Artificial Organs
23(5):413–417, Blackwell Science, Inc.

Functional Electrical Stimulation and Arm Supported Sit-To-Stand Transfer After Paraplegia: A Study of Kinetic Parameters

*Roman Kamnik, *Tadej Bajd, and *Alojz Kralj

**Faculty of Electrical Engineering, University of Ljubljana, Ljubljana, Slovenia*

Abstract: The sit-to-stand transfer of paraplegic patients using functional electrical stimulation (FES) of the knee extensors and arm support was analyzed in the study. In a group of 8 completely paralyzed subjects who were trained FES users, kinematic and dynamic parameters were recorded during standing up trials. A contactless optical system was used to assess the human body motion. The forces acting on the human body were measured by multi-axis force transducers. On the basis of recursive Newton-Euler inverse dynamic analysis, the forces and torques acting on the body joints were calculated. The joint moments in the lower and upper extremities during the sit-to stand task are presented in this paper. The influences of the patient's strength, FES training duration, and rising strategy on the joint loading are discussed. **Key Words:** Functional electrical stimulation—Standing up—Paraplegia—Joint torques—Dynamics.

The ability to rise from the sitting to the standing position is of major importance for impaired persons to achieve minimal mobility and independence. In paraplegic patients who are candidates for FES usage, the standing up strategy based on the open-loop stimulation of the knee extensors is well accepted (1). Within this strategy, during the preparation phase, the patient brings his body to an initial pose with the upper body leaned forward and arms almost fully flexed in the elbows and supported by the walker frame. At the same time, the hip joints resting at the chair are pulled forward toward the edge of chair as much as possible and the feet brought backward. For the start of rising, stimulation is voluntarily triggered by the patient, and the body is lifted upward from the initial to the extended upright position by the help of the stimulated quadriceps muscles and arm support. The arm support plays an important role. It is unloading the knees while providing sufficient lifting forces and assuring body balance. Because the stimulation of the knee extensors is open-loop and on/off triggered with maximal stimulation amplitudes throughout the rising process, the existent way of standing up is not optimal regarding the applied forces and torques in the upper and lower extremities. At the end of standing up when the knees are almost fully extended, the excessive knee joint torques cause high terminal velocities in the knee joints, which can result in ligament injuries (2). Furthermore, the overloading of the shoulder joints represents additional excessive loading in the upper extremities of paraplegic patients.

Recent research efforts have been concentrated on investigating closed-loop FES control systems accounting for the rising phases, state of the lower extremities, or voluntary upper body effort (2–5). While the biomechanics of standing up have been extensively studied in healthy subjects (6,7), the biomechanics of rising from sitting to a standing position in paraplegic patients has been investigated only on the basis of single trials (8). When using arm support, the paraplegic patients's body forms a closed-loop chain which includes both the voluntarily controlled upper body segments and those segments of the lower body that are passive or the motion of which is under FES control. Hence, designing a closed-loop FES control system should account for the voluntary trunk and arm contributions (9).

The purpose of this study was to obtain better insight into the existing paraplegic standing up pro-

Received December 1998.
Presented in part at the 6th Vienna International Workshop on Functional Electrostimulation, held September 22–24, 1998, in Vienna, Austria.
Address correspondence and reprint requests to Dr. Roman Kamnik, Faculty of Electrical Engineering, Tržaška 25, 1000 Ljubljana, Slovenia. E-mail: kamnikr@robo.fe.uni-lj.si

cess, examining a greater number of paraplegic patients. Dynamic and kinematic parameters were measured and joint loads were calculated. The results presented in this paper can be valuable when designing novel FES standing up control systems.

MATERIALS AND METHODS

Eight paraplegic patients with different levels of spinal cord injury and with different experiences of FES usage participated in the study. Table 1 summarizes the patients' data. The kinematics of the body segment movement were assessed by the OPTOTRAK optical system (Northern Digital Inc., Waterloo, Canada) measuring the 3-D positions of active markers (infrared LEDs) at a 50 Hz sample rate. Markers were attached to the human body joints in a way such that 2 adjoining markers defined the 3-D pose of a single segment. Two AMTI force plates (AMTI, Inc., Newton, MA, U.S.A.) were used to determine the ground reaction force vectors acting below the right foot and below the chair. The forces on the arm support frame were assessed by the 6 axis JR^3 robot wrist sensor (JR3, Inc., Woodland, CA, U.S.A.) mounted underneath the right walker handle. Measurements were accomplished only for the patient's right side and were calculated for the left side. Human body symmetry during the standing up task was presumed. In Fig. 1, the measuring setup is presented.

