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Closed-Loop Control Using a Stretch Sensor for Restoration of Standing with Functional Electrical Stimulation in Complete Paraplegia

Yoichi Shimada, Kozo Sato, Toshiki Matsunaga, Yoshihiro Tsutsumi, Akiko Misawa, Shigeru Ando, Takashi Minato, Mineyoshi Sato, Satoaki Chida and Kazutoshi Hatakeyama

Department of Orthopedic Surgery and Rehabilitation Division, Akita University School of Medicine, Akita 010-8543

Shimada, Y., Sato, K., Matsunaga, T., Tsutsumi, Y., Ando, S., Minato, T., Sato, M., Chida, S. and Hatakeyama, K. *Closed-Loop Control Using a Stretch Sensor for Restoration of Standing with Functional Electrical Stimulation in Complete Paraplegia.* Tohoku J. Exp. Med., 2001, **193** (3), 221-227 —— A closed-loop control system for standing with functional electrical stimulation (FES) using percutaneous intramuscular electrodes in complete paraplegia is described. The system consisted of ultrafine percutaneous intramuscular electrodes, a 32-channel stimulator and a stretch sensor with active current control to detect knee buckling. The closed-loop control system was applied in a T8 completely paraplegic patient. Compared to the stretch sensor with a wide use flexible goniometer for direct current control during standing, the stretch sensor was superior to the flexible goniometer in both ease of use and response. The average time delay from the start of knee buckling until the sensor turned on was 0.56±0.19 seconds (Mean±S.D.) in the goniometer and 0.21±0.06 seconds in the stretch sensor. The average time delay from the start of knee buckling until the recovery from knee buckling was 1.01±0.05 seconds in the goniometer and 0.78±0.06 seconds in the stretch sensor. The continuous standing ability of the patient increased from 12 minutes with open-loop stimulation to 30 minutes with the closed-loop control. No complications such as falling occurred during clinical use. This system prevented falling due to knee buckling during standing and prolonged upright activities in complete paraplegics.———— closed-loop control; functional electrical stimulation (FES); stretch sensor; complete paraplegia; standing

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Address for reprints: Yoichi Shimada, M.D., Rehabilitation Division, Akita University School of Medicine, 1 1-1 Hondo, Akita 010-8543, Japan.

e-mail: yshimada@med.akita-u.ac.jp

Fig 1. Knee buckling during standing in a complete paraplegic patient.

Recent advances in computer technology have made it possible to control paralyzed muscles by electrical stimulation. We have used functional electrical stimulation (FES) with percutaneous intramuscular electrodes to restore paralyzed muscles in the lower extremities since 1990 (Shimada et al. 1996). However, muscle fatigue causes knee buckling during standing (Fig. 1). The "C"-posture which means the floor reaction vector is in front of the knee joint, with hip hyperextension allow the patient to stand stably using FES. When the floor reaction vector shifts behind the knee joint, knee buckling occurs. The amount of muscle fatigue can be reduced using closed-loop control by shortening the stimulation time during standing. Although some investigators have developed closed-loop control systems using surface electrodes and several sensors to control standing in paraplegics (Petrofsky et al. 1984; Petrofsky and Philips 1986), no system is available using percutaneous intramuscular electrodes. We developed a closed-loop control system which consisted of ultrafine percutaneous intramuscular electrodes, a multichannel stimulator and a stretch sensor with active current control to detect knee buckling during standing. Here, we described the system and the clinical results in a complete paraplegic patient.

MATERIALS AND METHODS

The closed-loop control system was applied in a T8 completely paraplegic patient to restore the function of standing. The patient involved spinal cord injury and was a 28-year-old male. The time since injury was 1.3 years and the follow-up time of FES was 3.1 years. The number of percutaneous intramuscular electrodes was 34. The muscles or nerves that received therapeutic electrical stimulation (TES) and FES were as follows: the iliopsoas muscle for flexion of the hip, the gluteus maximus muscle for extension of the hip, the gluteus medius muscle and the superior gluteal nerve for abduction of the hip, the femoral nerve and quadriceps muscle including the vastus medialis, vastus lateralis and rectus femoris for extension of the knee, the hamstrings for flexion of the knee, the common peroneal nerve for dorsiflexion of the ankle, the gastrocnemius muscle for plantar flexion of the ankle, the peroneous longus muscle for eversion of the ankle and the spinal erector muscles for extension of the trunk. The patient underwent a 6-month muscle strengthening program and had no joint contractures during the time when this investigation was performed. He was previously able to perform standing-up, standing and sitting-down using only FES. He was also able to walk using both FES and ankle-foot orthosis (hybrid-FES).

