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Wireless Control of Functional Electrical Stimulation Systems

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Abstract: With the assistance of crutches and functional electrical stimulation (FES), we are able to restore standing and simple gait in some spinal cord injured (SCI) patients. In present rehabilitative systems, the patient divides the gait cycle into stance and swing phases via pushbuttons mounted on the handles of the crutches, which are hardwired to the functional electrical stimulator. The surface-mount technology based telemetry system, which makes use of the radiofrequency medium at 40 MHz, was developed to provide wireless control of the FES system. Signals from crutch pushbuttons were coded and transferred from the transmitter to the receiver. The receiver was firmly attached to the patient's waist and was connected to the stimulator. **Key Words:** Functional electrical stimulation—Spinal cord injury—Gait—Wireless control—Radio telemetry.

Considerable efforts have been directed to investigations of functional electrical stimulation (FES) assisted gait of complete and incomplete spinal cord injured (SCI) subjects (1). The Ljubljana FES assisted gait patterns are based on control events triggered voluntarily by the paralyzed person. In the simple 4-channel pattern, the gait cycle is divided into a stance phase and swing phase by pushbuttons built into the handles of the crutches. These pushbuttons are hardwired to the stimulator in present systems. Interconnecting wires between the switches and the stimulator are inconvenient in daily activities and represent a frequent source of malfunctions. Further, they represent an obstacle during walking, and they hinder the patient when standing up or sitting down. Finally, these wires are not aesthetic, and this is an important factor for a patient's acceptance of a rehabilitative device.

In the future, we expect the development of more complex gait patterns that will include other muscle groups in addition to those used in the minimal reciprocal gait pattern. Additional control events will be introduced during the gait cycle. The contact force of the crutch may be valuable information to include in FES control synthesis. However, transferring the force signals from the crutch to the stimulator would require additional wires. Such a solution is not acceptable for the same reasons that interconnecting wires between the switches and stimulator are not acceptable. Therefore, a reliable telemetry system for transferring the control signals from the crutches to the stimulator is of great importance for an SCI subject.

There have been only a few attempts in the past that were directed towards development of a telemetry system for the purpose of FES control. Jennings (2) developed a system that uses infrared transmission of pushbutton signals on the crutch handles and provides on/off switching of electrostimulation. The system was specially designed for controlling an FES system that was used in conjunction with mechanical orthosis. The receiver was attached to the side of the mechanical orthosis while the transmitter was clipped onto the shank of the crutch. A reliable communication link was achieved due to the rather unchanging positions of the transmitter and receiver.

Graupe (3) patented a stimulation system that employs an ultrasound wireless link. The telemetry link provides transmission of the switch signals to the stimulator. Switches and the transmitter are mounted on the walker, which is used to provide support to the patient during walking. The receiver is

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integrated in the stimulator, which is attached to the patient's waist.

Visibility between the transmitter and receiver is required for error-free communication in both telemetry systems, due to the narrow emitting and receiving angles of infrared diodes and ultrasound sensors. When the visibility is not assured, the infrared and ultrasound communication is not possible. As a consequence, the receiver cannot be hidden under the patient's clothing, and the transmitter cannot be built into the crutch, which is another inconvenience. Therefore, the radiofrequency medium was selected for our telemetry system.

METHODS

The following requirements and limitations were imposed at the beginning of the telemetry system development. First, the time delay between pressing the pushbutton and the stimulator response should not exceed 100 ms. Second, the transmitting system should not consume power while inactive. Third, the telemetry system should be designed in such a way that several patients are able to use it in the same room at the same time. Fourth, the transmitter should be installed in a crutch, together with the rechargeable power supply, so that the dimensions of the transmitter should be as small as possible. Fifth, the energy consumption of the telemetry system should be minimal, and sixth, the system should provide reliable communication in case of radiofrequency disturbances.