First, the patient was seated on an instrumented seat with his arms resting on the arm support frame. The height of the seat coincided with the height of a wheelchair while the arm support frame height was adjusted according to the patient's preferences. The patient was asked to take an initial pose and after approximately 2 s from the start of data collection, he\she was asked to stand up in a preferable way at a preferable speed. Five rising trials were recorded for each participant, with a 50 Hz sample rate, each measurement lasting for 10 s. The signals collected from active markers, force plates, and the force wrist were interpolated and filtered by the 4th order Butterworth filter with a 5 Hz cutoff frequency. The coordinate systems of all the sensors were transformed to coincide with the reference coordinate system placed on the floor in the center of the arm supportive frame. A 3-D, 15 segment model of the human body was developed, embodying the feet, shanks, thighs, pelvis, trunk, head, upper arms, lower arms, and hands. Each segment of the body had 6 degrees of freedom, and the segmental anthropometric parameters (segment masses, mass centers, and inertia tensors) were

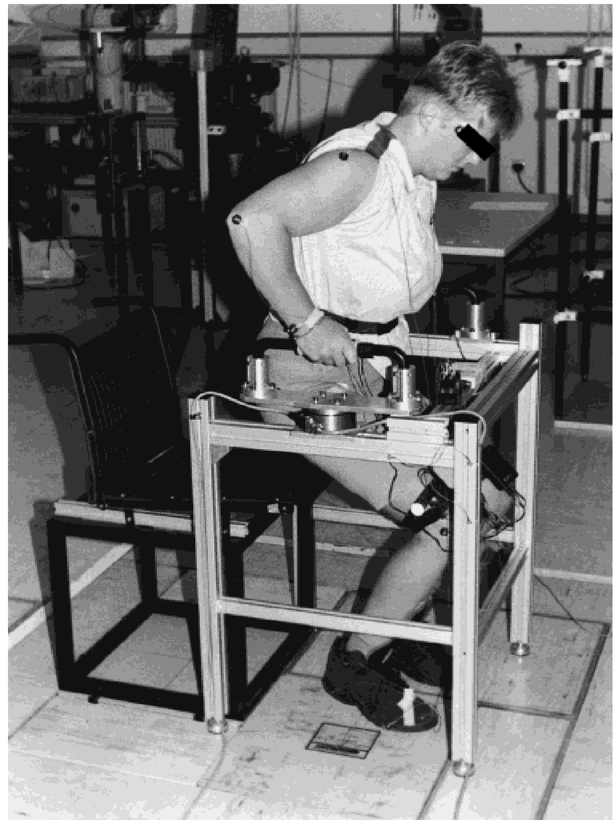

FIG. 1. The photograph is of the paraplegic standing up measurement setup.

based on the De Leva study (10). From the segment position, orientation, and anthropometric data, the forces and torques acting on the joints were calculated recursively using Newton-Euler inverse dynamic analysis (11). This analysis is based on the Newton's law that states that the sum of the external forces acting on a rigid body is equivalent to the time derivative of the linear momentum of the body, and similarly, the sum of the external moments acting on a rigid body is equivalent to the time change in the angular momentum of the body. Thus, the human

TABLE 1. *Data of paraplegic patients participating in the study*

Patient	Sex	Age (years)	Height (cm)	Weight (kg)	Lesion level	Postinjury time/FES usage (years)
MK	M	23	168	58	T9	1.5/0.2
SB	M	31	183	64	T10–12	1/0.9
BJ	M	23	185	85	T9	1.2/0.5
MT	F	28	171	75	T4–5	7/5
TM	F	19	178	59	T3–4	5/3.5
ZJ	F	57	159	53	T11	4.5/3
KA	M	44	180	74	T10–11	1.5/0.5
ZB	M	22	184	94	T3–4	3/2

body can be modelled as a chain of constant mass and rigid body segments whereby for each segment, the external forces and moments consist of a net force and a net moment reaction at both the proximal and distal joints and a gravitational force. Additional forces are involved in the segments where interaction with the environment occurs. Ground reaction force vectors acting from the floor on the foot, from the walker on the arm, and from the chair on the thighs were all measured and thus readily used in the analysis.

