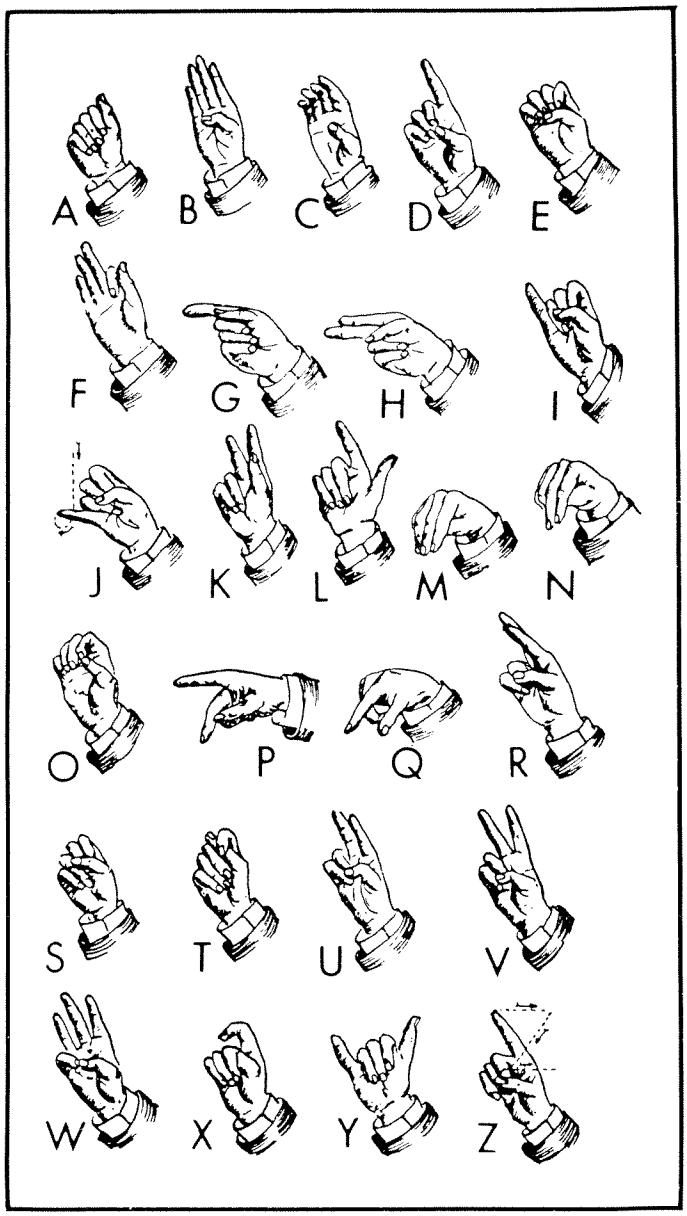

Figure 1.
The manual fingerspelling alphabet.

While such tactile reception works fairly well for many deaf-blind people, it does have significant drawbacks. Since very few people are skilled in these manual communication techniques, there are very

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few people with whom to "talk." The need for interpreters poses still other problems: locating, procuring, and paying for the interpreter service. A problem unique to deaf-blind individuals is that many interpreters are accustomed to being "read" visually by deaf clients and may not be comfortable with the physical restrictions involved in signing while another person's hands are touching theirs. In addition, the rapid fatigue resulting from these tactile methods often requires two interpreters so that a break may be taken from continuous fingerspelling or signing. The need for an interpreter may also intrude on the deaf-blind individual's privacy and place him/her in an extremely dependent situation due to the complete reliance on an interpreter for any communication.

THE FIRST ROBOTIC FINGERSPELLING HAND

Method

In an attempt to alleviate these problems, the Southwest Research Institute (SWRI) in San Antonio, TX, conceived and developed a mechanical fingerspelling hand in 1977 (1). This early device demonstrated the feasibility of transmitting linguistic information to deaf-blind people by typing messages on a keyboard connected through electrical logic circuitry to the mechanical hand. The hand responded by forming the corresponding letters of the one-hand manual alphabet. To receive the information, the deaf-blind user placed his/her hand over the mechanical one to feel the finger positions, just as he/she would with a human fingerspelling interpreter. This system finally enabled deaf-blind people to receive communications from more than a few select individuals; anyone who could use a keyboard could express themselves to the deaf-blind person through the mechanical fingerspelling hand.

