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Standing and balancing exercise after spinal cord injury

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Prolonged immobilisation results in several physiological problems. It has been demonstrated that standing exercise can ameliorate many of these problems. Standing exercise can be efficiently performed by the help of functional electrical stimulation (FES). A novel active frame for unsupported standing of paraplegic persons providing balancing exercise was developed. The balancing strategy is based on voluntary activity of the paraplegic person's upper body and artificially controlled stiffness in the ankles. The importance of the use of cognitive feedback during standing and balancing was also studied.

Key words: Standing, Balance, Functional electrical stimulation (FES), Spinal cord injury.

Spinal kord yaralanmalarından sonra ayakta durma ve denge egzersizleri

Uzun süreli immobilizasyon ciddi fizyolojik problemlere neden olur. Ayakta durma egzersizlerinin bu problemlerin çoğunu iyileştirebildiği gösterilmiştir. Ayakta durma egzersizleri, fonksiyonel elektrik stimulasyonu (FES) yardımı ile etkili olarak uygulanabilmektedir. Paraplejiklerde desteksiz ayakta durmak amacıyla denge egzersizi sağlayan yeni bir aktif düzenek geliştirilmiştir. Denge stratejisi, paraplejik kişinin üst gövde istemli aktivitesi ve ayak bileğinde yapay kontrol temeli üzerine kurulmuştur. Ayrıca, ayakta durma ve denge sırasındaki kognitif feedback üzerinde çalışılmıştır.

Anahtar kelimeler: Ayakta durma, Denge, Fonksiyonel elektrik stimulasyonu (FES), Spinal kord yaralanması.

Introduction

Prolonged immobilization, such as occurs after the spinal cord injury, results in several physiological problems. It has been demonstrated that standing exercise can ameliorate many of these problems: it prevents disuse atrophy and contractures, improves blood flow and prevents development of pressure sores, improves bone density, blood pressure, and spasticity, prevents urinary tract and bladder infections and improves functioning of internal organs.

Standing for therapeutic purposes can be achieved by a minimum of two channels of functional electrical stimulation (FES) delivered to both knee extensors through two pairs of large surface electrodes.[1] The patients must make use also of the arm support usually provided by a walker or simple standing frame as shown in Figure 1. Through the use of two stimulation channels and the arm support some paraplegic persons can stand for an hour and even more. However, paraplegic subjects are not equally successful in performing FES assisted standing. Good alignment of the posture, not only in the knees but also in the ankle joints, appears to be the prerequisite for efficient FES assisted and arm supported standing exercise.

Standing exercise can be performed also by the help of mechanical bracing of the paralysed lower extremities. The goal of the active standing frame is not merely to provide support but also to enable balancing exercise. The strategy of arm-free paraplegic standing is based on voluntary balancing by the paraplegic person's upper body. It was our idea that with a properly selected artificial stiffness in the ankles, paraplegic person should be able to stand by voluntary activity of the preserved trunk muscles.[2,3]

No sensory information from the lower

paralysed limbs can reach the central nervous system during the balancing exercise performed by completely paralysed spinal cord injured persons. On the other side this group of patients has entirely normal visual and vestibular sensing. It was hypothesised that these powerful sensor systems provide sufficient feedback information necessary for balancing exercise. It was our aim to study to what extent the cognitive feedback information from the artificial sensors attached to the patient's lower body can improve the balancing performance.[4]

Standing exercise

A study was undertaken which biomechanical parameters are important for efficient standing exercise.[1] The patients were standing with one leg on the force plate. The balance was provided by the help of arm support, while FES was delivered to both knee extensors. The markers were attached to approximate centers of hip, knee, and ankle joint rotation. The torques were calculated in the three joints from the force plate data and photographic presentation of the lower extremity during FES assisted standing.

