Artificial Organs
24(3):185–188, Blackwell Science, Inc.

Artificial Grasping System for the Paralyzed Hand

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Abstract: Neuromuscular electrical stimulation has been used in upper limb rehabilitation towards restoring motor hand function. In this work, an 8 channel microcomputer controlled stimulator with monophasic square voltage output was used. Muscle activation sequences were defined to perform palmar and lateral prehension and power grip (index finger extension type). The sequences used allowed subjects to demonstrate their ability to hold and release objects that are encountered in daily living, permitting activities such as drinking, eating, writing, and typing. **Key Words:** Neuromuscular electrical stimulation—Quadriplegic artificial hand—Grasping.

Upper limb functions are grasping and manipulating objects. Our agility and dexterity are reflections of the capabilities of the motor system to plan, coordinate, and execute movements. Even a relatively simple task such as grasping a glass of water requires contraction of many muscles that should act together to achieve that goal (1,2). In patients with spinal cord injuries at cervical levels, communication between supraspinal centers and muscles below the level of the lesion is often completely absent. This means that the motor systems do not have available to them proprioceptive information, and command inputs from the brain do not reach the muscles, resulting in severe paralysis of the upper extremities and definitely loss of independence.

Neuromuscular electrical stimulation (NMES) systems have been used as an important rehabilitation tool, allowing patients to incorporate the affected limbs into their corporal schemes because electrical stimulation has the potential for exciting every muscle with intact peripheral enervation (3–10).

This article discusses NMES in upper limb rehabilitation. Sequences of muscle activation were defined in order to achieve functional grasp to perform daily living activities such as drinking, eating, writing, and typing.

MATERIALS AND METHODS

Two quadriplegic subjects (C5-C6 levels) and 1 hemiplegic were part of the program. These subjects retain voluntary shoulder and elbow control but no voluntary motor hand function can be achieved. Thus, they can position their hands in space to reach the objects but are not able to grasp and release them. None of them had surgical procedures such as tendon transfer, joint arthrodesis, or tenodesis.

Upper limb movement control requires stimulation of smaller muscles that are close to each other. Towards achieving more selectivity, implanted electrodes have been extensively used by many groups (5–10). Because this program is one of the first experiences in upper limb stimulation in Brazil, and to avoid infections and other complications, adhesive surface electrodes (Axelgaard and Dynatronics) were preferred. Small round (2 cm diameter) and square (16 cm^2) electrodes were used to achieve a reasonable selectivity. The active electrodes were placed over the motor sites of the selected muscles. Indifferent electrodes were larger (28 cm^2) and placed distally near the wrist.

Muscle selection was based on anatomical, kinesiological, and electromyographical studies of normal subjects and electrical stimulation viability with surface electrodes, resulting in the selection of 6 muscles. The synergic and principal motor muscles

Received August 1999.
Presented in part at the 1st Latin American Congress for Artificial Organs and Biomaterials—COLAOB-98, held in Belo Horizonte, Brazil, December 10–13, 1998.
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for the desired movement were chosen. The selected muscles were: Extensor Carpi Radialis (ECR), Extensor Digitorum Communis (EDC), Flexor Digitorum Superficialis (FDS), Lumbricalis (L), Abductor Pollicis Brevis (AbPB), and Opponens Pollicis (OpP).

An 8 channel microcomputer-controlled stimulator with a monophasic square voltage output was used, thus allowing the implementation of several strategies for grasping. Maximum pulse width was fixed at 300 μs and frequency at 20 Hz whereas the amplitude was individually adjusted to achieve the excitability threshold for each muscle. Some pulse width modulation was performed during transition phases allowing cocontraction of agonist and antagonist.

Temporal and spatial sequences are required to coordinate the movements of the upper limbs. Muscle activation sequences were defined to perform palmar and lateral prehension. Each sequence allows the definition of some subphases within each grasp pattern, such as opening, positioning, grasping, and object manipulation and releasing. Another grasp pattern defined as power grip (index finger extension type) by Kamakura et.al. (11) was also used. (Table 1).