System

The indwelling electrodes were made from 19 strands of helically wound Teflon-coated stainless steel (SES115, Nippon Seisen Co. Ltd., Tokyo) (Handa et al. 1989a, b; Hoshimiya and

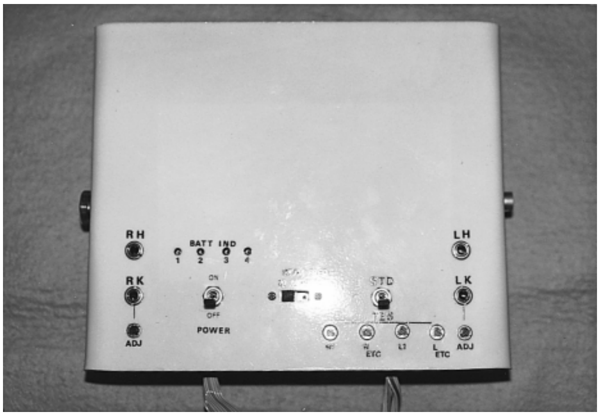

Fig. 2. Akita stimulator II.
The stimulator had 32 channels and enabled to connect with closed-loop control using percutaneous intramuscular electrodes.

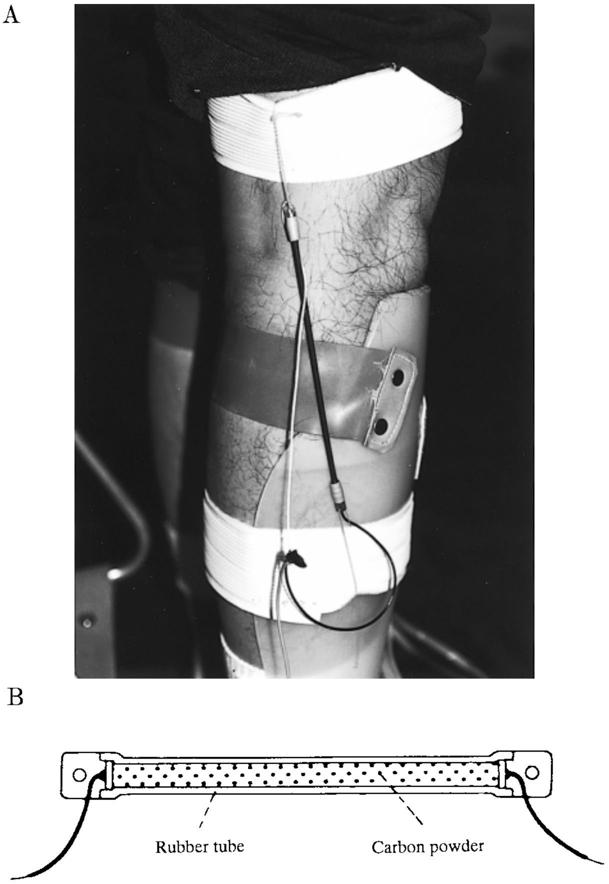

Fig. 3. A, B Akita stretch sensor I.
This stretch sensor, which was made from carbon powder, had an advantage in that threshold does not need to be determined each time.