Results

While the SWRI system demonstrated the concept's feasibility, it had many technical shortcomings: not all of the letters could be properly formed, it operated more slowly than a human interpreter, and the fluidity of motion which seemed to greatly enhance the intelligibility of receptive tactile fingerspelling was lacking. In addition, any changes in timing or how the hand formed the letters had to be achieved through mechanical alterations of the hardware. This limited the device's flexibility as a research tool.

DEXTER

Method

In 1985, the Rehabilitation Engineering Center of The Smith-Kettlewell Eye Research Foundation sponsored a class project conducted by four graduate students in the Department of Mechanical Engineering at Stanford University to design and fabricate an improved state-of-the-art fingerspelling hand (2–7). Its major goal was to develop a system with improved timing and easily modifiable finger positions. These qualities were realized in a new robotic fingerspelling hand named "Dexter" (**Figure 2.**)

Mechanical Hardware

Dexter looked like a mechanical version of a rather large human hand projecting vertically out of a box. The four machined aluminum fingers and a thumb were joined together at its palm. All digits operated independently of each other and had a range of motion comparable to human fingers. The thumb was jointed so as to allow it to both sweep across the palm as well as move in a plane perpendicular to it. A pneumatic rotary actuator allowed the palm to pivot in a rotary fashion around

Figure 2.
Dexter fingerspelling hand.

a vertical steel rod much the way a human hand can pivot from the wrist—except that Dexter could achieve a full 180° pivot.

All Dexter's finger and thumb motions were actuated by drive cables. Pneumatic cylinders pulled these cables which flexed the individual fingers and thumb, while spring-driven return cables extended the fingers. The cylinders, in turn, were activated by air pressure controlled by electrically operated valves. These valves were controlled by a microcomputer system. The actuating equipment and valves were housed in two separate assemblies below the hand.

Computer Hardware

The original student design was based on an Intel 8085 STD-bus "target system" used in ME218 (Smart Product Design Course) at Stanford. It consisted of the 8085 microcomputer, Forth programming language, memory, and counter/timer support. The timer generated the signals that determined the rate of hand motion and how long each finger position was to be held. The additional circuitry needed to control Dexter was fabricated on a standard card which plugged into the target system card cage. A single external 12 volt power supply activated the 22 valves under computer control. Digital output port latches received data from the microprocessor, while Darlington power transistors provided sufficient current to activate the electrically controlled valves. Letters to be displayed on the hand were entered on an IBM-PC computer's keyboard which was connected by a serial link to the target hardware.

Dexter's hardware was subsequently revised at the Rehabilitation Research and Development Center (RR&D), Palo Alto, CA, to consist of a Z80 microprocessor card, two medium-power driver cards, and a high-current DC power supply all housed in an STD bus card cage. The microprocessor card itself contained counter-timers, memory, and serial interfaces. Commercial medium-power DC driver cards replaced the student-built wire-wrapped version and the power supply for operating the pneumatic valves was included within the STD chassis. An Epson HX-20 laptop computer's keyboard and display were employed to communicate user messages over a serial link to the self-contained target system.

Computer Software

The Forth programming language was chosen because 1) its design cycle is approximately eight times shorter than assembly language, 2) it is an interactive and compact high-level language that can employ assembly language for critical timing and interrupt service routines, 3) it uses a standard host computer connected by a serial port to the target hardware for development, and 4) the application program can be stored in non-volatile memory after it is fully tested.

The student-designed Forth software was substantially updated by RR&D to 1) execute from non-volatile memory, 2) accommodate menu-driven alteration of critical parameters such as timing variables, 3) allow new characters typed on the keyboard to be accepted while previous ones were being fingerspelled, and 4) incorporate both modem and serial input of characters.

