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Rehabilitation of musicians with upper limb amputations

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Abstract—Three saxophone players with upper limb amputations have been successfully rehabilitated to play their musical instruments using skin-conductivity touch control. Each attained a standard of musicianship sufficient to perform the standard repertoire of the instrument in a concert setting. The mechanical and electrical modifications to the saxophone are described, as well as the principles of operation of the skin-conductivity touch control module. The touch control module is commercially available for prosthetists who wish to fit musicians or others with upper extremity amputations who require rapid accurate control of a number of channels of powered prosthetic function.

Key words: *Skin-conductivity touch control, upper limb amputation, powered prostheses, musical instruments, rehabilitation.*

INTRODUCTION

If a person who has played a musical instrument professionally loses a hand, the consequences to his livelihood and his psychological outlook on life can be severe. Non-musicians may not realize the extent to which the ability to play music serves as an emotional balancing factor in the life of a professional artist. When the limb is lost, the patient and his physician may assume that musical rehabilitation is impossible. The powered electric hand, as applied in clinical practice, only provides a grip function and not the individual movements that a musical instrument requires. Thus, a patient may be counseled to change occupations and to forget his previous professional musical talents.

However, the technique of "skin-conductivity touch control" offers the speed, dexterity, and accuracy of control required for the sophisticated task of controlling a musical instrument. The successful rehabilitation of the three musicians (**Figure 1**) may serve as an example for the more widespread application of touch control to rehabilitate non-musicians with upper limb amputations. Touch control also has been used to operate powered hands, powered elbows, and powered wrist rotators, and is particularly applicable to high-level and bilateral amputees (2). Any occupational task requiring rapid selective control of multiple channels may prove amenable to this technique.

Our objectives were to restore each individual's ability to earn a livelihood and to improve his morale through the satisfaction of playing music well. Two conventional methods of controlling electrically-powered prostheses are: 1) mechanical switches; and, 2) the surface electromyogram (EMG). Although both have important applications, they are not without limitations. Switches can wear out, bind mechanically, abrade the skin, and be difficult to adjust so that they do not require undue force, and yet are not activated inadvertently.

The surface EMG avoids some of the mechanical problems, but introduces other difficulties. The

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Figure 1.
Three musicians with upper limb amputations rehabilitated to play musical instruments. Left: H.D.M., Center: R.V., Right: H.W.

EMG signal contains a substantial amount of low frequency noise (1). Therefore, the signal is usually rectified and filtered with a circuit known as a leaky integrator. This filtering introduces a delay, often of the order of 200 ms. Such a delay is acceptable for powered electric hands, wrist rotators, and electric elbows, because the motors and gears of such prosthetic devices have an inertia which introduces comparable delays.

However, a good musician may execute several notes of a rapid musical passage within the time required to integrate and process an EMG signal from biceps or triceps. Sixteenth notes at a tempo of allegro, for example, may require execution of up to 8 notes per second in a run. The EMG signal as commonly obtained and processed does not provide enough high-speed channels for this application.

METHODS

Touch control

The principle of operation for skin-conductivity touch control is relatively simple (**Figure 2**). The subject's skin contacts the reference (ground) of the electronic circuit at more than one location to increase the reliability of the connection. When he moves his forearm to touch a chosen contact, a voltage divider circuit is formed between the 5 MΩ resistor R1 and the skin resistance, R2 of his limb. Touch control can be used with skin resistances up to 20 MΩ for amputees with skin grafts or scars.

After contact, the input signal to the inverting input of the operational amplifier falls from its original 12 V to a voltage lower than the reference voltage applied to the noninverting input. The change in voltage is amplified and inverted by the operational amplifier. The signal is conditioned to remove interference and to provide a clean 12 V transition corresponding to the playing of one note.

Control of a saxophone

The next step is interpreting the control information for the musical instrument and actuating the valves of the saxophone in a smooth, reliable, and natural manner. In the normal operation of a saxophone, the depression of a single key may close one or more valves. The use of 5 keys by the right hand and 4 keys by the left hand are sufficient to play the notes of a scale over 1 octave. Variation in lip tension on the reed, air pressure and other aspects of the interface between the player's mouth