RESULTS

The results are presented in Fig. 2 for 3 representative patients. Patient SB's joint torques are presented by the solid lines, those belonging to Patient KA by the dashed lines, and those for Patient BJ by the dot-dash lines. Figure 2 shows the flexion/extension torques acting in the right leg and in the lumbo-sacral joint. In Fig. 3, the reaction forces and sagittal plane torque acting in the right shoulder joint are depicted, representing the voluntary action of the upper extremities. All the forces (moments) are normalized and presented as a percentage of the patient's weight (weight × height product). The zero moment on the time axis is chosen as the seat-off moment, i.e., the moment when the body leaves the chair. Table 2 lists the force and torque peak values expressed with the standard deviations of all subjects' standing up trials.

Results show that most of the forces needed to lift the body in an upward position are provided by the upper extremities. Although the paraplegic patients are able to develop higher knee torques in isometric conditions, during the standing up maneuver, the electrically stimulated knee extensors provide only up to one quarter of the needed lifting forces.

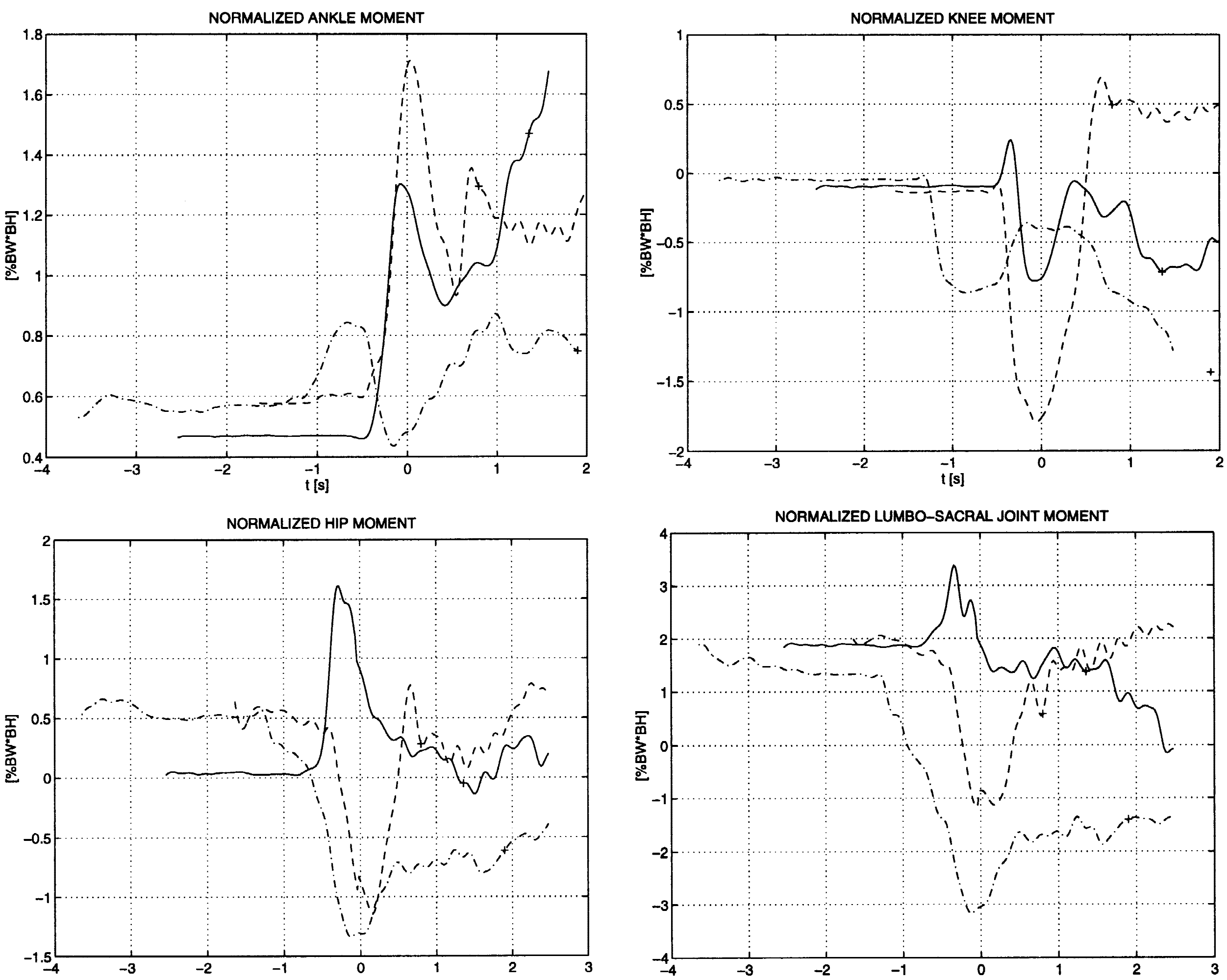

FIG. 2. The graphs contrast the flexion/extension torques acting in the lower part of the body for 3 patients (Patient SB: solid line, Patient KA: dashed line, and Patient BJ: dot-dash line).