Operation

The microcomputer and its associated software controlled the opening and closing of the bank of valves which directed air pressure to specific pneumatic cylinders which pulled on the drive cables which were the "tendons" of the fingers. As a message was typed on a keyboard, each letter's ASCII value was used by the software as a pointer into an array of stored valve control values. The states (open or closed) of all 22 valves were specified by three bytes. Two to six valve operations, each separated by a programmed pause, were needed to specify the finger movements corresponding to a single letter. The hand could produce approximately two letters per second, each starting from and returning to a partially flexed neutral position.

An additional bit in the valve control byte triad was used by the software to determine whether the current finger position was an intermediate or final letter position. Different programmed pause times were associated with each of these two situations.

Although the mechanical hand could not exactly mimic the human hand in fingerspelling all the letters (such as the special wrist and arm motions required in J and Z), the fact that Dexter always produced the same motions for a given letter was an important factor influencing its intelligibility. The inter-letter neutral position was another unnatural feature of the design that did not accurately reflect

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human fingerspelling and limited the speed of letter presentation. Despite these shortcomings, users of Dexter had little difficulty in accommodating to it.

Results

Deaf-blind clients of Lions Blind Center (Oakland, CA) served as subjects for the initial testing of Dexter. They were able to identify most of the letters presented by the robotic hand without any instructions, and in less than an hour were correctly interpreting sentences. Equally important was their positive emotional reaction to the hand. They seemed to enjoy using it and seemed to be intrigued by its novelty. There were no negative comments made concerning its mechanical nature or any other aspect of the system.

DEXTER-II

Method

Dexter-II was built by a second Stanford student team in 1988 as a second-generation computer-operated electro-mechanical fingerspelling hand (8,9). This device, like its predecessor, translated incoming serial ASCII (a computer code representing the letters and numbers) text into movements of a mechanical hand. Dexter-II's finger movements were felt by the deaf-blind user and interpreted as the fingerspelling equivalents of the letters that comprise a message (**Figure 3**).

Figure 3.
Dexter II fingerspelling hand.

Dexter-II was approximately one-tenth the volume of the original Dexter mechanical system. It was designed by three Stanford graduate mechanical engineering students and employed DC servo motors to pull the drive cables of a redesigned hand, thereby eliminating the need for a supply of compressed gas. A speed of approximately four letters per second, double that of the original design, could be achieved with the improved design.

Mechanically, the hand (a right hand the size of a 10-year-old) was oriented vertically on top of an enclosure housing the motors. Each finger could flex independently. In addition, the first finger could move away from the other three fingers in the plane of the hand (abduction). The thumb could move out of the plane of the palm (opposition). Finally, the wrist could flex. Each hand motion was driven by its own servo motor connected to a pulley. Wire cables anchored at the hand's fingertips and wound around pulleys served as the finger's "tendons." As the motor shafts were powered, they turned the pulleys, pulling the cables, to flex the fingers. Torsion springs at the "knuckles" separating the Delrin finger segments provided the force to straighten the fingers when the motors released tension on the cables.

Dexter-II's computer used the STD-bus enclosure, Z80 microprocessor card, and Epson HX-20 computer from Dexter. Two commercial counter timer cards replaced the medium-power driver cards and were used to produce the pulse-width modulated waveforms required to control the DC servo motors. In operation, a message was typed on a keyboard (the Epson HX-20) by a nondisabled person. Each letter's ASCII value was used by Dexter-II's computer software to access a memory array of stored

control values. This data stream programmed the pulse-width modulation chips to operate the eight servos and flex the fingers. The resulting coordinated finger movements and hand positions were felt by the deaf-blind communicator and interpreted as letters of a message.

Results

Dexter-II was first tested by a deaf-blind woman who is extremely proficient at "reading" tactile fingerspelling. She provided many suggestions for improving Dexter-II's letter-shape configurations. Later, it was introduced to 12 deaf-blind people during an annual retreat in Sacramento, California.

In June of 1989, about 20 deaf-blind attendees at the annual Deaf-Blind Conference in Colorado Springs had an opportunity to experience Dexter-II. The device was also exhibited at the 1989 RESNA Conference in New Orleans, Louisiana, and at the InvenTech meeting in Anaheim, California in September, 1989. In all cases, the deaf-blind individuals' ability to initially understand Dexter-II varied considerably. Some were able to understand Dexter-II immediately, while others had trouble translating a few letters.

