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Methods for Dynamic Balance Training During Standing and Stepping

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Abstract: The regaining of walking ability is one of the main goals of rehabilitation following stroke. An important aspect of bipedal locomotion is efficient balancing of the trunk. In this article a novel methodology for dynamic balance training during standing and stepping is presented in a commercially available mechanical balance training device. A case study that lasted for two-weeks with two half-hour training sessions per day, involving a single subject with chronic hemiparesis, investigated the effects of the proposed dynamic balance training. Instrumented kinesiological evaluation of the subject's gait indicated important improvement in the subject's postural control during walking. Finally, the possibility of combining therapeutic functional electrical stimulation of selected lower extremity muscles with the methodology for dynamic balance training presented here is discussed.
Key Words: Posture—Gait—Rehabilitation—Sensory-motor re-learning—Functional electrical stimulation (FES).

One of the major consequences of cerebrovascular insult is impaired walking ability (1). Various neuro-therapeutic techniques and methods combined with strength training are traditionally used in rehabilitation. In the last few years a philosophy of task-oriented therapy has been proposed as a result of recent findings from basic research studies on reorganization of the impaired brain subjected to a repetitive and intense practice of various functional movements (2). Several new techniques, such as partial body-weight-supported (BWS) treadmill and overground walking, functional electrical stimulation (FES)-supported gait-training, and development of robotized gait trainers have been developed and evaluated (1). A common denominator of all the listed techniques is that they assist in obtaining repetitive cyclical activity of both lower extremities in very early stages post stroke, thus also allowing rehabilitation of walking in nonambulatory subjects. Simultaneously, trainees use their upper extremities to hold onto a firm support, e.g., parallel bars, to control equilibrium of the trunk and to provide assistive forces required for generation of propulsive forces. Bipedal walking requires harmonization of three basic gait components: cyclical movement of lower extremities, generation of propulsive forces, and maintenance of balance and upright posture of the upper body consisting of the pelvis, trunk, head, and arms, which represent approximately two thirds of the total body mass. As the above mentioned gait-training techniques fully address only the first component, partially address the second component, and do not address at all the third component because of the use of upper extremities, we can question whether any of the existing methods optimally exploits the residual capacity of damaged brain to re-learn the skills necessary for independent, bipedal walking. It seems that at this stage of development, a training modality, focusing on improving the control mechanisms to maintain balance of the trunk without using the upper extremities, which would complement the existing techniques for training of the cyclical activity of both lower extremities, is missing. In recent years we have developed mechanical apparatus and methodology, which enables the neurologically impaired population fall-safe balance training during standing with feet positioned in parallel or tandem stance (3). The device also enables

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balance training while practicing different components of walking such as accomplishing the whole step where the sequence of push-off, swing, and weight acceptance of one extremity and complementary stance-phase weight-bearing activity of the other extremity is repetitively executed. While performing these maneuvers the trunk needs to be maintained erect, which should facilitate reorganization of the postural control system.

In this article we report on dynamic balance training of various gait components during standing in a mechanical balance training device (3) and its evaluation in a case study. In discussion we elaborate on the natural merging of the presented balance training technique with FES-assisted transfer of weight during standing and stepping.

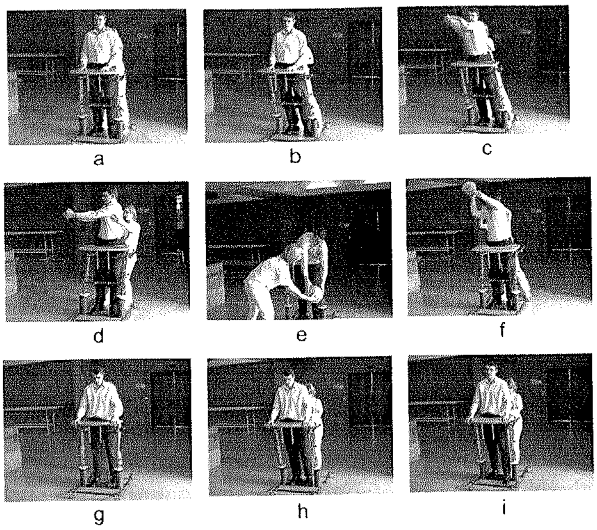

FIG. 1. Elements of dynamic balance training during standing and executing a step as demonstrated in a neurologically intact person.

