Analysis of Paraplegics Sit-to-Stand Transfer Using Functional Electrical Stimulation and Arm Support

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Abstract: The sit-to-stand transfer of paraplegic subjects using functional electrical stimulation of knee extensors and arm support is analyzed. Kinetic and kinematic parameters were recorded during several chair-rise trials performed in a group of completely paralyzed subjects who were trained FES users. Based on measuring results, characteristic phases and events were defined in the chair-rise maneuver of paraplegic subjects. Possible applications of artificial or natural foot sole pressure sensing for surveying and control of the paraplegic sit-to-stand transfer are discussed.

I. Introduction
Ability to rise from sitting to the standing position is of major importance for impaired persons in order to achieve minimal mobility and independence. The existent way of paraplegic standing-up employs open loop stimulation of the knee extensors with maximal stimulation amplitudes throughout the rising process [1]. Maximal torques and maximal speed in the knees motion at the end of the rising can cause damage of the knee joints [2]. The arm support plays an important role in unloading of the knees and assuring the body balance. The evident need for adapting the stimulation sequences to the rising phases and to the state of the lower extremities, resulted in attempts of closed loop control of standing-up [2, 3]. These studies are based on the presumption that kinematics of body motion is known and that time events that divide process of standing-up in subsequent phases are similar as in healthy persons. In the near future the use of natural joint positional sensors cannot be expected, while external artificial sensors are rather awkward for every day usage. Utilizing the artificial or natural pressure sensing systems in the soles of the feet presents more practical solution. The artificial in-shoe pressure measuring systems are already commercially available. Furthermore, the restoration of natural foot sensory signals appears to be promising [4]. The influence of the arm support in the rising process can be easily assessed by instrumentalizing the walker using strain gauge technology. An attempt was made in this paper to identify the rising phases eg. characteristic events from the supportive forces under the feet and arms.

II. Methods
Subjects: Six paraplegic patients participated in the study, three men and three women. Their ages ranged from 17 to 57 years (mean 30.1), weights from 60 to 85 kilograms (mean 70.3) and heights from 159 to 185 cm (mean 174). Sample group included patients with different levels of spinal cord injury (T-3.4, T-4.5, T-9, T-11, T-10-12) and different experiences of FES usage (3 months to 5 years).

Instrumentation: The measuring system used in the analysis consisted from two measuring frames which were built as copies of a wheel chair seat and conventional walker. The seating frame was instrumented by the use of AMTI force plate providing information of the seat support forces, while the forces on the arm support frame were assessed by the six axis JR3 robot wrist sensor. Additional AMTI force plate was used for measuring the ground reaction forces under a foot. Kinematics of the body movement was assessed by the OPTOTRAK contactless optical system measuring the 3D active markers position. The markers were attached to the ankle, knee, hip, pelvis, shoulder, elbow, wrist, and head, defining thus thirteen segments of the human body.
Protocol: Subjects were seated on the instrumented seat with the arms resting on the arm support frame. The height of the seat coincided with the height of a wheel chair, while the arm support frame height was adjusted according to the patient's preferences. The feet were positioned in such a way that the right foot was placed flat on the force plate. After approximately two seconds from starting the data collection, the subject was asked to stand up. The subjects were asked to rise in their preferable way and speed, while using stimulation of knee extensors and arm support. At least five rising trials were recorded for each participant with the 50 Hz sample rate, each trial lasting for 10 seconds.

Data analysis: The signals collected from active markers, force plates and force wrist were interpolated and filtered by the 4th order Butterworth filter with 5 Hz cut-off frequency. The coordinate systems of all sensors were transformed to coincide with the reference coordinate system placed on the floor in the center of the arm frame. Since the human body symmetry was presumed, all parameters were gathered only for the patient's right side and calculated for the left side. Based on the kinematic measuring data and anthropometric data, the trajectories of the segmental mass centers and the body center of mass were determined.

III. Results
The characteristic phases of paraplegic rising were defined in analogy with the formalization of standing-up in healthy persons who stand-up armless [5]. They were defined as initiation, seat unloading, ascending and stabilization. The time events, characterizing the beginning of particular phase, were first identified from kinematic parameters and forces under the seat. The process of standing-up started when the body center of mass (COM) started to move in the forward direction. The beginning of the seat unloading and ascending phase was detected by the seat force sensor. The stabilization phase begun with the knees in almost fully extended position. On the figure 1 the stick diagram of a typical paraplegic standing-up trial is presented. Reaction force vectors in sagittal plane and the position of the COM are denoted by arrow and asterix respectively.
In figures 2b and 2d vertical supportive forces under the right foot and right arm during standing-up are shown together with the derivative of the arm force (fig 2c). Here, the discrete phase starting events were defined by the help of force sensing. The seat unloading phase begins when vertical arm force starts to rise (first change in $dF_{z,arm}/dt$). The seat-off event occurs when vertical arm force reaches its maximal value, while the acceleration phase starts when the first derivative of the vertical arm force reaches its maximum. The deceleration phase begins when a predetermined ration of vertical arms and legs reaction forces is established (in our study 1:1 ratio).

**IV. Discussion**

Standing-up of impaired persons using FES and hand support is significantly different from the rising of healthy persons. The main differences occur during the initiation phase where paraplegic subjects do not generate the forward momentum by pushing the upper body forward. Instead, they are using their arm forces to lift their upper body upwards. This can be clearly observed from the figure 2 where the body COM travels only in the upward direction. Thus, it is not reasonable to apply directly the phases as defined for healthy persons when recognizing the standing-up process in paraplegic subjects. In this study the events defined on the basis of the body COM movement were used as a reference for determining the same events from the supportive force information. The analysis was concentrated only to the vertical components of the supportive forces as they can be more easily assessed than horizontal components. From the table 1, containing the mean values of event recognition errors, it can be noticed that for the first three subjects the events recognitions from the supportive forces was adequate.

<table>
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<tr>
<th>subjects</th>
<th>SU</th>
<th>ACC</th>
<th>SO</th>
<th>DCC</th>
<th>rising duration</th>
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</table>

Table 1: Mean errors in characteristic events recognition expressed in percentage of rising duration

The first three subjects were far better trained in comparison with others what means that they were using lower extremities support to much larger extent. This is the cause of considerable errors in deceleration event (DCC) recognition for the last two subjects. DCC event was not defined appropriately in the cases when paraplegic persons stood-up by predominantly using their arm forces. Our results suggest that simple force sensors applied under the feet and arms can be satisfactorily used as a source of feedback information in control of FES assisted standing-up.

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**References**