Adaptive Dynamic Balance Training During Overground Walking
With Assistive Device

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Abstract—In this paper we describe a motorized device and corresponding adaptive control strategy for dynamic balance training during overground walking. The device provides adjustable level of supporting forces at the pelvis whereas adaptive control strategy periodically adjusts the training difficulty by adjusting gait velocity with respect to selected performance criterion. Results suggest that the proposed training paradigm may successfully ascertain training conditions that correspond well to patient capabilities and therefore may potentially be useful in improving dynamic balance during overground walking in gait rehabilitation of neurological individuals.

I. INTRODUCTION

Continuous alternations between single and double support phases, repeating weight transfers from supporting to the opposite leg as well as gait rhythm changes in an inherently unstable human locomotion system continuously challenge human balance system. Energy efficient gait requires well coordinated and synchronized collaboration between intact central nervous system, somatosensory system and musculo skeletal system [1],[2]. However, a neurological disorder very often leads to functional deficits associated with impaired muscle recruitment and balance control, which impose walking constraints [3]. Studies from neuroplasticity show that if a subject undergoes repetitive and intense functionally oriented therapy, reorganization of impaired brain may to some extent mitigate these walking constraints and improve postural stability, thus improving functional walking abilities [4].

Gait rehabilitation and dynamic balance training is typically performed in presence of at least two expert therapist that manually assist the subject to walk and to maintain dynamic balance at the same time. Since this is physically very intensive task several technical solutions have been proposed recently that introduce partial body weight supported treadmill and over ground gait training [5]-[7] as well as robot assisted gait training on treadmill [8],[9]. They relieve the therapists from strenuous task, ensure fall safe training environment, facilitate in delivering repetitive task oriented training and prolonged training sessions under therapist’s supervision and provide tools for objective quantitative assessment of performance progress. The most noteworthy shortcomings of these devices are the physical constraints. Recent studies suggest that fixating the pelvis to weight unloading or due to technical limitations of the device alters muscle recruitment and sensory input, which interfere with proper weight transfer and forward propulsion [10]. While these constraints may be welcome in early phases of gait rehabilitation, when the training is focused on reinstating cyclical leg movement, they are generally considered as significant restrictions when attempting to restate balancing activities during gait in later phases. Namely, large portion of human body mass that is located above hips acts as an inverted pendulum that requires active participation of pelvis muscles as well as torso muscles to maintain postural stability during walking. Therefore, to properly exert pelvis and torso movement, it is imperative to gradually decrease and eventually minimize (ideally completely remove) body weight support and pelvis constraints when lower extremity function improves. Some recent robot assisted treadmill gait training devices [11] narrow this gap by incorporating intelligent control strategies that continuously minimize the level of assistance according to subject’s capabilities. Furthermore, they enhance subject’s participation during training by encoding gait objectives as a set of tasks in virtual environment that adapt according to subject’s performance. In parallel, there is an ongoing debate in the literature as to whether treadmill training adequately replicates over ground walking. Evidence exist that treadmill walking induces somewhat different gait kinematics as opposed to natural walking on ground surface [7],[12]. Another reason for continuing with over ground gait training lies in the necessity to train different gait maneuvers. Gait initiation and stopping, accelerating and decelerating, turning left and right as well as turning at place are elementary maneuvers that one cannot avoid in daily activities and require dynamic balance control mechanisms that cannot be trained in forward walking. Since present gait training
The most likely reason for slow implementation is the lack of practical and financially sustainable technical solution.

We present a novel motorized device for fall safe dynamic balance training during over ground walking that provides adjustable level of stabilizing forces. In this paper we focus on adaptive control strategy that follows and records subject’s performance and adapts to performance progress by periodically adjusting gait velocity.

I. Methods

A. Gait Balance Trainer

Fig. 1 shows schematic representation of the Gait Balance Trainer (GBT). It is a therapist controlled motor driven device that is structurally closely related to Balance Trainer (Medica Medizintechnik GmbH), an apparatus for balance training during standing. Two independent motorized wheels on each side of the mounting frame provide necessary actuations to exercise the essential movement maneuvers (moving forward, accelerating/decelerating and turning left/right) with adjustable linear and angular velocity. On the same mounting frame and one on each side is a helical spring housed in a steel cylinder. Between the helical spring and the walls of the steel cylinder there is a resistance adjustment ring with a handle. By displacing the adjustment ring upwards the bending length of the spring becomes shorter, thus making the spring stiffer. Conversely, by lowering the adjustment ring the bending length of the spring is longer, which makes the spring more compliant. Each spring connects to vertical rod that is coupled with supporting horizontal bars and the tabletop to constitute a standing frame. During training the subject is embraced around pelvis with leather harness and attached to the horizontal rods on each side in a way to minimize the relative movement.

