Robot Supported Gait Rehabilitation: Clinical Needs, Current State of the Art and Future

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Abstract. Rehabilitation robots have made their way into clinical practice and are being readily used in the routine rehabilitation treatment of people with disabilities following neurological insult/disease. Currently, rehabilitation robots for training walking have limited number of mechanical degrees of freedom thus enabling also limited scope of gait training, limited to training of cyclical leg movement in the plane of progression. Efficient training of proper weight shifting, overall dynamic balance as well as turning capabilities is currently poorly incorporated in contemporary rehabilitation robots. In this paper we propose two conceptual approaches of mechanical devices that may overcome limited factors listed above. We further discuss possible control approaches for the presented concepts that will inevitably have to include some degree of cognitive abilities in future rehabilitation robotic devices.

1 Introduction

In the last decade rehabilitation robots have made their way into clinical practice where they are becoming an indispensable tool in neurological rehabilitation of the upper and lower extremities [1, 2]. Rehabilitation of walking is readily aided through the use of commercial devices in the form of robotic exoskeletons or foot-plate based robotic platforms. These devices however currently enable gait training only of straight-line walking due to a lack of appropriate mechanical degrees-of-freedom (DOF). Selection of appropriate leg kinematics and relevant training parameters such as speed of walking and a level of robotic assistance are under the discretion of a therapist while patients are statically stable due to an appropriate level of body-weight-support (BWS) and use of their arms holding onto firm support. Therefore, there is clear challenge to extend the number of DOFs to enable appropriately robot supported movement also in frontal and transverse planes; consequently i) this will enable practicing of a more challenging maneuvers during walking such as turning thus significantly extending the scope of cognitive involvement of a patient, which will require also adequate cognitive-based control of a robot and ii) it will present an additional challenge to both patient and robot to jointly take care of adequate dynamic balance control during walking.

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The aim of this contribution is 1.) To review clinical needs associated with therapist and/or robot supported gait training in neurological population, 2.) To review current state of the art in the field of rehabilitation robotics currently incorporated into clinical practice and 3.) To propose possible further development addressing the needs for training of turning and dynamic balancing capabilities during walking.

2 Clinical Needs and Current State of the Art

From the biomechanical and functional point of view there are several aspects of walking that need to be practiced following neurological insult/disease in order to make the most from neural plasticity of the damaged brain and consequently to re-learn functional abilities. These are:

- Cyclical leg movement (mostly in the line of progression)
- Weight-shifting capabilities (mostly in the frontal plane)
- Dynamic balancing abilities (in all three planes of motion)
- Turning skills (mostly in the transverse plane around the vertical body axis)

Physiotherapists during their clinical work readily focus first on restoring the cyclical leg movement, which can be done in the beginning also while patient assumes lying position. In parallel weight bearing abilities are practiced during standing and stepping in place. Further step involves training of weight shifting between both lower limbs, frequently while making use of partial body weight support (BWS). This is done while standing and also while walking on a treadmill. After certain walking speed is achieved on a treadmill progression to over ground training of walking is possible while patient can be supported by one or two therapists and/or using moveable parallel bars or a suitable walking aid such as rolator. Like in any sensory-motor task a substantial number of repetitions of all the above listed tasks are needed to take advantage of neural plasticity of the brain to acquire necessary skills. This is why rehabilitation robotic devices have made way into clinical practice since they can offer large number of repetitions on one hand while on the other hand the degree of variability of the executed movement may be under control and within the limits that facilitate successful learning. Table 1 illustrates skills to be practiced and the current state of the art in rehabilitation robots (only commercially available devices are listed) together with its limitations.

Limited number of DOFs that are currently used in the contemporary rehabilitation robots limits the completeness of walking training. The clinical practice have shown that the listed devices are excellent tools for various phases of rehabilitation where isolated motor skills can be reliably practiced in a safe and repeatable manner while at the same time relieving the therapists from physical effort as well as substantially increasing the number of repetitions of the practiced

Table 1 Overview of clinical needs and state of the art rehabilitation robots in walking training