Some of the requirements are contradictory. The use of the rehabilitative system by several patients in the same room at the same time requires frequency separation among the communication channels. In such cases, it is difficult to meet the need for minimal dimensions. One possibility to achieve the first multiple user requirement is to introduce the phase locked loop (PLL) principle. However, PLL requires a precise frequency oscillator for reference frequency, a voltage-controlled oscillator (VCO), a presetable frequency prescaler (to enable generation of different frequency channels), a phase comparator, and finally, a low pass filter, all for generation of a suitable carrier frequency. By the application of the PLL principle with electronic components that are available on the market, we can design, for example, a frequency synthesizer from 143.82 MHz to 148.92 MHz with channel separation of 20 kHz. This enables 256 different communication channels. This solution would enable the system to be used by several patients at the same time, but it would disregard the requirements for small dimensions and low energy consumption. The power consumption of the system would be 40 mA at 5 V, which is rather high. The system would consist of a large number of components, which would increase its volume. Therefore, this solution is not acceptable. Another possibility to achieve several communication channels is to use a crystal oscillator in a frequency range for which a wide variety of crystals are accessible on the market. In this way we could separate channels simply by replacing the crystal resonator in both the transmitter and the receiver. Manufacturers offer more than 60 frequency channels in the 27, 40, and 49 MHz bands.

Other important considerations in radiofrequency transmission are the transmitting and receiving antennas. Because the patient uses a crutch, it is natural to use the crutch as a transmitting antenna. Another important issue is the type of modulation used. In today's commercially available telemetry systems, there are only 2 modulation techniques. Frequency modulation (FM) offers better quality of transmission than amplitude modulation (AM) while the latter results in a substantial reduction of complexity of modulating and demodulating circuits. In cases for which only the state of the signal is relevant (low or high, i.e., digital signal), AM is an adequate choice because the quality of transmission is not of prime importance.

We developed a telemetry system employing the amplitude shift keying (ASK) modulating principle and operating in the 27 MHz band. Our intention was to use different crystals in order to obtain different communication channels, which would fulfill the requirements for multiple users and small dimensions. The system was built around 2 integrated circuits dedicated to control of plane models. The crutch was cut in half, thus providing a dipole antenna for transmission. The receiver antenna was a 15 cm long wire. The receiver used the single superheterodyne principle. The transmitter was placed into the crutch, together with the power supply, and the receiver was placed into a separate plastic case, which was tied to the patient's waist.

For comparison, we also tested a commercial telemetric system operating at 433.92 MHz and also using the ASK modulating principle. The output power of both telemeric systems was 10 mW. The bandwidth of our receiver could be set either to 10 kHz or 100 kHz, while the commercial system had a 400 kHz bandwidth.

RESULTS

The evaluation previously described (4) revealed that the narrow band 27 MHz system behaved reli-

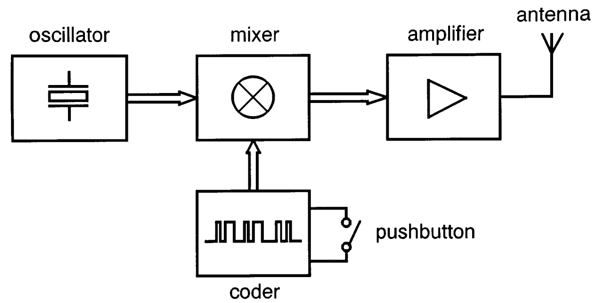

FIG. 1. The components of the transmitter are shown in this block diagram.

ably in all environments evaluated (in a room with no radiofrequency [RF] disturbances, in the presence of a microwave therapy device, and in the presence of a running car engine) while that was not the case with the wider bandwidth configuration. The commercial system operated reliably only in environments with no RF disturbances. The range of the commercial system was at least 100 m due to its optimal antenna size, which was realizable within its wavelength. The evaluation also revealed that our system operated reliably only when the patient held the crutch and wore the receiver firmly attached to his waist and showed a very limited range of operation.