The selected paraplegic subjects (all with thoracic spinal cord lesion) were not equally successful in performing FES assisted standing. From the upper diagram in Figure 2 it can be observed that the first three SCI subjects were able to stand for about 15 min (T_{max}), while the subjects 4 and 5 could stand for over one and even two hours. In the next diagram of the Figure 2 the hip joint torques (M_H) are presented. Rather large positive values were obtained in subjects 2, 4, and 5. These patients were assuming characteristic “C” posture with hyperextended hip joints where the body weight vector was passing behind the axis of the hip joints rotation. In this way the hip joints were passively locked during standing. Low hip joints torque values were found in patients 1 and 3 what is also the main characteristic of the knee joint torques (M_K) presented in the third diagram. This is a necessary condition for FES assisted standing as electrical stimulation of knee extensors cannot counteract large external joint moments. The highest correlation was found between the maximal standing time and the ankle joint moments (M_A) presented in the lower diagram of the Figure 2. Large ankle joint torques (over 30Nm) were found in paraplegic persons who were able to stand for only about 15min, while rather low ankle torques were assessed in subjects who were able to perform long lasting standing exercise.

The static ankle joint torque is a sum of two components, the first is produced by the vertical component and the second by the horizontal component of the ground reaction force. The part of the ankle joint torque appertaining to the horizontal ground reaction force represents less than 10% of the total ankle joint moment. Apparently, the component belonging to the vertical reaction force is crucial for the efficacy of FES assisted standing. It is a product of the vertical reaction force and the lever represented by the horizontal distance between the ground reaction vector and the center of the ankle joint. For an adequate standing exercise we wish that as much as possible of the body weight is carried by the legs. To minimize the ankle joint torque, the lever belonging to the vertical reaction force should be decreased. The length of this lever was around 10cm in the subjects who were able to stand for about 15min and around 5cm in the patients who were performing standing exercise more efficiently. Good alignment of the posture, not only in the knees but also in the ankle joints, is a prerequisite for efficient FES assisted and arm supported standing exercise.

Balancing exercise

A hypothesis was made that arm-free paraplegic standing in complete SCI subjects can be obtained only in the case when an artificial ankle joint stiffness is added around the ankle joint. Such artificial joint stiffness can be produced by a mechanical spring. It was further assumed that the knee and hip joints are during standing locked in extended position. Patient can perform the balancing exercise by the help of voluntary activity of the preserved trunk muscles around the lumbosacral joint.

Figure 1. Standing exercise performed by the help of arm support and functional electrical stimulation of knee extensors.

Figure 2. Maximal time of FES assisted standing and hip, knee and, ankle joint torques measured during standing in five paraplegic subjects.