Skill to be practiced	Robotic system	Brief description	Limitation
Cyclical leg movement	LOKOMAT (Hocoma AG) G-EO (Reha Technologies) AutoAmbulator (Motorika Ltd) LokoHelp (LokoHelp Group) Gait Trainer (RehaStim GmbH)	BWS supported treadmill walking with robotic guidance (either exoskeleton or foot-plate based mechanisms)	Movement limited to sagittal plane; not all joints of the leg are supported
Weight shifting between both legs	Balance Trainer (medica Medizintechnik GmbH)	Adjustable mechanical impedance support at the level of pelvis enables weight shifting in left/right and forward/backward directions	Practicing is limited to standing. Axial rotation in the transverse plane is not possible.
Dynamic balancing during walking and turning – without using arms for support	E-go (medica Medizintechnik GmbH)	Motorized platform and adjustable mechanical impedance support at the level of pelvis enable practicing of dynamic balance and turning skills during over ground walking	Natural rotation of pelvis during turning is not supported in a repeatable manner. Turning can be initiated only by machine/therapists. Leg movement is not supported.

motor skill. However, the most evident deficits of the contemporary rehabilitation robots for walking are related to a lack of safe, adequately supported/controlled and stimulating training environment for 1.) Practicing proactive and reactive dynamic balance skills and 2.) Practicing abilities to initiate and execute turning during walking, which are both vital for safe and independent bipedal walking. It seems that in order to achieve the above two critical aspects of robot assisted rehabilitation of walking the future systems need to increase the number of DOFs to match those present in a human lower body such that movement of the lower limbs and the pelvis will be adequately supported /controlled in all three planes of motion.

3 Ongoing and Future Development

One possible design of an exoskeleton, which would enable movement in all three movement planes, is conceptually shown in Fig. 1a. The mechanism has in total 10 DOFs. In the hip of each leg there are three rotational joints that intersect in a single point that ideally should coincide with the biomechanical hip joint of a human, and then there is one rotational joint coinciding with the biomechanical knee joint and another translational joint performing ankle plantarflexion.

In the remaining of the Figure 1 possible DOFs of movement of a subject wearing the proposed exoskeleton are illustrated: Figure 1b shows hips abduction/adduction; Figure 1c shows hip flexion/extension; Figure 1d shows hip

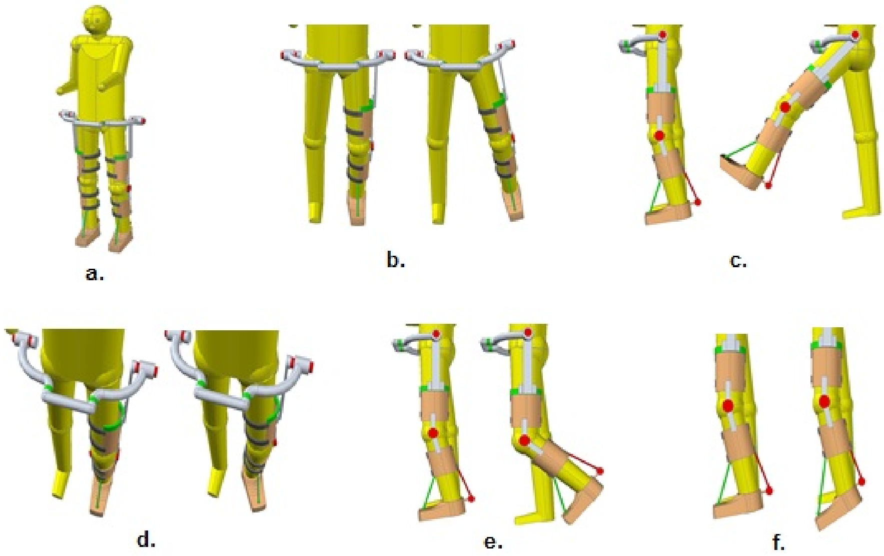

Fig. 1 Conceptual design of an exoskeleton enabling motion in all three planes

internal/external rotation; Figure 1e shows knee flexion/extension; Figure 1f shows ankle plantarflexion/dorsiflexion. These DOFs may be actuated or can be passive and gravity compensated by suitable spring arrangements. The conceptual mechanical linkage shown in Figure 1 has been used as a starting point in the development of an over ground walking rehabilitation robot within the EU 7FP project CORBYS. The exoskeleton is attached to a robotic mobile platform via a 4 DOF pelvis interface mechanism, which enables pelvic rotation in the frontal and transverse planes as well as pelvis vertical and side to side movement. All listed DOFs enable more physiological movement including turning, which is considerable step forward compared to the existing rehabilitation robots presented in Table 1. The CORBYS system has been constructed and assembled while the control modules including the “low-level” impedance-based control of the mechanism as well as “high-level” cognitive control modules are under the development.