MATERIALS AND METHODS

Device

The dynamic balance training program reported here is based on a previously developed mechanical apparatus (3), which is commercially available as the "Balance Trainer" (Medica Medizintechnik GmbH, Hochdorf, Germany). The Balance Trainer looks very much like an ordinary standing frame. It consists of two parallel bars that are connected to a base plate via a two-degrees-of-freedom mechanical joint. This joint consists of two helical springs positioned within two steel cylinders. Another cylinder made of a durable plastic material slides between the inner walls of the steel cylinder and the outer walls of the spring. By changing the vertical position of the plastic cylinder we also change the active length of the spring, thereby changing also the effective length and stiffness of the whole joint. One end of the helical spring is firmly mounted on the base plate while the other connects to the vertical bar. A knee support bar and the pelvis support table are connected to both parallel bars via simple hinge joints. These mechanical joints allow for the physiological movement of a person while standing as well as while performing a single step. The device is also equipped with a simple mechanical locking system that enables the locking of both parallel bars into the vertical position. In this way the device becomes an ordinary standing frame.

Training procedures

An overview of the derived balance training procedures is encapsulated in nine photographs as shown in Fig. 1. All photographs show a neurologically intact subject while performing various tasks during standing on the Balance Trainer and a physiotherapist guiding, correcting, and facilitating movement and proper posture of the trunk. Figure 1a shows a parallel stance, which is an initial and final posture for all training tasks. Figure 1b shows inclination of the subject to the right while therapists monitor the posture of the trunk. In a similar manner the subject can incline also to the left, forward, and backward. Thus, the device enables circular movement of the pelvis in the transverse plane. The movement of lower extremities can be complemented with associated movement of upper extremities as shown in Fig. 1c,d. Figure 1e,f shows training of a functional activity during parallel stance. In all six exercises described, the knee pellots were adjusted equally for both extremities. They can be displaced to control the degree of allowable knee flexion, which is useful for avoiding excessive knee hyperextension that is common in chronic hemiparesis. However, the knee pellots can also be positioned in such a way that they allow for a tandem stance of both extremities, thereby creating a posture which is similar to a double stance during walking. Similar exercises as shown in Fig. 1a–f can be performed in tandem stance as well, which facilitates weight-shifting activities. The last three photographs show a situation where the knee pellot bar is completely removed, which allows a standing subject to practice the whole step. Figure 1g shows a push-off of the left lower extremity and gradual weight acceptance by the right extremity. The pelvis and the trunk are held in the upright posture. In Fig. 1h the left lower extremity proceeds into a swing phase, while the right lower extremity fully supports the body weight.

Hip abductors and extensors control the posture of pelvis and trunk in the frontal and sagittal planes, respectively. Figure 1i shows the conclusion of the step with the beginning of weight acceptance by the left leg. Training procedures as outlined in Fig. 1 can be performed with an adjustable level of mechanical support, resulting from the adjustable stiffness action of both two-degrees-of-freedom mechanical joints. The judgment on the level of mechanical support needed for each individual patient resides with a physiotherapist.

Case description

The participant who was selected for a case study evaluation was a 57-year-old man who had a stroke which resulted in a right-sided chronic hemiparesis 14 months before participating in the study. The level of mechanical support was minimal as the subject could stand and walk independently, however, his balancing abilities were impaired. The therapeutic program lasted for 10 days with a 2-day break during the weekend of intensive practice. The duration of one session was approximately half of an hour, with two sessions per day. Kinesiological gait analysis was carried out before initiation of therapeutic intervention, at the end of the 2-week training period, and at follow-up, 3 weeks after the end of treatment. We used a VICON 370 (Oxford Metrics Ltd, Oxford, U.K.) three-dimensional motion-capturing and analysis system consisting of six 50 Hz cameras with infrared strobes and two force platforms AMTI OR6-5-1000 (Advanced Mechanical Technology Inc., Watertown, MA, U.S.A.). The participant, who was barefooted, was instructed to walk with self-paced velocity. At least six steps per leg were recorded for each measurement session and at least three steps per measurement for each leg were suitable for further analysis. Clinical Manager software, supplied by the same producer, was used for calculation of hip flexion/extension moment of force, which is the prime vehicle for postural control of trunk in the sagittal plane (4). We also performed a spectral power density analysis of hip moments of force in order to explore the underlying balance control aspects of walking. The participant's gait was also evaluated by means of clinical assessment tools: Functional Ambulation Category (FAC), 10-m walk, and 9-min walk. These assessments were performed only before and after therapeutic intervention.