Although neither Dexter nor Dexter-II could exactly mimic human hand movements in fingerspelling all the letters, they were able to display close approximations that have proven to be easy to learn by deaf-blind users. An advantage of Dexter-II's mechanical system was that it always produced the same motions for a given letter—an important factor in recognizing its fingerspelling "accent."

FINGERSPELLING HAND FOR GALLAUDET

Method

In 1992, Gallaudet University (Washington, DC), with funding from the National Institute on Disability Rehabilitation Research (NIDRR), contracted for the design and construction of two third-generation fingerspelling hands for clinical evaluation (10,11). These units were to be smaller, lighter, and more intelligible than previous designs (**Figure 4**). The effort involved two facilities: RR&D Center designed the new mechanical and computer systems, while the Applied Science and Engineering Laboratories (ASEL) (Wilmington, DE) provided critical hand position data and addressed telephone interface access issues.

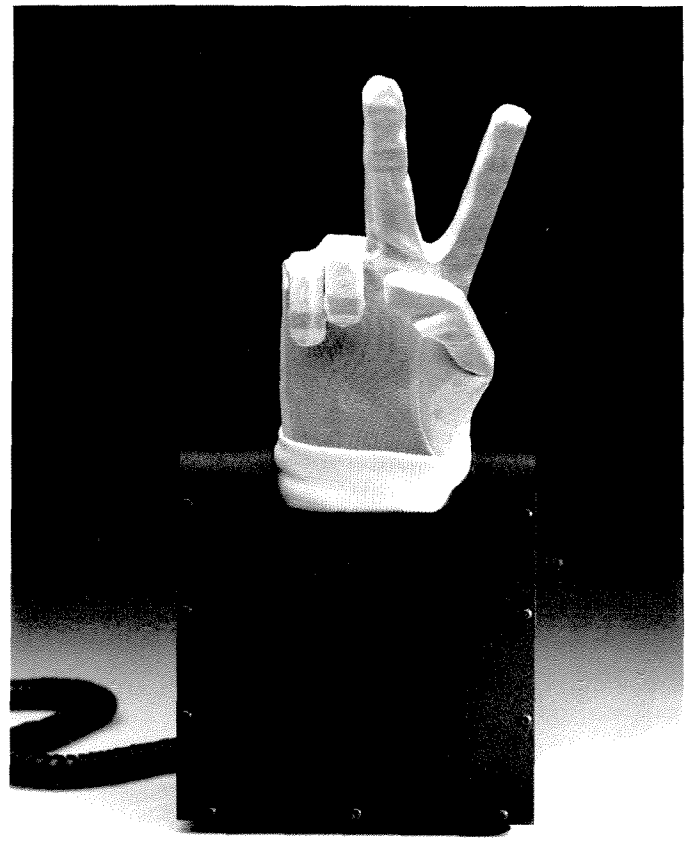

Figure 4.
Fingerspelling hand for Gallaudet University.

Mechanical Design

In this design, as in Dexter-II, each hand motion was driven by a servo motor connected to a pulley. A cable was wound around the pulley, routed up the finger, and attached to its tip. The fingers themselves were constructed of Delrin segments attached to each other by a strip of carbon fiber. The carbon fiber provided the flexible hinge and restoring force necessary to extend the finger. When the motor shaft and pulley rotated, the cable was pulled and the finger flexed. When the motor shaft rotated in the other direction, the tension on the cable was released and the finger straightened.

Computer Hardware Design

A Z180 SmartBlock (Z-World, Davis, CA) 8-bit microcontroller accepted RS232 serial data and

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choreographed hand motion by controlling eight DC servo motors. The controller itself was compact enough to be packaged within the hand's enclosure.