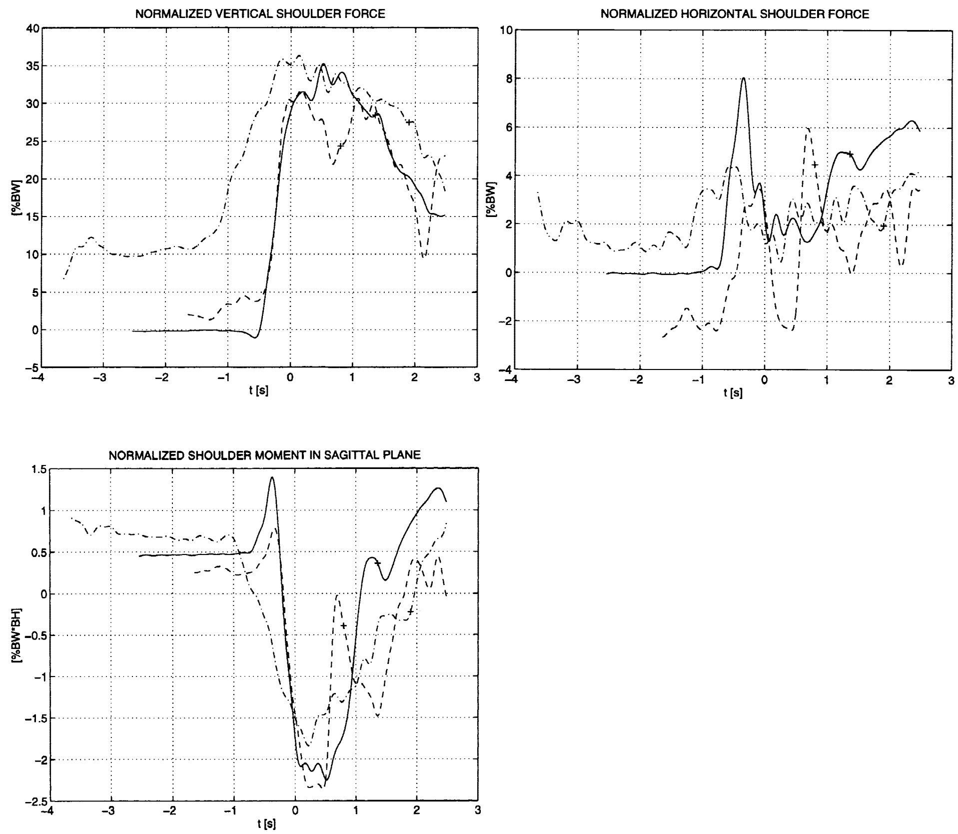

FIG. 3. The graphs contrast the upper body voluntary standing up activity represented by the reactions in the right shoulders of 3 patients (Patient SB: solid line, Patient KA: dashed line, and Patient BJ: dot-dash line).

DISCUSSION

Kinematic and dynamic parameters were assessed during the standing up process of a group of paraplegic patients. The measured joint torques in a lower limb and dynamic interactions in shoulder joints can be useful when designing advanced multichannel stimulation sequences for the standing up process. The measuring results of rising from sitting to a standing position proved that paraplegic subjects stand up in a completely different way than healthy persons. They employ arm supportive forces to a higher extent than was expected. It is interesting that in our sample group, 3 ways of standing up could be distinguished. First, there were patients whose electrically stimulated knee extensors muscles could not provide enough knee joint torque, and therefore they stood up primarily with the help of arm support. Second, there were regularly FES trained patients who made better use of lower limb support and hence unloaded the upper extremities. Characteristic representatives of these 2 groups are the Patients BJ and KA, respectively. Most interesting is the finding that some patients use a strategy similar to that of healthy persons. Prior to standing up, they push and pull their upper body forward to gain some linear momentum which is helpful in the initial standing up phase. A typical example of a patient using such a

TABLE 2. *Peak values of moments and forces during standing up for 8 paraplegic patients*