Handa 1989). Electrodes were percutaneously implanted into the motor point of the muscles. The stimulation data creating system (SDC) (Nippon Electric Co., Ltd., Tokyo) was used to compose and store the stimulation parameters that set the threshold voltages for each muscle and control pulse shape and individual pulse sequence (Handa et al. 1989a, b; Hoshimiya and Handa 1989). Akita stimulator II which had 32 channels was developed for the closed-loop control using percutaneous intramuscular electrodes (Fig. 2). Rectangular pulse trains consisted of a pulse width of 200 microseconds, a pulse interval of 50 milliseconds and a pulse amplitude from 0 to -15V. A new stretch sensor, Akita stretch sensor I, which was made from carbon powder was developed to detect knee buckling during standing with FES (Fig. 3A and 3B). The stretch sensor measured the changes in impedence of the carbon powder and detected changes in the length of the wire that were less than the threshold defined as the length of the wire during "C" posture standing. The stretch sensor had an advantage in that the threshold did not need to be determined each time due to active current control. The threshold was automatically determined when the stretch strength became fixed each time (Fig. 4). In the control study, a wide use flexible goniometer (XM180, P&G, Oxford, UK) was used and measured changes in the knee angle that were beyond the threshold set during "C" posture standing. Since the flexible goniometer was regulated by direct current control, that needed to be set, the appropriate threshold was determined each time. The anterior floor-reaction type ankle-foot orthosis (FRO) developed by Andrews et al. (1988; 1989) was employed for mediolateral support of the ankle and the sensors were attached (hybrid FES).

Clinical measurements

Measurements of the response in sensors. Since the command algorithm includes some

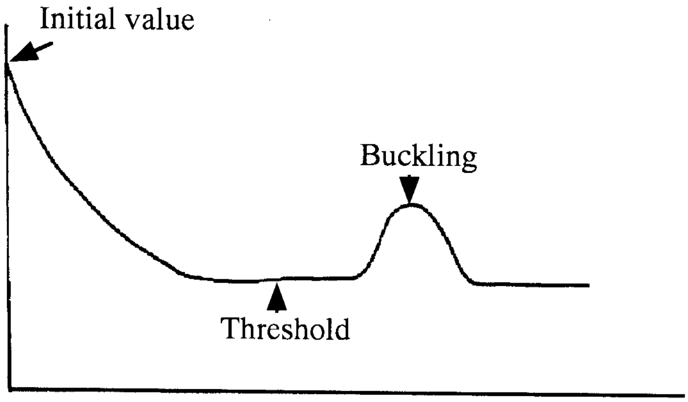

Fig. 4. Active current control in Akita stretch sensor I.
The threshold was automatically determined when stretch strength became fixed each time.

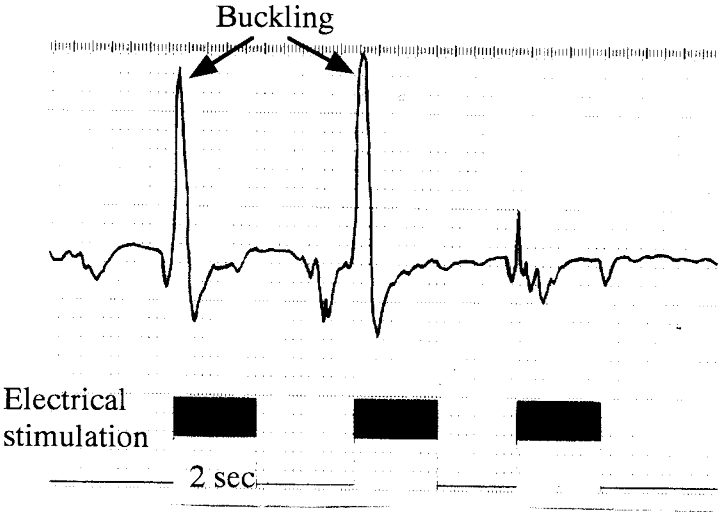

Fig. 5. Closed-loop stimulation for recovery from knee buckling.
When knee buckling was detected by the stretch sensor, hip and knee extensor muscles were stimulated for 2 seconds to recover from knee buckling.

time delays such as the time required after buckling for detection by the sensor, the time required after detecting the buckling for extensor muscles to be stimulated, and the time required after the initiation of the electrical stimulus for the force to develop the steady state force, we compared the sensors with the response to the time delay under 20 Hz stimulation. The patients was requested to remain standing with the hybrid FES system. Then, electrical stimulation was stopped to induce knee buckling artificially or he was requested to voluntarily buckle the knee. When knee buckling was detected by the knee sensor, hip and knee extensor muscles were stimulated for 2 seconds to recover from knee buckling (Fig. 5). We measured the accuracy of the response to knee buckling in each sensor and time delay from the start of knee buckling until recovery from knee buckling in the flexible goniometer and the stretch sensor. We detected the start of knee buckling when the impedence of the stretch sensor changed, which represented the time when physiological knee locking during standing was off. A block diagram to analyze knee buckling is shown in Fig. 6. Time delays