The presented conceptual exoskeleton from Figure 1 enables/supports movement of the lower extremity in the frontal and transversal plane, thus enabling practicing of turning motion. Training of dynamic balance during walking may be also possible within presented concept, however clinical practice shows that powered exoskeletons may be suitable in the early stage of rehabilitation when physical support in the joint of lower extremity are necessary, while later when practicing of dynamic balancing and turning during walking becomes primary goal of rehabilitation, active support of an exoskeleton might no longer be a necessity.

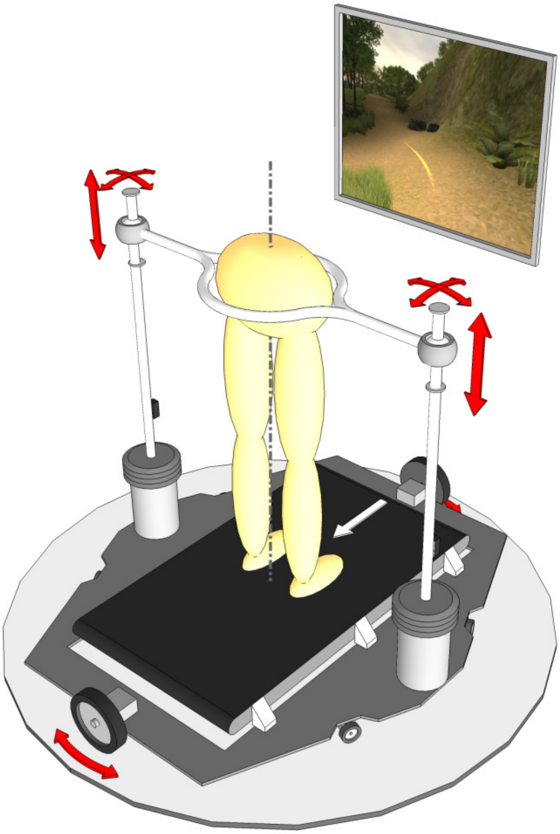

Fig. 2 Conceptual design of a rehabilitation robot for training dynamic balancing and turning while walking on a regular treadmill

Figure 2 shows a conceptual design of another rehabilitation robotic device, which is designed to target specifically dynamic balancing and turning training issues during walking. The key element of the system shown in Figure 2 is a pelvic support mechanism which is based on two parallel bars that are at the bottom connected to helical springs while at the top two hole-through spherical joint arrangements are used to connect with a pelvis support link. This passive mechanism has all six DOFs needed for physiological movement of the pelvis in space. Pelvis forward/backward, left/right and up/down translations are possible as well as pelvis tilt, list and rotation are enabled. The three DOFs are supported via visco-elastic forces provided by the helical springs: forward/backward translation, left/right translation and rotation of pelvis around the vertical axis. The remaining three DOFs are passive and enable unhindered motion of the pelvis. The helical springs are at the bottom tightened to a platform that has one DOF and enables rotation around the vertical axis. A regular treadmill is placed on the platform and a human subject is walking on the treadmill while being supported at the level of pelvis by the described mechanism. A virtual reality scheme that moves in accordance with the selected speed of treadmill provides a visual feedback to a walking subject, indicating also the curvature of the path. When a curved motion is indicated, also the rotation platform rotates for a given angle with selected angular velocity. In this way the presented stationary device to considerable extent emulates situation that occurs also during turning while walking over ground.

With the presented concepts shown in Figure 1 and 2 the possibilities for movement training may be considerably increased and are closely related to the way the rehabilitation robots are controlled. Control approaches may be traditional in a sense that robots based on various sensory inputs execute pre-determined actions. However, it seems that much more versatile training environment could be achieved if the control of rehabilitation robots would also poses a certain degree of “cognitive” capabilities. By this term we mean a capability of a device “to reason” and make appropriate decisions based on the behavior of a training subject assessed by various sensory systems, which can be distributed between the man (various physiological parameters) and machine (kinematic and kinetic parameters). Also, incorporation of a control scheme that can efficiently take into account dynamic balance maintenance of the man-machine system is one of the key challenges that need to be solved before a successful implementation of the proposed concepts can be expected. Research addressing specifically balancing aspects is currently underway in the EU 7 FP project BALANCE.

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