The ECR was used in all subphases to guarantee a functional position of the hand, allowing a stronger prehension. The EDC and the AbPB were used to achieve an adequate opening size of the hand. During the positioning subphase, the L was stimulated to guarantee the metacarpal joint flexion, allowing the fingers to surround the object. Grasping was achieved by stimulating the FDS and OpP, providing sufficient closure force on the object. The same muscle activation to open the hand was used to release the object. (Table 2).

The opening and releasing subphases in lateral grasp were equal to those of the palmar grasp. The FDS was stimulated flexing the metacarpophalangeal and proximal interphalangeal joints, allowing the object to be positioned on the lateral surface of the index finger. Finally, the OpP was activated until contact with the object applying the adequate force to grasp it.

Power grip (index finger extension type) was used as nonprehensive movement and did not require the subphases defined earlier. The L was stimulated to guarantee the metacarpal joint flexion and the interphalangeal joint extension. The FDS was used to flex the interphalangeal joints. Electrode position prevents the index finger from the FDS's action. In this case, both limbs were stimulated.

TABLE 1. *Stimulation sequence for the palmar grasp*

Subphases	Muscles	Duration(s)
Opening	ECR, EDC, AbPB	2
Positioning	ECR, AbPB, L	1
Grasp and manipulation	ECR, AbPB, L, FDS, OpP	7
Releasing	ECR, EDC, AbPB	2

TABLE 2. *Stimulation sequence for the lateral grasp*

Subphases	Muscles	Duration(s)
Opening	ECR, EDC, AbPB	2
Positioning	ECR, AbPB, FDS	3
Grasp and manipulation	ECR, AbPB, FDS, OpP	7
Releasing	ECR, EDC, AbPB	2

RESULTS

The subjects were able to achieve good grasp performance in all grasp patterns studied in this program. Despite using an open-loop system with fixed stimulation parameters and surface electrodes, it was possible to obtain the desired movements.

The sequences used in this study allowed subjects to demonstrate their ability to hold and release objects that are encountered in daily living. The palmar grasp is usually used to hold small objects with fingertips but larger objects can be held with the same muscle activation sequence using the palm of the hand. A glass and a knife could be held by means of the palmar grasp (Fig. 1) whereas holding a fork or a pen used lateral prehension (Fig. 2). In this case, the object was positioned between the lateral surface of the index finger and the palmar surface of thumb. The defined subphases associated with pulse width modulation during phase transition allow a smooth grasping movement. The pattern achieved by means of power grip (index finger extension type) was suitable to typing activity (Fig. 3). This means that the subjects could perform some professional activity using a computer.

The manipulation of the grasped objects could be achieved by voluntary control of the shoulder and elbow because all of the subjects retained these movements. None of them had to use mechanical

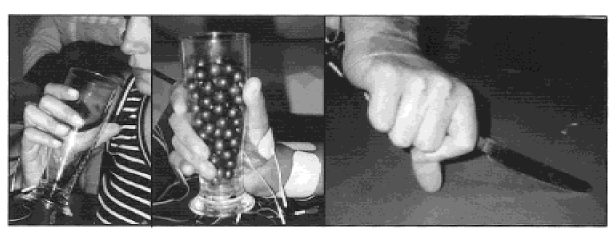

FIG. 1. The photographs demonstrate drinking and holding a knife using a palmar grasp pattern.