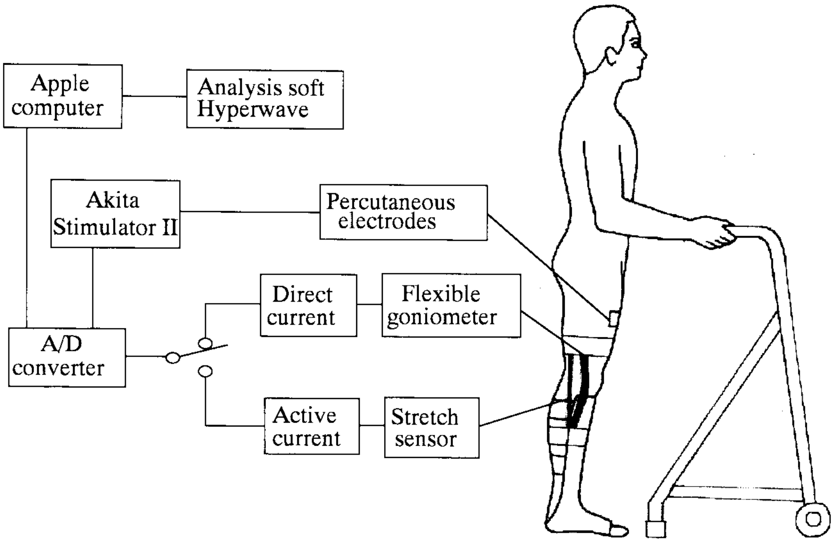

Fig. 6. Block diagram to analyze knee buckling.

were measured 30 times in each sensor.

Data were reported as means ± standard deviations (s.d.). Two-factor factorial ANOVA was used for statistical analysis. Results were considered significant if $p<0.05$.

Measurements of standing ability. The continuous standing ability of the patient was compared with the closed-loop control and the open-loop that stimulated the muscles and nerves continuously.

RESULTS

Measurements of the response in sensors

The average time delay from the start of knee buckling until the sensor turned on was 0.56±0.19 seconds (Mean±s.d.) in the flexible goniometer and 0.21±0.06 seconds in the stretch sensor ($p<0.001$) (Fig. 7). The average time delay from the start of knee buckling until recovery from knee buckling was 1.01±0.05 seconds in the flexible goniometer and 0.78±0.06 seconds in the stretch sensor ($p<0.001$) (Fig. 8). The appropriate threshold of the knee angle for the flexible goniometer to control standing efficiently was 12 degrees. The stretch sensor was superior to the flexible goniometer in both ease of use and response.

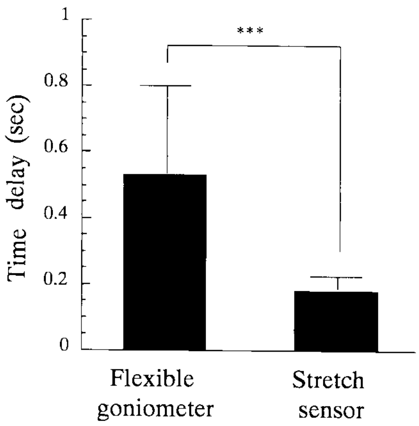

Fig. 7. The average time delay from the start of knee buckling until sensor on. ***$p<0.001$. Mean and s.d.

Measurements of standing ability

The continuous standing ability of the patient increased from 12 minutes with the open-loop stimulation to 30 minutes with the closed-loop control. No complications such as falling occurred during clinical use.

