HapticWalker – haptic foot device for gait rehabilitation

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Introduction

The restoration of gait for patients with impairments of the central nervous system (CNS), like, e.g., stroke, spinal cord injury (SCI) and traumatic brain injury (TBI) is an integral part of rehabilitation. The rehabilitation of CNS impairments usually takes several months at minimum and its outcome often influences whether a patient can return home or to work. Particularly stroke is the leading cause for disability in all industrialised countries; the incidence is approximately one million patients in the European Union each year [1, 2]. Modern concepts of motor learning favour a task specific training, i.e., to relearn walking, the patient should ideally train all walking movements, needed in daily life, repetitively in a physically correct manner [3]. Conventional training methods based on this approach proved to be effective, e.g., treadmill training [4], but they require great physical effort from the physiotherapists to assist the patient – so does even more training of free walking guided by at least two physiotherapists. Assisted gait movements other than walking on even floor, like for instance stair climbing, are practically almost impossible to train, due to the overstrain of the physiotherapists. Robotic haptic gait training devices may offer a solution to fill this gap and lead to an intensified patient training plus a relief for the physiotherapists from strenuous work.

Different rehabilitation robotics research groups already developed a number of robotic gait rehabilitation devices with haptic features [5, 6], all of them are based on the exoskeleton principle and need to be operated in combination with a treadmill on which the patient walks. The exoskeleton robot then substitutes the physiotherapist and moves the patients' legs. Due to their operating principle, all of these machines are restricted to training of walking on even ground and do not allow physical interaction between patient and physiotherapist during training.

In contrast, it was a major goal of the HapticWalker project to develop a robotic walking simulator, which offers training of arbitrary and freely programmable foot motions. This lead to the development of a machine based on the principle of programmable footplates. On this type of machine the patients' feet are attached to two footplates, on which he stands. The footplates are located at the end-effectors of two robot arms which carry the patients' body weight and move his feet along the foot trajectories. In addition to daily life walking trajectories like walking on a plane floor or stair climbing, the machine dynamics should allow the simulation of asynchronous events, such as stumbling or walking on rough ground, which require high acceleration capability. For application in gait rehabilitation it is essential for the machine to provide a permanent foot attachment to the footplate, i.e., it needs to comprise foot support and guidance during all phases of the gait cycle (stance and swing phase).

Even though fully guided foot motions are needed for the most part of gait rehabilitation, due to the patients' lack of ability to perform voluntary leg motions, the machine support should be gradually reduced depending on his learning success. Thereby the machine should mimic the physiotherapist's behaviour of appropriately reducing the degree of assistance in later phases of the rehabilitation training.

The HapticWalker is equipped with force/torque sensors under each footplate in order to measure the contact forces between foot and footplate continuously. These force values are used for gait analysis purposes, as a measure for the patients' learning success, and for compliance control algorithms.

For the HapticWalker control software, it was necessary to develop algorithms for the simulation of arbitrary natural foot walking trajectories regarding position and velocity profiles, because classical robot motion commands would not be suitable to perform this kind of motion task. In addition, it was essential to develop an intuitive graphical user interface that allows safe programming and operation of the machine by nontechnical personnel such as physicians or physiotherapists. Therefore, appropriate algorithms for the intuitive synthesis of gait trajectories were developed.

Locomotion interfaces

The HapticWalker was designed as a generic haptic foot device, not only to be applied for gait rehabilitation, hence it belongs to the class of so-called 'locomotion interfaces'. Haptic locomotion interfaces allow walking and other foot movements within virtual environments. In order to present kinesthetic feedback to the foot during all phases of gait, these haptic foot devices need to comprise a permanent contact between the foot and the device. Such locomotion devices belong to the group of 'programmable footplates'; they present haptic foot sensations to the user, similar to hand haptic interfaces presenting haptic sensations to the hand. The main purpose of human foot movements is to move the body into a desired direction. Hence inside a virtual world the user could use a haptic foot device in order to navigate in this environment. During daily life a human performs different kinds of walking trajectories (e.g., walking on a plane floor, up/down staircases). This takes place on different types of terrain (even or rough ground); it could also happen that one trips over an obstacle and stumbles. A haptic foot interface should be able to simulate all these and other foot movements. So far only a very small number of haptic locomotion interfaces based on the principle of programmable footplates have been developed and built [7–12] or are under development [13]. Some of them do not have permanent contact between foot and footplate, but provide foot support only during stance phase. In contrast, the presentation of haptic sensations during swing phase or the application of tractive forces to the foot requires permanent foot attachment to the footplate. Values for footplate workspace and dynamics that have been published are rather small [11, 13] or only qualitatively given and indicate slow walking speeds [8, 10].

The goal of the HapticWalker project was to design and build a haptic foot device based on the principle of programmable footplates with permanent foot machine contact and high dynamics, in order to enable walking speeds up to 5 km/h and simulate walking situations requiring very high dynamics (e.g., stumbling).

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Gait analysis

The analysis of different walking trajectories was the major basis for the design of the HapticWalker. Motion capturing and analysis was done particularly for walking on even floor at speeds up to 5 km/h with cadences up to 120 steps/min and stepping staircases up/down at speeds up to 2.3 km/h and cadences up to 120 steps/min [14].

Gait data was captured using a ZEBRIS ultrasonic motion capture system (see Fig. 1a, c and e). Data processing was done using the method described in [15]. Figure 1b, d and f show the measured and transformed walking trajectories for walking on plane ground, walking up and down a staircase. A detailed trajectory analysis can be found in [14]. For the three DOF base module gait data was analysed in the sagittal plane, since all major foot movements occur in