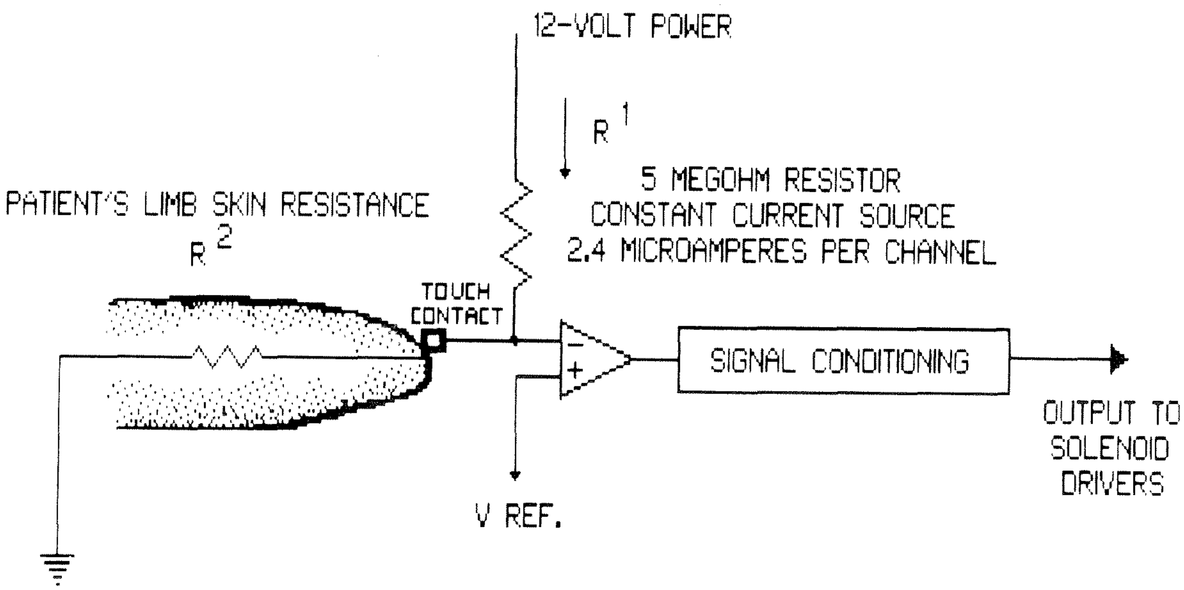

Figure 2.
Skin conductivity touch control: principle of operation.

and the instrument (referred to in general as the embouchure) allow switching between octaves. A variable velocity of finger impact is important for musical expression on the piano and guitar, but the valves of a saxophone are always closed quickly and completely. Musical expression is provided by changes in the air pressure and embouchure. The fact that proportional control of the valves was not required simplified the design of the prosthesis.

The combination of valves producing particular notes can be stored in a permanent logic array within the control circuitry and recalled instantly when the stump of the amputee touches a particular contact associated with that note. Thus, the subject need not touch more than one contact simultaneously to produce a single note. The diode matrix shown in the circuity of **Figure 6** allows a full musical scale to be developed from contacts installed in a sequential order (see Subject-electronic interface below).

Electro-mechanical design

A solenoid matches the electro-mechanical requirements well because of its speed, lightness, and high final closing power. A solenoid consists of a hollow cylindrical coil of insulated magnet wire with an iron core free to slide inside it. When electrical current is applied, the core is pulled into the coil, causing an extension of the core to protrude from the end of the coil. The force of this extended core depresses the key of the saxophone, as illustrated in **Figure 3**. When the current is turned off, the core is free to move back to its original position. The restoring force is provided by springs which are already present for the keys of the saxophone.

The solenoids were matched to the stroke and force required for the application. For the large tenor saxophones played by H.D.M. and H.W., type TP12 × 13 solenoids (Guardian Electric Manufacturing Co., Chicago, IL) were used; while for the smaller alto saxophone played by subject R.V., Guardian type TP8 × 16 solenoids were used. The forces generated ranged from 8 to 12 N with a travel distance from 1 to 3 mm. The power drawn was only 4–7 watts per solenoid.

Both solenoids may be considered relatively long-throw solenoids because they still develop substantial force when the saxophone key is open. A shorter length may be cosmetically more attractive on the saxophone, but its shorter throw will result in a steeper force-stroke curve. More current will be needed to overcome the initial friction of the key mechanism resulting in a much shorter battery life. The final closing force of a short-throw solenoid under high current conditions may actually deform the metal of the instrument.