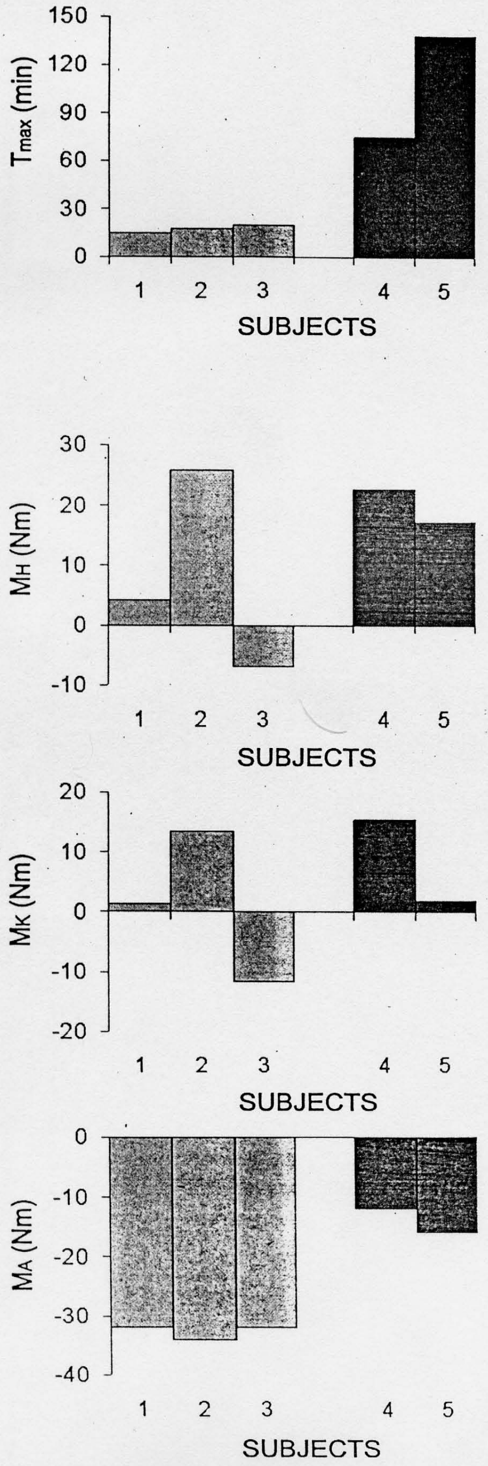


Figure 3. Neurologically intact subject while balancing in active standing frame.

