THE BIOMECHANICS OF STANDING AND BALANCING IN PARALYZED PEOPLE

TADEJ BAJD[1], MATJAŽ MIHELJ[1] and ZLATKO MATJAČIĆ[2]
[1]Faculty of Electrical Engineering, University of Ljubljana, Ljubljana, Slovenia,
[2]Center for Sensory-Motor Interaction, Aalborg University, Aalborg, Denmark

Abstract: Prolonged immobilization results in several physiological problems. It has been demonstrated that standing exercises can ameliorate many of these problems. Standing exercises can be performed efficiently with the help of functional electrical stimulation (FES). A novel robotic mechanism which aids the unsupported standing of paraplegics, providing balancing exercise has been developed. The balancing strategy is based on voluntary activity of the paraplegic's upper body and artificially controlled stiffness in the ankles.

Key Words: Functional Electrical Stimulation, Rehabilitation Robotics, Spinal Cord Injury

INTRODUCTION

Prolonged immobilization, such as that occurring after spinal cord injury, results in several physiological problems. It has been demonstrated that standing exercises can ameliorate many of these problems [1] by preventing disuse atrophy and contractures, improving blood flow, preventing the development of pressure sores, improving bone density, blood pressure and spasticity, preventing urinary tract and bladder infections, and improving the functioning of the internal organs.

Standing for therapeutic purposes can be achieved with a minimum of two channels of functional electrical stimulation (FES) delivered to both knee extensors through two pairs of large surface electrodes [1]. Patients must also make use of an arm support, usually in the form of a walker or simple standing frame. Arm-free standing exercises are based on voluntary balancing by the paraplegic's upper body and properly selected artificial stiffness in the ankles [3].

METHODS AND RESULTS

Standing exercise

A study was undertaken to establish which biomechanical parameters are important for efficient standing exercise. Patients stood with one leg on a force plate. Balance was provided in the form of arm support, while FES was delivered to both knee extensors. The markers were attached to the approximate centers of the hip, knee and ankle joint rotation. The torques were calculated in the three joints from the force plate data and a photographic presentation of the lower extremity during FES-assisted standing. The highest correlation was found between the maximal standing time and the ankle joint moment (Tab. 1). Large ankle joint torques were found in paraplegics who were able to stand for about 15 min, while rather low ankle torques were found in subjects who were able to stand for one or even two hours. Proper alignment of the posture in the ankle joints is a prerequisite for efficient FES-assisted and arm-supported standing exercises.

Tab. 1 Paraplegic patient general data and standing properties

Subject	Sex	Age	SCI level	Time past injury	Maximal standing time (min)	Ankle joint torque (Nm)
1	M	20	T – 11	11m	13	-32.5
2	M	50	T – 5	3y 3m	20	-33.9
3	M	26	T – 8	5y 5m	23	-32.6
4	M	20	T – 5	1y 7m	73	-12.2
5	M	26	T – 5, 6	2y 5m	136	-15.3

Balancing exercise

A hypothesis was made that arm-free paraplegic standing in complete SCI subjects can be obtained when artificial ankle joint stiffness is added around the ankle joint. Such artificial joint stiffness can be produced either by FES of the ankle joint agonist and antagonist, or with a mechanical spring. It was further assumed that the knee and hip joints are in the extended position during standing, resembling a normal quiet standing posture. The patient can perform the balancing exercise with the help of the voluntary activity of the preserved trunk muscles around the lumbosacral joint (the anatomy of the spinal column has been simplified with one joint lying between vertebrae L5 and S1).

Initial testing of the hypothesis was made via mathematical modelling. A linear double-inverted pendulum model was composed of the body segmental dynamics, the central nervous system delay, the trunk muscle activation properties and passive mechanical impedance behaviour around the ankle joint [2]. The nonlinear equations of motion were derived by the Newton-Euler method. Of special interest were the equilibrium states of the double inverted pendulum model characterized by zero values of accelerations and velocities in the ankle and lumbosacral joint. It was observed that such a value of ankle stiffness exists where the equilibrium lumbosacral angle is approximately zero, regardless of the ankle angle values [2]. For selected numerical values of a standing subject this value was 11.2 Nm/°.