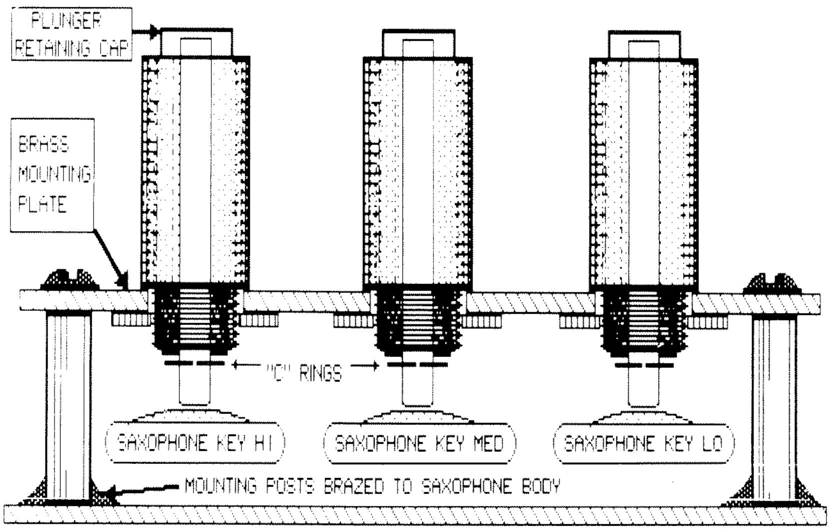

Figure 3.
Three solenoids mounted to activate saxophone keys.

Several design constraints must be satisfied. 1) The final travel distance should be small to ensure fast closure of the valve. To do this, the resting position of the plunger must be adjusted so that the valve is partially closed. The adjustment should be made with the assistance of an experienced saxophone player to check on the quality of the sound produced. 2) The closing forces should be large enough to create a positive air seal between the valve and the saxophone body, but the noise must be controlled. To do this, the saxophone valve should close just prior to the solenoid plunger coming to its own internal end stop so that the pad on the valve seat acts as a noise damper. 3) Friction on the hinges of the valves must be minimized by careful perpendicular alignment of the plunger to the saxophone valve seat. Four brass standoffs brazed onto the shell of the saxophone provide support and adjustments for aligning the mounting plate.

Subject-electronic interface

A prosthetic shell was designed to hold the contacts in an orderly array, to sense the notes that the subject wishes to play. The shell fits as a cylinder whose diameter is slightly larger than the diameter of the stump. The difference in diameters creates a small gap between the skin and the contacts, thus requiring only small movements of the stump to initiate different notes. This gap between the stump and the touch contacts should be adjusted for each separate note to be played.

Large changes in clearance can be made by heating the plastic shell and deforming it under pressure. Smaller changes can be made by placing or removing washers underneath the contacts. In all 3 subjects it proved necessary to start training with large clearances for ease of operation, reducing the clearances gradually as the subject progressed. Later, the smaller clearances enabled the subject to roll from one contact to an adjacent one without releasing solenoids shared by both notes, which resulted in a smoother playing technique. The contacts had to remain in the same position relative to the body to prevent inconsistencies in the rhythm of the music. Three different methods of maintaining the contacts in the same relative position were developed for the 3 saxophone players.

Our first subject (H.D.M.), who had an elbow disarticulation, achieved good repeatability of note selection with the prosthesis supported in position mainly by a harness strap over his left shoulder. The distal end of the prosthetic shell was prevented from excessive movement by being held against his leg. He was the only subject with a single limb joint to control (the shoulder), thus decreasing the requirements of fixation points.

Subject R.V. was amputated at the midforearm level and achieved the most consistent results in a sitting position with the prosthetic shell fixed to his leg. By resting the elbow on the leg, the upper arm was supported, which allowed reproducible positioning of the distal end of the stump in the shell.

The prosthetic shell was fixed to the armrest of a chair for subject H.W. Having had a wrist disarticulation, his stump was the longest of the 3 musicians. His elbow was supported by the arm-

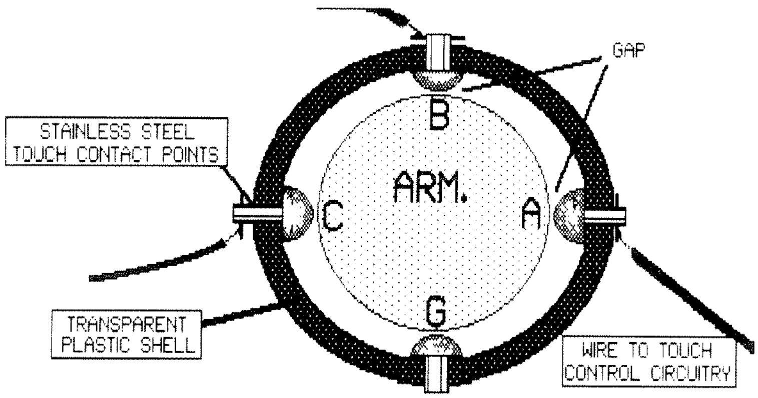

Figure 4.
Arrangement of touch contacts inside plastic UVEX shell for tenor saxophone player: left-side amputation, H.D.M.