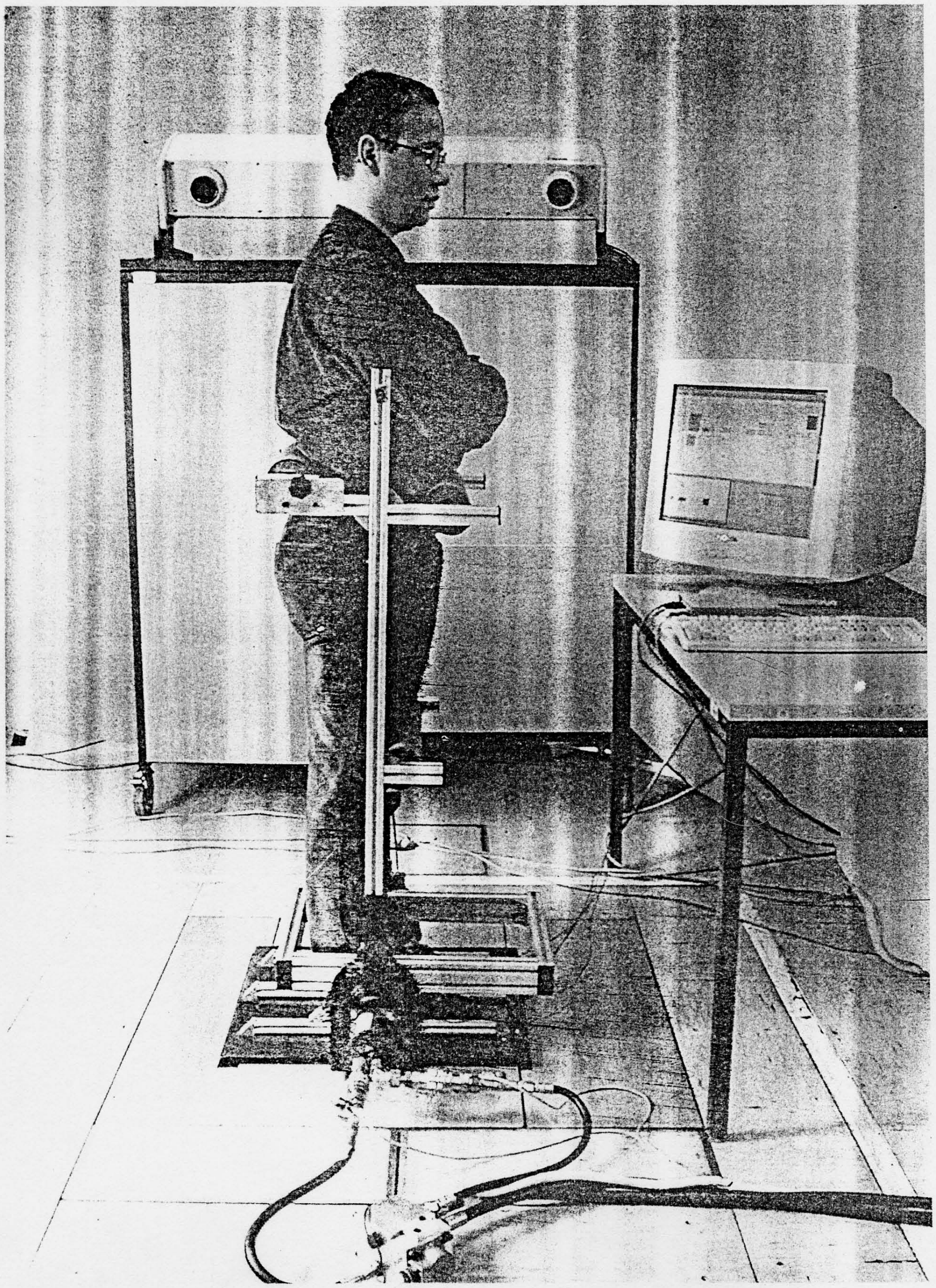
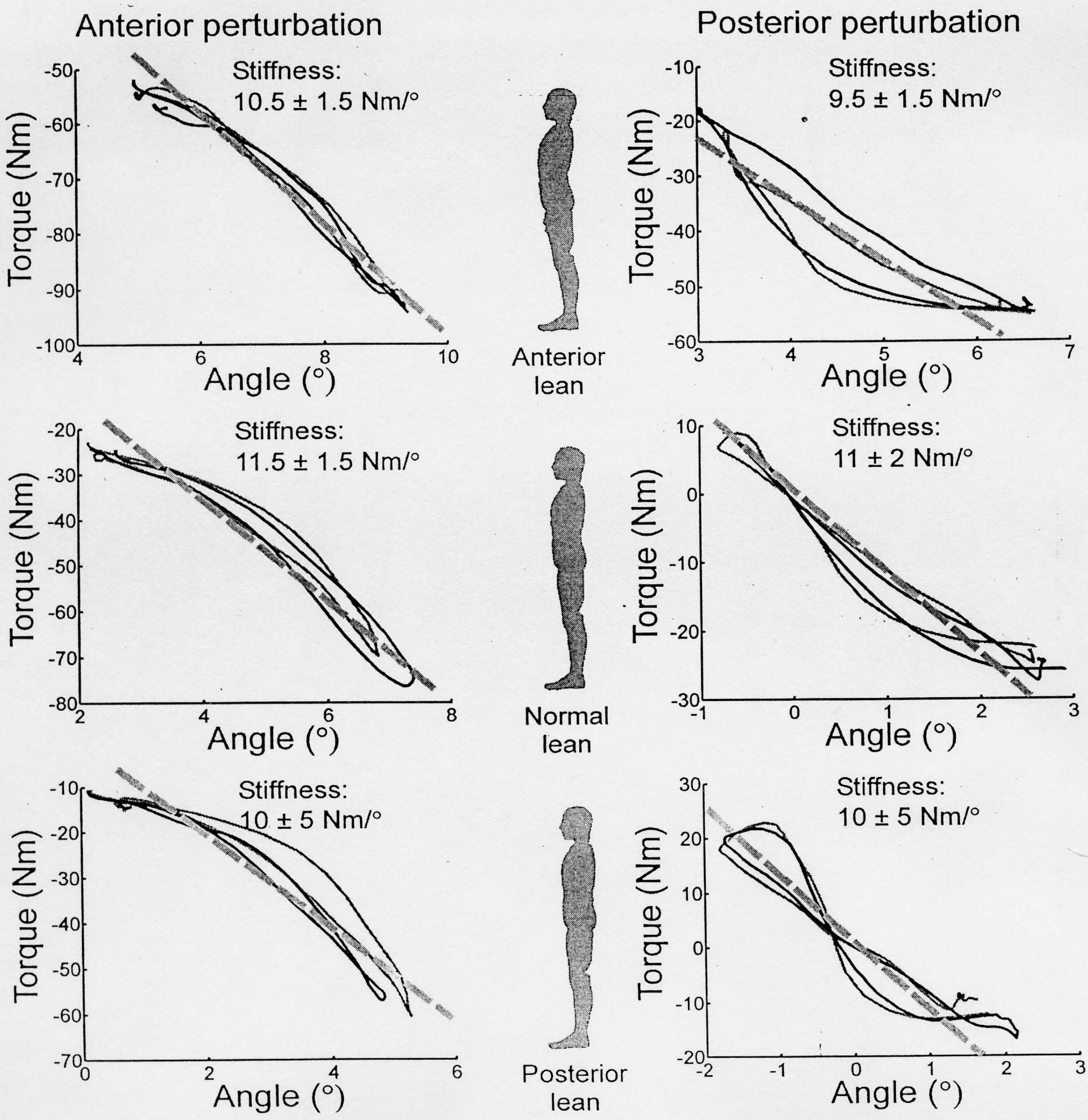