Peak values	MK	SB	BJ	MT	TM	ZJ	KA	ZB
Ankle moment (Nm)	8.6 ± 0.6	15 ± 0.6	14.1 ± 1.5	15.9 ± 3.9	7.4 ± 0.8	9.8 ± 1.1	18.5 ± 2.1	17.6 ± 1.3
Knee moment (Nm)	−9.6 ± 1.8	−10.9 ± 1.6	−14.1 ± 4.4	−15.4 ± 2.3	−8.0 ± 1.9	−1.3 ± 1.6	−22.4 ± 1.8	−17.4 ± 2.2
Hip moment (Nm)	−9.0 ± 1.6	19.7 ± 3.9	−17.6 ± 7.2	−12.9 ± 2.5	−18.3 ± 3.3	−0.7 ± 0.7	−14.1 ± 3.4	−11.2 ± 2.4
L-Sc joint mom. (Nm)	−18.5 ± 3.8	38 ± 7.2	−40.4 ± 15.1	−18.6 ± 4.2	−27.4 ± 7.4	1.7 ± 5.5	−17.2 ± 6.9	−24.8 ± 8.8
Vert. should. force (N)	237.8 ± 8.9	223.6 ± 13.5	306.8 ± 10.9	279.4 ± 13.6	226.6 ± 15.7	230.9 ± 8.9	235.1 ± 25.6	343.4 ± 13.4
Hor. should. force (N)	22.3 ± 4.9	43.3 ± 7.6	33.8 ± 5.3	44.8 ± 6.6	32.7 ± 9.0	28.5 ± 10.5	36.5 ± 7.0	53.0 ± 12.4
Sagitt. should. mom. (Nm)	−17.5 ± 6.5	−21.5 ± 4.4	−30.2 ± 2.5	−19.9 ± 4.9	−37.6 ± 8.0	−34.2 ± 4.6	−25.4 ± 4.6	−35.3 ± 5.7

standing up process is Patient SB, who initiates standing up from a more backward initial sitting position on the chair with higher activity in the shoulder joint and different activity in the hip and lumbosacral joints prior to the seat-off phase.

Acknowledgments: The authors acknowledge the financial support of the Republic of Slovenia Ministry of Science and Technology and European Commission (BIOMED 2, SENSATIONS - PL 950897). Special thanks for helpful suggestions are offered to Mr. Rahman Davoodi and Dr. Brian Andrews from the University of Alberta, Alberta, Canada.

REFERENCES

1. Kralj A, Bajd T. Functional electrical stimulation: Standing and walking after spinal cord injury. Boca Raton, Florida: CRC Press, 1989.
2. Mulder AJ, Veltink PH, Boom HBK. On/Off control in FES-induced standing up: A model study and experiments. *Med Biol Eng Comput* 1992;30:205–12.
3. Heinze S, Veltink PH, Jensen PL, Mayagoitia RE, Hermens HJ, Koopman HFJM, Huijing PA. Development of control strategies for FES-supported closed-loop standing-up. In: Pedotti A, Ferrarin M, Quintern J, Riener R, eds. *Neuroprosthetics from basic research to clinical applications*. Berlin: Springer-Verlag, 1996:209–16.
4. Davoodi R, Andrews BJ. FES standing up in paraplegia: A comparative study of fixed parameter controllers. *Proceedings of the 18th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*. New York: IEEE, 1997;1:447–8.
5. Riener T, Fuhr T. Patient-driven control of FES-supported standing-up: A simulation study. *IEEE Trans Rehab Eng* 1998;6:113–24.
6. Kralj A, Jaeger RJ, Munih M. Analysis of standing up and sitting down in humans: Definitions and normative data presentation. *J Biomech* 1990;23:1123–38.
7. Hutchinson EB, Riley PO, Krebs DE. A dynamic analysis of the joint forces and torques during rising from a chair. *IEEE Trans Rehab Eng* 1994;2:49–56.
8. Bajd T, Kralj A, Turk R. Standing-up of a healthy subject and a paraplegic patient. *J Biomech* 1982;15:1–10.
9. Davoodi R, Andrews BJ. A model of FES standing-up in paraplegics including upper limb interaction and closed-form dynamics. *Proceedings of the 18th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*. New York: IEEE, 1997;2:579–80.
10. De Leva P. Adjustments to Zatsiorksy-Seluyanov's segment inertia parameters. *J Biomech* 1996;29:1223–30.
11. Asada H, Slotine JJE. *Robot analysis and control*. New York: John Wiley, 1986.