chair, thereby limiting the total arm movement. This eliminated motion at the shoulder so that the stump position was mainly controlled by the elbow angle, and the repeatability of note selection was increased.

Power supply

Battery operation was mandatory for safety (the touch control system requires low impedance grounding to the skin) and the portability required for use outdoors in a marching band. Practicality required at least 2 hours of continuous playing and rechargeability. Batteries that met the requirements of economy, weight, power, and rechargeability were the 4 ampere-hour gel cells. Two 12 V gel cells were incorporated into each portable case, providing 24 V for the solenoids. A tap at 12 V operated the TC-2 touch control modules. For double insulation safety protection, the charger switch was designed to disconnect the ground when the AC-powered battery charger was in use.

Custom fitting of the modular components

A modular approach is frequently efficient for fitting subjects with diverse requirements. We therefore used an extension of the same modularized approach that has proven successful in the more than 50 powered prosthetic fittings with which we have been involved (3). The rehabilitation equipment differed in the number of solenoid channels needed to fit the alto horn (5 channels) as opposed to the tenor horn (4 channels) and in the shape and support system for the prosthesis which housed the touch points. The same electronic control system modules (Type TC-2 touch control module, Leaf Electronics Ltd., 11583 80 Ave., Edmonton, Canada T6G OR7) were used for all channels of each prosthesis. All 3 subjects were supplied with identical interchangeable portable control units having pin-compatible plugs for connection to the saxophone and the skin contacts in the prosthetic shell.

Prosthetic shell for touch contacts

Figure 4 and **Figure 5** show the order of contacts for left-arm and right-arm subjects respectively (**Figure 4**, H.D.M.; **Figure 5**, R.V.). These arrangements were based on the concept of mapping the location of the fingers of the missing hand to a circle around the forearm. The prosthetic implementation of a musical instrument maps the scale in an orderly progression, the same as traditional instruments. The amputee musicians could then learn the control techniques quickly.

Circuitry for operating electric actuators

Bipolar power transistors suffer from a voltage drop of 0.6 V across each device. The power Mosfets used in this system for solenoid control

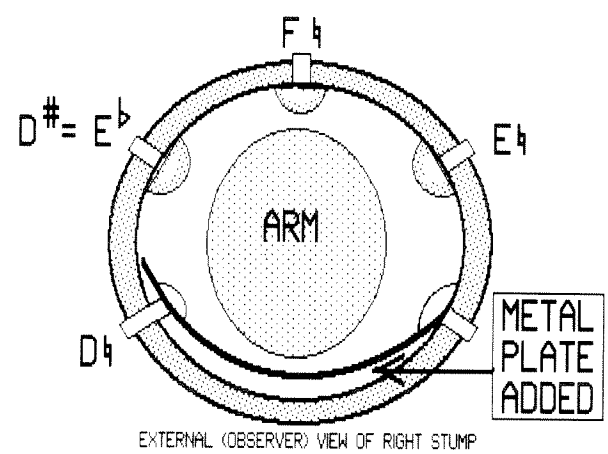

Figure 5.
Arrangement of touch contacts inside transparent solid plastic tubing for alto saxophone player, R.V.