An active standing frame was developed, bracing the knee and hip joints in the extended position. The single rotational degree of freedom of this standing robot is an artificial ankle joint aligned with the subject's ankle joint axis and activated by a hydraulic motor. A special bracing system, made from aluminum alloy profiles, is attached to the artificial ankle joint. Two vertical beams are parallel with the legs and there are three transverse beams, two anterior and one posterior, which maintain the subject's knees and hips in full extension. The lower anterior transverse beam is below the subject's knees while the upper anterior and the posterior beams are mounted at the height of the subject's pelvis. All three transverse beams are covered with soft material. The inclination of the rotating frame is measured by an optical incremental encoder. The hydraulic subsystem provides the torque required for stiffness control of the artificial ankle joint. Apart from maintaining the required stiffness, the software also allows disturbances to be applied in the artificial ankle joint [3].

An investigation of balancing strategy was performed in a group of 8 healthy male subjects (age 23±4 years, weight 75±10 kg, height 176±5 cm). The hydraulic actuator in the artificial ankle joint produced disturbances in the anterior and posterior direction of the sagittal plane [4]. The perturbations differed in torque intensity (30 and 50 Nm) and disturbance duration time (150 and 250 ms). The OPTOTRAK optical system was used to measure the kinematics of the balancing person. The base of the standing robot was firmly fixed to the force plate measuring the reaction forces and torques during the experiment. The amplitudes of the ankle joint angle and torque increased by increasing the total perturbation energy. A linear relationship between the ankle torque and ankle angle was observed, resulting in constant ankle stiffness determined as a ratio between the ankle joint torque and ankle joint angle. This relationship determines the minimal ankle joint stiffness required to stand unsupported. The average ankle joint stiffness value for normal stance postures was found 11.5±1.5 Nm/° as predicted by the modelling results.

The predictions of the simulation-based study and the findings of the investigation with healthy subjects were found to concur well with empirical assessments of stiffness-supported paraplegic patient arm-free standing [3]. A paraplegic patient (lesion T12, age 34 years, weight 90 kg, height 185 cm) was constrained in the standing frame and different artificial ankle stiffnesses were applied using the hydraulic motor. The results of the study confirmed the subject's ability to stand without arm support and even recover from small disturbances acting in the ankle joints when supported by an artificial ankle stiffness of 8 Nm/° or higher.

DISCUSSION

Continuous FES, causing the knee extensors to contract, maintains the knee joints in extension and thus permits standing. The advantages of FES-assisted standing are manifold. It can help to prevent decubiti, improve the function of bladder and other internal organs, and provide better blood flow in paralyzed parts of the body. Standing can also be a useful functional activity, e.g. to get an object which would be out of reach from a wheelchair. FES-standing at any location is enabled by a special wheelchair attached supporting frame. When the frame is folded it does not interfere with the normal use of the wheelchair. Biomechanical assessments revealed that well-aligned posture is a prerequisite for adequate FES assisted standing. Contractures or strong abdominal spasticity result in biomechanically inadequate posture and hence large joint torques that cannot be adequately counterbalanced by FES.

The analysis of the postural control system of healthy subjects shows that the most adequate ankle stiffness lies around 11 Nm/°. This concurs substantially with the findings of the simulation-based study, indicating that such an ankle stiffness value provides the most adequate conditions for disturbance rejection. It should be emphasized that although the average ankle stiffness was used to describe postural control during perturbed stance, the choice of stiffness as the measured variable does not imply that the nervous system primarily regulates joint stiffness.

The predictions of mathematical modelling and the results based on investigations performed on healthy and paraplegic subjects indicate that the residual sensory and motor functions of paraplegic subjects are sufficient to maintain arm-free standing in the presence of adequate ankle stiffness.

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