Computer Software Design

The Forth programming language provided a simple user interface, allowed modifications to the finger positions, and permitted the system parameters to be altered. Fingerspelling movements in this version were much more fluid due to the elimination of the inter-letter neutral position. The software includes two finger position tables for each letter pair. One table is permanently installed, while the other can be altered using a built-in editor. This facility permits movements to be changed to enhance a particular-letter pair's readability. Fingerspelling speed was adjusted by a six-position rotary switch. The first five positions selected increasing speeds by altering the length of the pauses between letters, while the final position offered a programmable speed.

Results

ASEL tested and configured the fingerspelling hands for use with TDDs. The letters were further optimized for improved recognition. Nine deaf-blind people tested the hands over a 2-month period at Gallaudet. One individual was able to interpret all 10 simple sentences without error. Other users were able to understand 70 percent of the sentences. Comparable performance was achieved with single isolated letters. The users identified confusing letter combinations and suggested improvements for a commercial prototype (12).

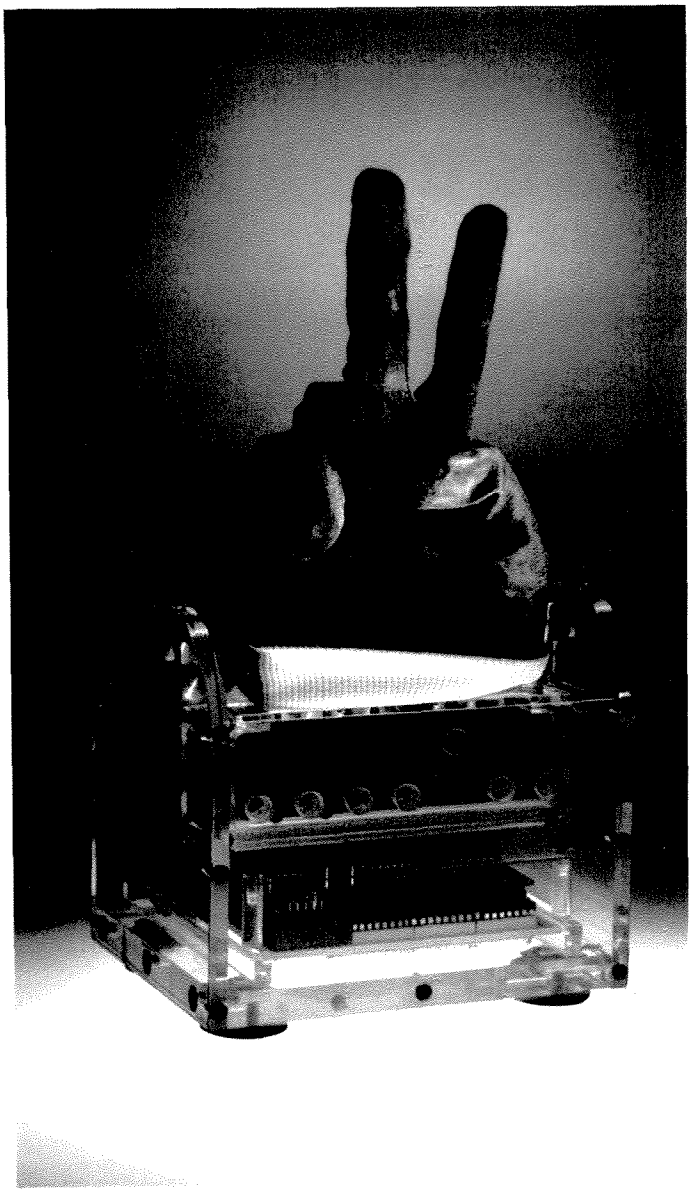

Figure 5.
RALPH fingerspelling hand.

RALPH

Method

A fourth-generation fingerspelling hand called RALPH (for Robotic ALPHabet) has been constructed by RR&D to serve as a basis for technology transfer and commercialization (**Figure 5**). Specifically, this design implemented an improved mechanical system.

Mechanical Design

RALPH's design is similar to the hands designed for Gallaudet. In this device, however, a new mechanical system replaces the pulleys and carbon fiber strips. Each hand motion is driven by a servo motor connected by a lever arm to a rod. The rods push and pull a system of linkages that flexes the individual fingers and the wrist. The elimination of the pulleys makes RALPH more compact and able to fingerspell faster. Its fingers are actively extended, unlike Dexter-II or the Gallaudet hands.