Figure 4. Three different average postures prior to perturbation (human silhouettes), typical subjects responses for two perturbation intensities (30 Nm for 250 ms – solid black and 50 Nm for 150 ms–solid gray) in anterior (right) and posterior direction (left), together with average stiffness based on results for eight subjects (dashed gray and numerical value).



An active standing frame was developed (Figure 3), bracing the knee and hip joints in extended position while both ankle joints are constrained in a neutral position. The single rotational degree of freedom of the apparatus is an artificial ankle joint activated by a hydraulic motor. A special bracing system, made from aluminium 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. The active standing frame is controlled by software running on a personal computer equipped with data acquisition units. Apart from maintaining the required stiffness, the software also allows disturbances to be applied to the artificial ankle joint.[3]

The active standing frame presents also an useful assessment tool. In our investigation we were particularly interested in the performance of the ankle joints in healthy subjects after the perturbation in the anterior and posterior direction of the sagittal plane.[5] A hydraulic actuator in the artificial ankle joint axis produced disturbances of different torque intensities (30 and 50 Nm) and duration times (150 and 250 ms) in the two directions. The OPTOTRAK optical system was used to measure the kinematics of the balancing person. The base of the standing frame was firmly fixed to the force plate measuring the reaction forces and torques during the experiment. Figure 4 presents average subjects responses for different experimental conditions. Human silhouettes indicate the initial measured posture prior to the implementation of perturbations. Plots on the right and the left of the silhouettes present subjects responses to anterior and posterior disturbances respectively. A noticeably linear relationship between the torque and angle can be observed in the majority of diagrams. This relationship determines the minimal ankle joint stiffness required to stand unsupported. A detailed analysis of the responses of eight subjects to perturbations of four different intensities confirms significant repeatability of average stiffness values of 10±2 Nm/° for anterior lean (6° ankle inclination prior the disturbance initiation) and 11±2 Nm/° for normal lean (3° ankle inclination prior the disturbance initiation). The overview of kinematics responses indicates that subjects mostly rely on ankle activity to compensate the perturbation. On the other hand, when the subject is forced to relay on trunk activity to compensate the disturbance, the variability of ankle stiffness increases. This can be observed in the case of posterior lean (0° ankle inclination prior the disturbance initiation), when posture stability is hindered due to the biomechanical constraints resulting from small support surface behind the ankle axis. High variability of stiffness values (10±5 Nm/°) prohibits any conclusions about the stiffness required to stand unsupported in posterior lean. However, since subjects in this posture mostly rely on trunk activity to compensate disturbances, knowing exact ankle stiffness is not imperative.

Cognitive feedback

The standing balance is influenced by the sensory signals from vestibular organ, eyes, muscle, tendon, and joint receptors. The completely paralysed SCI persons have vision and vestibular organ preserved, while no sensory information arrives from the lower extremities. Cognitive feedback was introduced in order to improve the balancing exercise. A precision pendulum was attached to the sacral part of a paraplegic patient. The amplified signal from the artificial sensor was split into positive and negative part, representing forward and backward leaning of the body. The voltage proportional to the angle of the leaning was transformed into sinusoidal signals of different frequencies which were led to two loud-speakers. When the standing person was leaning forward the loudspeaker placed in front was loud, when leaning backward the loudspeaker placed behind was active. The frequency of the tone was proportional to the angle of leaning. In the beginning the subjects were able to stand for about several seconds by the help of one arm support. After two weeks of training with cognitive feedback the standing time increased to several minutes.