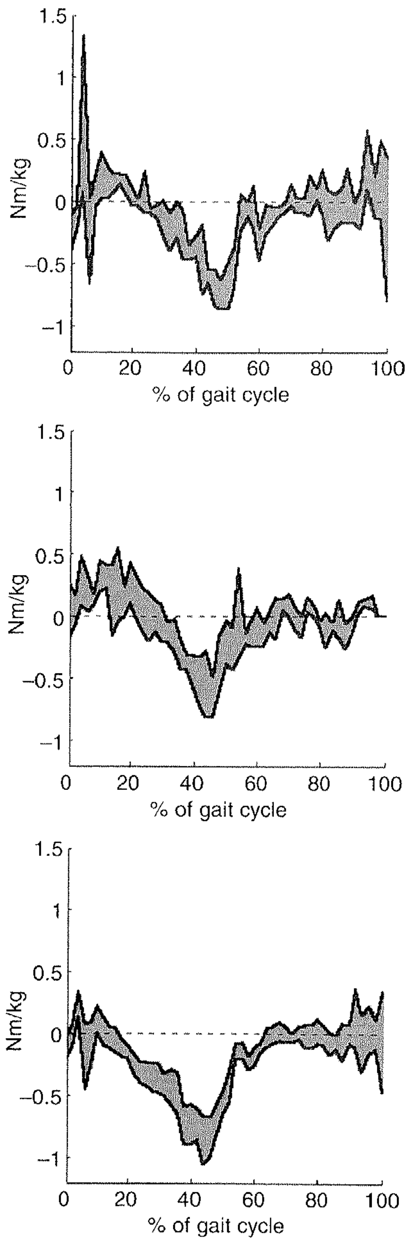

FIG. 2. Flexion/extension hip moment in the impaired right extremity shown within the boundaries of one standard deviation. Left graph—before intervention, middle graph—after intervention, right graph—at follow-up.

RESULTS

Figure 2 shows hip joint flexion/extension moments for the impaired right extremity for all three measurements. The hip flexion/extension moment as assessed before therapeutic intervention is similar to the one observed in normal gait for almost the whole gait cycle with the important exception of the first 10% of the gait cycle. We notice a rapid rise of hip extension moment, which in a very short time rapidly falls and then again rises. If we compare this with the hip flexion/extension moment as assessed in the measurement sessions after the therapeutic intervention and at follow-up, no such behavior can be observed. Figure 3 shows power density spectra for hip flexion/extension moments of the right extremity for all three measurements in the frequency range from 2.5 Hz up to 20 Hz. Comparing the mean values at different discrete frequencies and between the three measurement sessions we can see reduction of amplitude ranging from 100% up to 500% after the end of therapy and at follow-up. Before and after therapeutic intervention, FAC score was 5. Before therapeutic intervention the results for the 10-m walk test was 8 s, and for 9-min walk test 585 m. After therapeutic intervention these values were 8 s and 600 m.