Computer Design

RALPH utilizes the same computer hardware as its predecessor and its Forth software is organized in 17 modules. These modules provide enhancements for the Forth kernel, an assembler (including routines that implement special I/O instructions used by the microcontroller), an ANSI display driver, serial port utilities, timer port utilities, clock utilities, servo motor pulse width modulation generation, speed switch driver, interrupt routines, input buffer software, timing control, hand data storage, fingerspelling algorithm, hand position editing support, and the user interface. As with the Gallaudet hand, RALPH's software provides a menu-driven user interface, allows the finger positions to be edited, and permits alteration of system parameters.

Operation

Any device that produces RS232 serial data, including terminals, modems, computers, OCR scanners, speech recognizers, or modified closed caption systems, could be used to control RALPH. The user interface is implemented as a menu system that provides easy access to the unit's various functions including displaying and setting the microcontroller's parameters, testing the hand motions, editing hand position data, and entering letters to be fingerspelled.

In the fingerspelling mode, key presses are entered on the keyboard. The hand's software translates these key presses into commands for the DC servo motors. As the motor shafts rotate, they push/pull on the rods that connect to the fingers' mechanical linkages. It is by this coordinated series of motor commands that keyboard input is transformed into choreographed motion representing fingerspelling.

The mechanical system provides sufficient torque to move the fingers against the resistance of a user's hand, but not enough to cause any pain or injury if the user's finger happens to get caught under RALPH's. The servo motors simply stall when their torque limit is exceeded.

Results

Over a 2-day period at ASEL, RALPH was evaluated for approximately 8 hours by two individuals. One was familiar with the Gallaudet fingerspelling hand and was completely deaf and blind. The other had not used mechanical fingerspelling hands before and had some residual sight and hearing capabilities. They both reported trouble with some letters, but the first user was able to correctly identify isolated characters over 75 percent of the time.

When short sentences were presented, the experienced user completely understood approximately 75 percent of the sentences. Furthermore, in each of the failures, after a second presentation, the sentence was either understood in its entirety or just one key word was incorrectly identified.

Additionally, both users appreciated the new rounded design of RALPH's finger segments because they felt more natural than the hands built for Gallaudet.

DISCUSSION

Beyond evaluation, technology transfer issues must be addressed. The market for fingerspelling hands needs to be assessed. A collaborative effort with a manufacturer will be required to move this device out of the laboratory and into the hands of deaf-blind people. A potential manufacturer has been found in southern California. Current plans involve pursuing Small Business Innovative Research (SBIR) funding for technology transfer and the additional design changes to address remaining concerns identified during Gallaudet's evaluation.

A potential solution exists for the provision of fingerspelling hands to deaf-blind people. Within California (and some other states), all telephone subscribers support a fund which provides telephone access equipment for persons with disabilities. Under this program, approved commercial versions of this fingerspelling hand could be furnished at no charge to deaf-blind people.

Research has also been done on a "Talking Glove" (13). This device consisted of an instrumented glove worn by a deaf-blind person that sensed the flex of each finger. Its pattern matching software translated the wearer's fingerspelling gestures into letters that could be displayed or vocalized by a speech synthesizer. This system could provide an expressive communication channel for RALPH's users.

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CONCLUSION

RALPH was intended to serve deaf-blind users as a complete receptive communication system, not just a means of receiving information in face-to-face situations. Its ability to respond to computer input means it can be interfaced to a TDD to provide deaf-blind people with telephone communication. It can also be connected to computers to provide improved vocational and avocational potential to the deaf-blind community.

All encounters with RALPH and previous fingerspelling hands have been enthusiastic, positive, and at times, highly emotional. The increased communication capability and ability to "talk" directly with people other than interpreters are powerful motivations for using fingerspelling hands. They have the potential to provide deaf-blind users with untiring personal communication at rates approaching that of a human interpreter.

A commercially available product may help alleviate some of the extreme isolation experienced by people who are deaf and blind. It is a device that performs a worthy task—that of enabling human beings to communicate with each other.

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