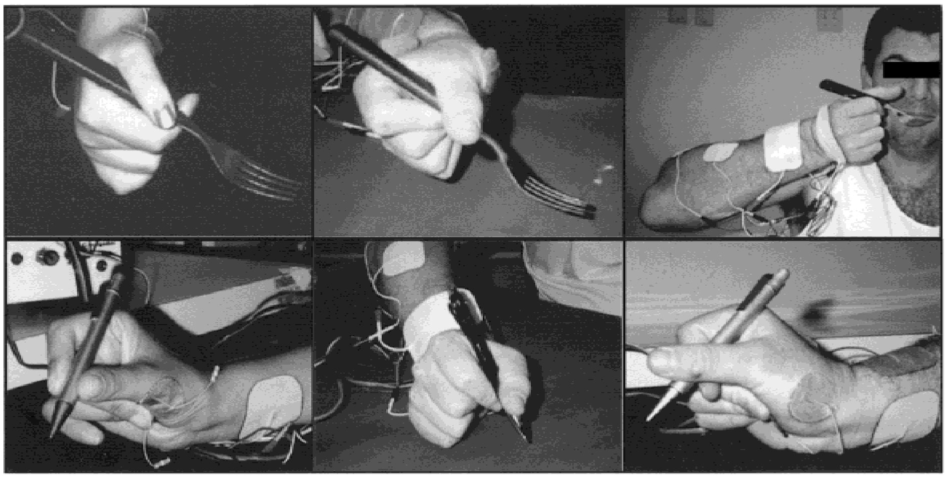

FIG. 2. The photographs demonstrate eating and writing using a lateral grasp pattern.

orthosis to help movement performance. The objects remained stable and fixed during manipulation and against perturbation forces. Fine movements of the hand could also be performed by voluntary movements of the shoulder and elbow, allowing subjects to write (Fig. 4). Training can improve pen control and writing speed.

DISCUSSION

Although we used fixed parameters of the stimulation and surface electrodes, it was possible to obtain the desired movements. Implanted electrodes are more selective and adequate for daily living use. For laboratorial studies and control systems design, however, surface electrodes are simpler to use. In addition, they do not have the problems that can occur with implanted electrodes such as failures, breakages, and infection. On the other hand, many muscles were not available to be stimulated with surface electrodes. However, this work has shown that it is possible to achieve functional movement by activating a few muscles with surface electrodes. Furthermore, Grill and Mortimer (12) mentioned that selectivity also could be obtained by improving stimulation parameters such as pulse width and signal frequency. The main problem that still persists is movement of the surface electrode that does not follow the muscle during limb movement, affecting the repeatability of the grasp pattern.

The sequences presented allowed subjects to demonstrate their ability to hold and release objects that are encountered in daily living, permitting activities such as eating, drinking, writing and typing. Subjects expressed their satisfaction, in particular, with their ability to write and to type.

Subphases defined in the studied sequences as opening, positioning, and closing associated with pulse width modulation during phase transition allowed a smooth grasping movement due to agonist and antagonist cocontraction. Furthermore, the time of each subphase and other stimulation parameters were predefined at the beginning of each section. For functional use, it would be better if the subject could command the movement, varying the parameters (time and pulse amplitude) to achieve the necessary and sufficient grasp force for object manipulation. Usually the command signal is provided by means of the shoulder position (13–16), but voice can also be used as a command signal (17).

CONCLUSIONS

This work has shown that it is possible to obtain a functional grasp despite an open-loop fixed stimulation parameter system and surface electrodes. For practical daily use, however, implanted electrodes

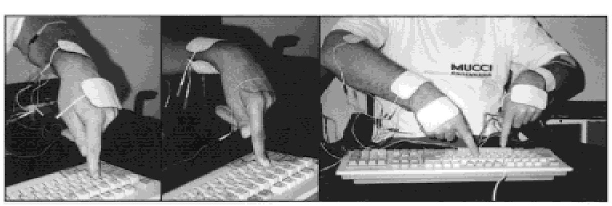

FIG. 3. The photographs demonstrate typing using a power grip (index finger extension type).

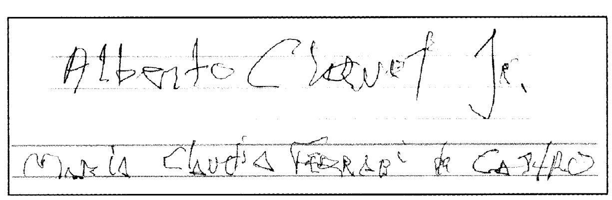

FIG. 4. A writing example is shown.

and a closed-loop system with force modulation control should be chosen. Future research on electrode material and movement control strategies will focus on the long-term use of the neuroprosthesis.