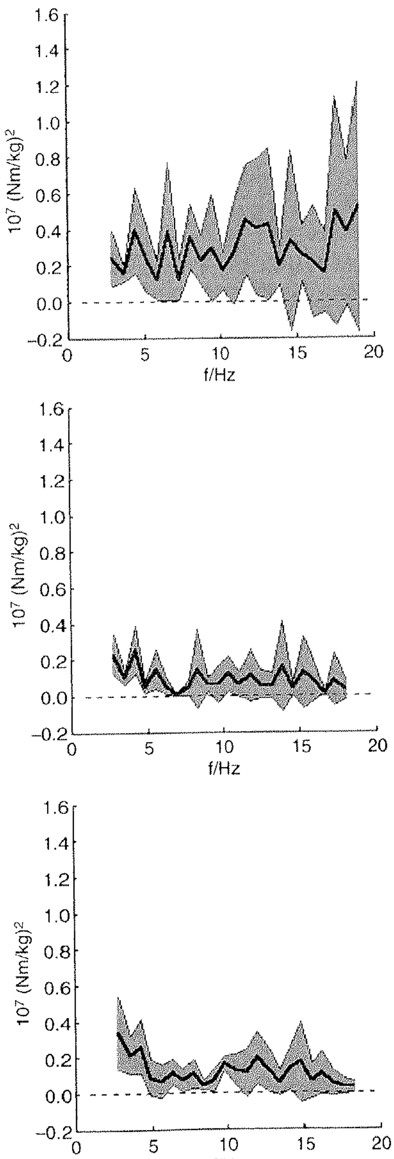

FIG. 3. Spectral power density plots for flexion/extension hip moment in the impaired right extremity shown within the boundaries of one standard deviation and for the frequency range from 2.5 Hz to 20 Hz. Left graph—before intervention, middle graph—after intervention, right graph—at follow-up.

DISCUSSION

The main purpose of this article was to present novel dynamic balance training techniques during standing and stepping and to explore whether training of various gait components during standing in a previously developed mechanical balance training device improves balance mechanisms that control the posture of the trunk during level-ground walking for a selected subject with chronic hemiparesis. The results of detailed analysis of instrumented gait assessment indicate improvement of postural mechanisms that are the prime vehicles for balancing the trunk during walking for the selected patient who underwent the developed training intervention. This improvement was retained beyond the training period as shown by the results of follow-up assessment.

We have focused in our analysis on the moments produced by the hip flexor/extensor muscles, which were shown to be the main mechanisms for trunk posture regulation in the sagittal plane during walking (4). A marked difference was seen in hip moment trajectories of the right extremity before our therapeutic intervention. This difference was mainly reflected in a large jerk in hip moment immediately after the foot contact that started stance phase. The observed oscillation was likely due to a highly sensitive postural reflex response. Since the duration of this jerk was too short to have any noticeable effect on hip and trunk movement, it was not functional and only resulted in significant loading of the hip joint via the compressive forces that accompany the observed moment jerk. The oscillatory behavior in the flexion/extension hip moment could be observed also throughout the whole gait cycle in power density spectra. This complements the observations made in the time domain and further demonstrates the high gain in the hip flexion/extension postural mechanisms. The results assessed immediately after the therapeutic intervention and at follow-up show marked decrease in the gain indicated by reduction of power density spectra. From the clinical point of view, we can pose the question of clinical relevance of the observed improvement, especially because the accompanying assessment of clinical outcome measures did not show any improvement. Firstly, the reduction of the jerk in hip moments is beneficial as it reduces the unnecessary stress on the musculoskeletal structures. Secondly, the patient as well as his therapists observed much more confident walking following the intervention, which has a positive effect on self-confidence, self-image, and reduced fear of falling. Thirdly, we need to take into account that the patient we selected for this case study was, in terms of walking abilities, exceptionally good. This choice was necessary because the selected subject had to be capable of independent walking in order to be eligible for instrumented gait analysis procedures. In such patients it is fairly difficult to improve any aspect of walking, which was confirmed also by the results of clinical assessment. If we had not also undertaken objective gait analysis measures, we would not see a significant difference in the patient's gait performance. Also the patient was well into the chronic stage of hemiparesis, which ruled out otherwise possible effects of spontaneous recovery.

The developed methodology for efficient balance training during standing and stepping in a fall-safe and variable support level environment offers possibilities for natural merging with FES techniques. This would be of special importance for the patients in the very early stages of rehabilitation where relearning of compensatory sensory–motor patterns takes place. It has been demonstrated that a combination of repetitive machine-driven movement, like Gait Trainer (5) and treadmill walking (6,7) with FES of selected leg muscles brings about better results as compared to training without FES. Similarly, movement using the Balance Trainer in sagittal and frontal planes can easily be measured via tilt sensors that can be interfaced either to a personal computer for provision of cognitive feedback or/and to an FES system. The FES system could, depending on the type of postural activity during standing or stepping, deliver electrical stimuli to, e.g., hip abductors when transferring weight sideways, to plantarflexors/dorsiflexors and knee extensors when transferring weight in an anterioposterior direction, and to a combination of the above-mentioned muscles when practicing push-off and weight acceptance in tandem stance. The functioning of an open-loop FES system, triggered by the movement of the Balance Trainer and executing preprogrammed FES sequences delivered to selected muscles at selected intensity, would depend on the particular patient at the discretion of the therapist.

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