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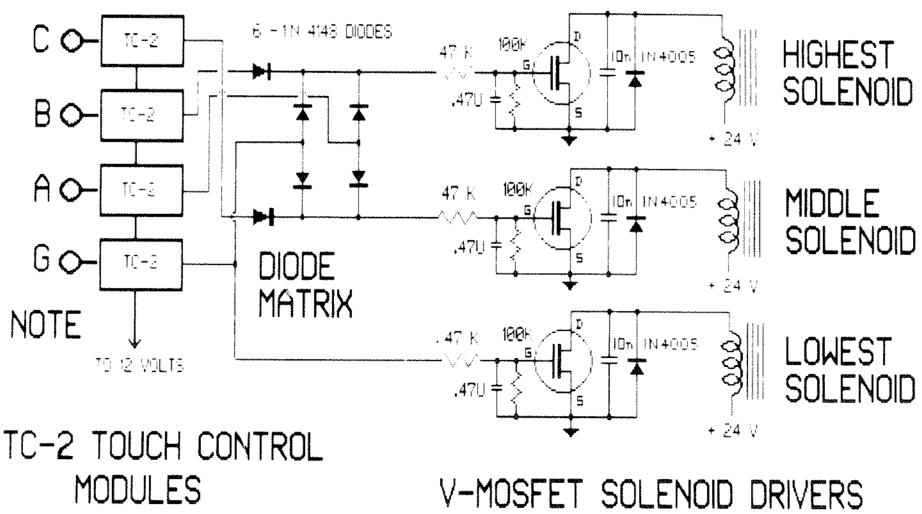

Figure 6.
Schematic diagram of diode logic array and V-Mosfet solenoid driver circuitry for H.D.M.

offer advantages of long playing time and portability. The V-Mosfet Power Transistors (Type VN89AF, Intersil Inc., Cupertino, CA) shown in **Figure 6** were chosen as solenoid drivers for all 3 subjects. The diodes across each V-Mosfet help to prevent damage due to high voltage inductive transients from the solenoids when the drive signal turns off. The integrator formed by the 47 KΩ resistor and 0.47 μF capacitor in the gate circuit of each V-Mosfet helps prevent transients and holds each solenoid on long enough to permit the musician to move his stump to the next touch point before the saxophone valves reopen.

RESULTS

Subject 1: H.D.M.

The first saxophone player rehabilitated (H.D.M.) had been amputated due to bone cancer. He had a normal range of motion above the elbow and could position the stump to contact any part of the interior circumference of the prosthetic shell. Several different diameters of shells were tried, and the size and shape was gradually modified using the transparent plastic material "Uvex" with the goal of making all 4 contact points equally easy to reach with the distal portion of his stump (**Figure 4**).

Subject 2: R.V.

This subject was a music student at the University of Western Ontario, London, Canada with a talent for the alto saxophone at the time he lost his right forearm in an industrial accident. The accident appeared to end his hopes of playing the music he had spent so much time and effort to learn. However, he learned to play the trumpet and went on to become an accomplished secondary school music teacher.

The transparent prosthetic shell was positioned relative to the subject's leg with a wide leather belt for stability (see **Figure 1**). This position places one of the forearm bones (the radius) at the top of the prosthetic shell and the other (the ulna) at the bottom. Proprioceptive feedback from the end of the stump helps him to maintain the proper position. The auditory output of the horn also serves as sensory feedback indicating proper arm positioning. His forearm has some rotational ability, which allows the skin overlying the radius to contact "E flat," "F natural," and "E natural" along the top of the prosthesis. The ulna can be moved quickly to reach the curved piece of metal which represents "D natural," independently of the other notes being played at the time.

R.V. is a creative and imaginative person, and made a number of improvements to the system after returning home. Certain portions of his stump were less sensitive to touch than others, so he modified portions of the touch contacts to facilitate playing the notes affected. He also removed the "F sharp" touch contact from the prosthetic shell, and placed it on the spatula of the saxophone itself, which operates the "G sharp" key of the saxophone. This modification reduced the number of contacts being operated by the stump from 5 to 4, and moved one of the contacts over to the sound hand. In this way, he obtained more speed and precision for playing serious (classical and orchestral) music.

R.V. always uses a small dab of Beckman electrode gel on the 2 bony protuberances, because his skin is not always moist enough to get a speedy reaction from the equipment. With these modifications, he has given a number of public performances, playing university-level music, including a sonata for saxophone and piano.

Subject 3: H.W.

The third saxophone player (H.W.) had lost his left hand (wrist disarticulation) in a paint mixing machine in 1953. He had a normal range of motion over all remaining joints. Thirty-two years had passed since he had played the saxophone with 2 hands and he was 70 years old at the time of fitting.

The first attempts used a prosthetic shell held in place with straps over the left shoulder, as was done successfully with the first subject. Little progress was made in 3 days with this arrangement because the subject could not find a stable reference point. An analogy can be made to a person first learning to write with a pencil. If the elbow is not flat on a desk while manipulating the pencil with the wrist and fingers, there is no solid reference point to make the movements reproducible.