Subjects' satisfaction in performing daily living activities certify that this program achieved its major goal, aiming at maximizing the physical and psychologic potentials of quadriplegic subjects.

Acknowledgments: The authors would like to thank CNPq (National Council for Scientific and Technological Development) and FAPESP (State of São Paulo Foundation for Research), Brazil.

REFERENCES

1. Ghez C. The control of movement. In: Kandel RE, Schwartz JH, Jessej MT, eds. *Principles of neural science.* New York: Elsevier, 1991:533–47.
2. Ghez C. Voluntary movement. In: Kandel RE, Schwartz JH, Jessej MT, eds. *Principles of neural science.* New York: Elsevier, 1991:609–25.
3. Peckham PH, Keith MW, Freehafer AA. Restoration of functional control by electrical stimulation in the upper extremity of the quadriplegic patient. *J Bone Joint Surg* 1988;70-A(1): 144–8.
4. Seeger BR, Law D, Crewell JE, Stern LM. Functional electrical stimulation for upper limb strengthening in traumatic quadriplegia. *Arch Phys Med Rehab* 1989;70:663–7.
5. Kilgore KL, Peckham PH, Thrope GB, Keith MW, Gallaher-Stone KA. Synthesis of hand grasp using functional neuromuscular stimulation. *IEEE Trans Biomed Eng* 1989;36(7): 761–70.
6. Hoshimiya N, Naito A, Yajima M, Handa Y. A multichannel FES system for the restoration of motor functions in high spinal cord injury patients: A respiration controlled system for multijoint upper extremity. *IEEE Trans Biomed Eng* 1989;36(7):754–60.
7. Nathan RH, Ohry A. Upper limb functions regained in quadriplegia: A hybrid computerized neuromuscular stimulation system. *Arch Phys Med Rehab* 1990;71:415–21.
8. Smith BT, Mulcahey MJ, Betz RR. Development of an upper extremity FES system for individual with C4 tetraplegia. *IEEE Trans Rehab Eng* 1996;4(4):264–70.
9. Triolo RJ, Bieri C, Uhlir J, Kobetic R, Scheiner A, Marsolais EB. Implanted functional neuromuscular stimulation systems for individuals with cervical cord injuries: Clinical case reports. *Arch Phys Med Rehab* 1996;77(11):1119–28.
10. Kilgore KL, Peckham PH, Keith MW, Thrope GB, Wuolle KS, Bryden AM, Hart RL. An implanted upper-extremity neuroprosthesis. *J Bone Joint Surg* 1997;79-A(4):533–41.
11. Kamakura N, Matsuo M, Ishii H, Mitsuboshi F, Miura Y. Patterns of static prehension in normal hands. *Am J Occ Ther* 1980;34(7):437–45.
12. Grill WM, Mortimer JT. The effect of stimulus pulse duration on selectivity of neural stimulation. *IEEE Trans Biom Eng* 1996;43(2):161–6.
13. Lan N, Crago PE, Chizeck HJ. Feedback control methods for task regulation by electrical stimulation of muscle. *IEEE Trans Biom Eng* 1991;38(12):1213–23.
14. Lemay MA, Crago PE, Katorgi M, Chapman GJ. Automated tuning of a closed-loop grasp neuroprosthesis. *IEEE Trans Biom Eng* 1993;40(7):675–85.
15. Hines AE, Owens NE, Crago PE. Assessment of input–output properties and control of neuroprosthetic hand grasp. *IEEE Trans Biom Eng* 1992;39(6):610–23.
16. Johnson MW, Peckham PH. Evaluation of shoulder movement as a command control source. *IEEE Trans Biom Eng* 1990;37(9):876–85.
17. Cliquet A Jr, Mendeleck A, Quesnel DRF, Sovi FX, Felipe P Jr, Oberg TD, Lemos GJP, Guimaraes EA, Quevedo AAF. A neural network–voice controlled neuromuscular electrical stimulation system for tetraplegics. *Rehabilitation Engineering Society of North America (RESNA)*. ISBN: 0–932101–30–5/ ISSN: 0883–4741. Washington, DC: RESNA Press, 1992;12: 29–31.