Similar cognitive auditory feedback was introduced also into the arm-free standing exercise performed by the active standing frame.[3] The hypothesis was confirmed that visual and vestibular sensory systems are sufficient for maintaining arm-free standing in the presence of adequate ankle stiffness (8 Nm/°). We observed that in the perturbed standing the auditory feedback has no influence on the latency of the posture control loop. However, when balancing blindfold the subjects were not able to perform arm-free standing exercise. The auditory feedback was found successful in replacing the visual information.

Fatiguing of electrically stimulated paralysed muscles is a major factor limiting the duration of the FES assisted standing exercise. Fatiguing can be significantly delayed by changing the posture. Standing by FES stimulated knee extensors is not the only possible standing posture. When the body weight line is passing in front of knee joints (when the subject is leaned slightly forward) standing can be achieved by stimulating ankle plantar flexors only. Fatiguing of a stimulated muscle is considerably decreased when applying cyclical rather than continuous FES. By switching between the posture with stimulated knee extensors and the posture with activated ankle plantar flexors, the total standing time can be significantly increased.

As the completely paralysed SCI persons are not aware of the posture of their legs, a cognitive system was developed providing the information about the posture in the sagittal plane.[4] The center of the pressure (COP) under the feet was assessed by a shoe insole measuring system. The acquired signals were transformed into electrotactile sensory input. Three pairs of concentric surface electrodes were symmetrically placed with respect to both sides of the upper body. The range of the COP signal was divided into anterior, middle, and posterior regions of the foot. The location of the COP in the anterior, middle, and posterior region corresponded to stimulation pair at the shoulders, lateral back skin, and medial back skin, respectively. The subjects were asked to incline in the anterior and posterior directions to different extent. The target posture, that a standing subject had to reach, was provided to the patient through a visual display. If the time duration when the current posture matched the target posture exceeded 50% of the total trial duration (10s), the trial was judged as successful. The results of the tracking experiment have demonstrated the ability of each participating subject to accurately relate the current and target posture when using electrocoutaneous cognitive feedback system. The success of the subjects without feedback was considerably poorer. It was, therefore, shown that the residual sensory system was not sufficient to track different postures consistently when the cognitive feedback was withheld.

Discussion

Continuous FES, causing knee extensors to contract, maintains the knee joints in extension and thus allows standing. The advantages of FES assisted standing are manifold. It can help prevent decubiti, improve function of bladder and other internal organs, and provide better blood flow in paralysed parts of the body. Standing can also be a useful functional activity, e.g. to get an object out of reach from the 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 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, which cannot be adequately counterbalanced by FES.

In our investigations we demonstrated that the residual sensory and motor functions of paraplegic subjects are sufficient for maintaining arm-free standing in the presence of adequate ankle stiffness. From the first experiences with the active standing frame, we believe that the device could present a useful therapeutic modality for neurologically impaired persons. The stiffness in the artificial ankle joint can be set, so that any paraplegic person can balance, however poor is his or her strength and voluntary control of the trunk muscles. Also the intensity of perturbations can be selected according to the abilities of an impaired individual, such as stroke, brain injury or spinal cord injury patient. By every day training in the device the balancing abilities can be significantly improved what can be demonstrated by decreased support provided by the active standing frame (6). Besides being a tool for balance and standing training, the standing robot can be used also as a tool for objective evaluation of balancing abilities in impaired people. In this regard, the device offers important advantages over passive standing frames, currently used in rehabilitation centers and patients' homes. Another important feature of the active standing frame is cognitive involvement of the subject while balancing after randomly delivered perturbations.

Cognitive feedback providing information about the inclination of the standing person was found useful in training of one-arm supported FES assisted standing. We proved experimentally that no artificial sensory feedback is necessary for arm-free standing exercise in the active frame. The preserved natural vestibular and visual sensory systems together with proprioception of the upper body are sufficient. The cognitive feedback communicating the information about the position of the center of pressure under the feet was found useful when switching between different FES assisted standing postures.

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