Several modifications were tried. 1) We made the movements more visible by installing the touch contacts in the walls of short sections of transparent plastic tubing. The tubing was laid on a flat, easily-accessible table surface, with good visibility of the contacts. The learning process was graded by starting out with tubing of a large diameter and working down to smaller sizes.

2) This subject had a particularly hairy forearm, so a depilatory cream ("Neet") was applied to remove skin hair during the training period. Beckman electrode gel was applied to the skin to improve the reliability in the timing of the skin contact.

3) A table-mounted prosthetic cup was made, rather than a shell covering the whole arm. The improved visibility afforded by the open cup allowed the subject and all members of the team to see exactly where the arm was making contact.

4) The cup was mounted at the end of a support board that was padded with foam rubber, and covered with soft leatherette. A series of large-diameter, nickel-plated grounding contacts were distributed along the board in 2 rows, spaced just far enough so that the forearm would rest comfortably between and touch both rows. This eliminated the inconvenience of a separate ground wire connected to some other location on the body.

When a support for the contacts had been satisfactorily shaped, the subject's performance began to improve, but he had the most difficulty of the three in his attempts at relearning to play the saxophone. Just as guitar players develop callouses on their fingertips, the horn player's lip must be hardened somewhat against the pressure of the reed. The condition of this player's lip limited his practice time and thus limited the initial learning of the coordinated limb movements required. Conversely, the motivation for hardening the lip was not present unless reasonable musical notes were being produced.

Initially, he used gross movements and banged the stump against the side of the prosthetic shell to ensure solid contact. Only after receiving a proper-sized prosthetic cup for the touch electrodes did he begin to use finer movements, such as turning his stump, utilizing its asymmetry within the cup in a partial rotation to improve the accuracy and speed of contact. Despite the problems, within 10 days he could play many of the standard tunes he knew from playing in the big bands of the 1930's and 1940's. After returning home he has joined with some of his former colleagues to give informal concerts.

DISCUSSION

With only 3 musicians, a statistical analysis is not meaningful and we could not compare the results with the performance of each musician before he lost his arm. Furthermore, the 3 played different styles of music and one's musical preferences will influence any assessment of the level attained. Some of the evaluation must be left to subjective impressions supported by published statements made by each musician.

The first subject, H.D.M., seemed to have the highest motivation and attained a very high level of musicianship. The selections he mastered included, "Take the A Train" and Duke Ellington's "Satin Doll," which are generally considered in the upper echelon of jazz standards. He appeared on the television production "That's Incredible" (first broadcast on Oct. 18, 1982). The effects that the musical prosthesis had in boosting his morale are evident in statements he made when he was again fighting cancer.

"I couldn't care less if I had an arm or not," he laughed. "I don't worry any more about living or dying because all my life has a new meaning; now I know where I'm going. You know, this isn't for my own self-glory. I'd like to use it in a way that can be a hopeful sign. I'll play any place. I'm just out to help every amputee who wants to be rehabilitated." (*Edmonton Journal,* May 5, 1982)

"I never dreamt in a million years I would be playing again," he said. "It's the greatest miracle God ever put in my life. The greatest thing that ever happened to me." (*The News World,* Nov. 16, 1982)

Although cancer claimed his life in June 1985, he lived and played music, entertaining and inspiring others, for several years after his fitting.

Subject R.V. returned to teaching music, including the saxophone, after his fitting. He commented: "I just can't tell what the limits of it are, because I haven't gotten anywhere near them yet. The system is, for all intents and purposes, instantaneous. I'm going back and playing the pieces that I worked on at university but never performed. It's hard to imagine that the system is really as good as 10 fingers. Right now I can see myself playing anything but the most difficult pieces." (*Haliburton County Echo,* November, 1983)

Subject H.W. made the following comments when asked what he would advise other amputee musicians in a videotaped interview on Sept. 17, 1985: "It is possible; I would most heartily recommend that it is possible, and practical—beyond a doubt."

Interested health care professionals may contact the authors to arrange for receipt of a videotape of all 3 musicians performing. The sound and picture together convey what is difficult to express on the printed page.

In conclusion, 3 handicapped professional musicians have been successfully rehabilitated to play the saxophone. The quality of rehabilitation achieved is sufficient for professional musicianship in teaching and performing. We have attempted to include enough details here so that others will be able to duplicate our work and extend the benefits of touch control to more people with upper limb amputations. A control system capable of the level of speed and accuracy needed for rehabilitating a musician should provide excellent prospects for other occupations that require specialized motor patterns. Future developments should make the possibilities even more dramatic and the applicability more widespread.

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