DISCUSSION

There are psychological, functional and physiological advantages for the paraplegic patients in being able to stand. The ability to

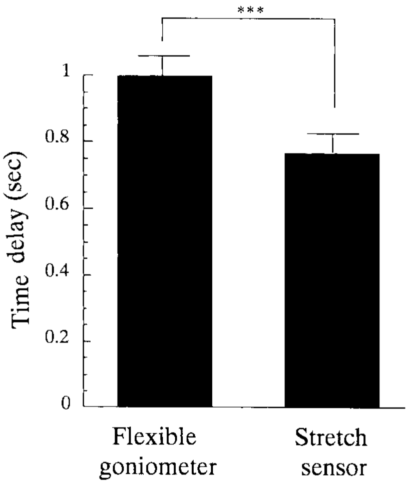

Fig. 8. The average time delay from the start of knee buckling until the recovery from knee buckling.
$***p < 0.001$. Mean and S.D.

stand provides a more positive body image by improving physical function and expanding options related to the environment and other people. Many activities of daily living are possible if standing is achieved in paraplegic patients. The physiologic advantages that result from standing include the positive effect on digestive function and bowel and bladder function, decreased frequency of ischial decubiti due to direct pressure relief, cardiovascular conditioning and increased bone density (Marsolais et al. 1991).

One principle difference among the various approaches to standing with FES in complete paraplegia is the use of surface versus internal electrodes for stimulation. Since our percutaneous intramuscular electrodes are easy to remove when problems arise, are available for long-term use (Shimada et al. 1996a), can regulate many muscles including deep muscles, and are easy to connect with the closed-loop control system, we employed this percutaneous intramuscular electrode.

The presently available clinical FES standing systems involve continued activation of the lower limb extensors resulting in rapid muscle fatigue. The amount of muscle fatigue can be reduced using the closed-loop control. Some investigators have already developed a closed-loop control system using surface electrodes in lower extremities (Petrofsky et al. 1984, 1986; Phillips 1989; Andrews et al. 1989). Petrofsky et al. (1984, 1986) used the closed-loop control system on the knee in combination with Reciprocating gait orthosis (RGO) and FES. Their preliminary data showed reduction of weight borne on the arm and a doubling of energy efficiency compared to that using RGO alone. The complexity and functional limitations of this hybrid system made it appropriate only as a clinical treatment system rather than as a functional system. Andrews et al. (1988, 1989) indicated that it was possible for the paraplegic patient to remain standing without muscle activity in the lower limb as long as the floor reaction vector was in front of the knee joint, with hip hyperextension. This "C"-posture allowed the patient to stand stably using a hybrid FES. When the floor reaction vector shifts behind the knee joint, knee buckling occurs. In cases of buckling, the knee sensor detects it and the knee extensor muscle is stimulated. This closed-loop control reduces muscle fatigue and prevents falling due to knee buckling. To reduce knee motion during buckling, it is necessary to shorten the time delay by detecting knee buckling as soon as possible and stimulating the muscle immediately to induce rapid muscle contraction. The pressure sensor, flexible goniometer (Andrews et al. 1988) and potentiometer (Petrofsky et al. 1984; Phillips 1989) have been used to detect knee buckling. In our department, a pressure sensor was initially used to detect knee buckling, but the accuracy of its response was not reliable. The flexible goniometer must be reset to the threshold of the knee angle each time due to direct current control and determination of the appropriate threshold is difficult. The potentiometer is not available for daily use due to its complexity. Compared with these sensors, our stretch sensor may be useful for closed-loop control of knee buckling during standing considering both ease of use due to active current control and response time. In addition, it was cheap and durable. Andrews et al. (1988, 1989) used surface electrodes in his hybrid FES system combined with closed-loop control using several sensors, but a hip/trunk brace was necessary for stability. Our system has the advantages of sufficient stability of the trunk and hip joint using electrical stimulation with percutaneous intramuscular electrodes and the same capability of closed-loop control using sensors as in Andrews' system (Andrews et al. 1988: 1989). This improves the appearance, and allows easier donning, easier standing-up and sitting-down, and easier toilet transfer than RGO and Hip knee ankle foot orthosis (HKAFO) combined FES systems. However, endurance of the sensor and three-dimensional analysis and control by the sensor should be further examined.

CONCLUSION

The closed-loop control system using a new stretch sensor prevented falling due to knee buckling during standing and prolonged upright activities in complete paraplegia.

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