This gave us the idea to use the patient's body as part of the transmitting antenna, which would be closely coupled with the receiving antenna. In this way, we could obtain a reliable transmission of control signals from the crutch pushbuttons. On the other hand, lower sensitivity of the receiver (due to using a very small antenna dimension in comparison to the wavelength) was highly desirable in our application. In this case, we would not need channel separation since the operating range of the system was only the width of the patient's body.

According to the findings of the evaluation, we developed the final version of the telemetric system. We retained the principle of the previous system and used surface mount technology (SMT) parts in order to reduce the size of the system. Since the 40 MHz frequency band is reserved for general telemetry, it was used instead of the 27 MHz band. Figure 1 shows the block diagram of the transmitter. When the crutch pushbutton is pressed, the power is supplied to the transmitter circuit. The carrier frequency of 40.655 MHz is generated by a crystal-controlled Colpits oscillator. A coded word representing the state of the pushbutton is generated by a commercial integrated circuit. Afterward, both signals are multiplied in the modulator. The modulated signal is amplified and fed to the antenna. The hot part of the

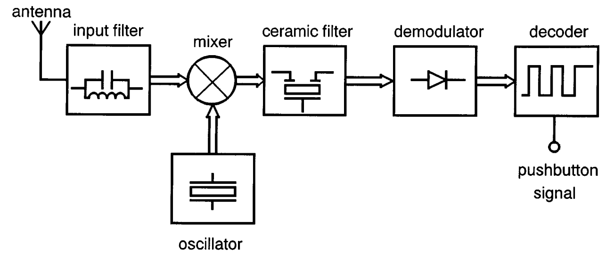

FIG. 2. The components of the receiver are shown in this block diagram.

antenna is represented by the patient pressing the pushbutton, the metal part of which is connected to the transmitter. The cold part of the antenna is represented by the crutch. A printed circuit board of the transmitter is placed into the handle of the crutch. Figure 2 shows the block diagram of the receiver. The receiving antenna is a 4 cm long and 1 cm wide metal clip, which is also used for attaching the receiver to the patient's waist, thus providing close coupling between the transmitting antenna (the patient) and the receiving antenna. The input filter matches the impedance of the antenna to the input impedance of the mixer. The double balanced mixer multiples the input signal with the signal generated by the local crystal controlled oscillator. The frequency difference of the 2 signals is 455 kHz, which is the resonant frequency of the ceramic filter. The bandwidth of the receiver is determined by the 10 kHz ceramic filter passband. The filtered signal is demodulated, and after decoding, the signal triggers an adequate FES sequence. The time delay between issuing the command and the appropriate gait event is 80 ms. Technical properties of the telemetry system are presented in Table 1. Figure 3 shows an

FIG. 3. This photograph shows an incomplete tetraplegic patient walking with the assistance of a 2-channel stimulator and the telemetry system. The receiver module and the stimulator are tied to the patient's waist.

TABLE 1. *Technical properties of the telemetric system*

Transmitter		Receiver	
Output power	5 mW	Inter. freq.	455 kHz
Max. mod. freq.	2 kHz	Bandwidth	10 kHz
Voltage supply	6 V	Voltage supply	4.8 V
Current draw	5 mA	Current draw	5 mA

Max. mod. freq., maximum modulated frequency; inter. freq., intermediate frequency.

incomplete tetraplegic patient walking with the assistance of a 2 channel stimulator and the telemetry system.

DISCUSSION

We developed a small-size interference-resistant telemetry system for wireless control of FES assisted walking. The system fulfilled the imposed requirements and was extremely well accepted by both complete as well as incomplete SCI subjects. The position and orientation of the transmitter and the receiver did not affect the transmission reliability as long as the receiver was firmly attached to the patient. It should be stressed that the telemetric system was of special importance to the SCI subjects who used the FES orthotic device for time periods of several hours daily. Since the patients were free of hindering wires, many activities of daily living could be accomplished: standing up and sitting down, entering and exiting a vehicle, opening and closing the doors, and using a toilet. Another important feature is the improved appearance; the stimulator and the receiver can be hidden under the clothing of a patient.

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