Fig. 1. Schematic representation of Gait Balance Trainer. The helical springs allow the standing frame to comply in sagittal and frontal plane while interacting with the subject during training which assures natural pelvis movement. At the same time it provides a stabilizing force to the pelvis that ensures maintenance of vertical posture.
between the standing frame and the subject but to allow natural pelvis movement and to ensure fall safe training conditions. If the subject leans forward or backward and/or sideways, the standing frame follows the same movement which provokes the helical springs to bend. Since the springs oppose any displacement from vertical, a stabilizing force acts on pelvis in the transversal plane with a magnitude that depends on spring compliance i.e. on the position of the adjustment ring. To maximize subject’s participation during gait training the level of supporting force should be selected in a way to motivate the subjects to walk without supporting themselves on the standing frame. To acquire information about dynamic balance performance the standing frame is equipped with a tilt sensor, which measures sagittal and frontal sway during training. We used xPc Target to realize real time control of GBT.

B. GBT Control

During training the therapist can choose between two control modes. In manually operated control mode experienced therapist must properly assess subject’s capabilities and manually select appropriate training conditions by continuously adapting desired gait velocity, gait direction.

Alternatively, in an adaptive control mode the therapist instructs the GBT only when to turn and assign the GBT to periodically and adaptively adjust desired speed according to subject’s performance. Given that the aim of dynamic balance training is to improve postural control we selected the following performance criterion to indicate the quality of postural responses during walking:

\[ C_n = \frac{1}{T} \int_{nT}^{(n+1)T} \sqrt{\dot{\theta}_L^2 + \dot{\theta}_S^2} \, dt \]  

In (1) \( \dot{\theta}_L \) and \( \dot{\theta}_S \) denote lateral and sagittal swing angle respectively and \( T \) represents an observation period. We assume that by improving dynamic balance during walking the subject regains better postural control which reflects in smaller deviations from vertical position, hence lower performance criterion \( C_n \). However, to conform to performance progress as well as to each individual, GBT adaptively and periodically (with period \( T \)) adjusts gait velocity according to the value of selected performance criterion \( C_i \) at the end of each period \( T_i \). Fig. 2a illustrates that two neighboring performance levels \( C_{L,n+1} \) and \( C_{L,n} \) determine a performance range and each performance range defines exactly one gait velocity. GBT selects gait velocity according to performance range that current \( C_i \) belongs to. The set of performance levels \( C_{L,i} \) was experimentally determined according to subject’s capabilities in preliminary testing. The values selected and corresponding gait velocities are shown in Fig 2b.

C. Experimental conditions

Gait Balance Trainer and the performance of the proposed adaptive control strategy were tested in a female patient with proprioceptive deficits that reflect in balance dysfunction. Two experimental conditions were assumed. In the first experiment high vertical positions of the adjustment rings provided relatively stiff helical springs and less compliant standing frame which assured considerable higher stabilizing force. In the second experiment, we minimized the level of stabilizing force by lowering the vertical positions of the adjustment rings to the minimum. The set of performance levels \( C_{L,i} \) was experimentally determined in preliminary testing. Due to severely diminished patient’s balancing capabilities we selected gait velocity should not exceed \( v = 0.3 \) m/s and set \( T = 10 \) s. The values selected and corresponding gait velocities are shown in Fig 2b.

II. Results

Performance of the proposed adaptive control strategy

![Fig. 2. Adaptive control mode: a) schematic representation of adaptive control scheme and b) selected gait performance levels and corresponding gait velocities.](image-url)
with respect to subject performance criterion is displayed in Fig. 3. Performance criterion graph in the first experiment when high stiffness of helical springs assured high stabilizing force indicates relatively stable postural responses during walking. Except from four short-term bursts the subject was able to keep the performance criterion well below the selected performance level of $C = 30^\circ$. The adaptive control strategy responded with four short-term corrections when gait velocity dropped from $v = 0.3$ m/s to $v = 0.2$ m/s and returned back to $v = 0.3$ m/s. On the other hand, with more compliant helical springs subject performance criterion displayed considerably more diverse pattern. Performance criterion $C$ repeatedly crossed selected performance level $C = 30^\circ$. Adaptive control strategy accompanied each crossing with corresponding gait velocity adjustment, hence frequent jumps between the two gait velocity levels $v = 0.3$ m/s and $v = 0.2$ m/s.

### III. Conclusion

This paper describes a motorized device and proposes an adaptive control strategy for adaptive dynamic balance training during overground walking. The device provides adjustable level of supporting forces at the pelvis which assists in reinstating vertical posture, thus creating training conditions in which the subject must progressively (as the level of support decreases) learn appropriate balancing mechanisms in order to improve gait stability. Furthermore, by periodically adjusting gait velocity according to performance criterion the proposed adaptive control strategy additionally stimulates the subject to actively participate and cooperate in order to ascertain the most suitable training conditions. In this context we may consider experimental conditions in the first experiment less challenging that necessary according to patient capabilities. Stable postural responses and gait velocity suggest that high supporting force assured greater assistance than necessary and did not optimally stimulate the patient to actively participate in dynamic balance training. On the other hand, frequent gait velocity adjustments in the second experiment indicate that the selected training conditions were more stimulative. It seems from the results that imposing gait velocity of $v = 0.2$ m/s established comfortable training conditions whereas gait velocity of $v = 0.3$ m/s demanded active cooperation from the patient. This suggests that the proposed training paradigm may successfully ascertain training conditions that correspond well to patient capabilities which will be explored in the future through clinical case studies.

### REFERENCES


