

DEVELOPMENT ASPECTS OF A ROBOTISED GAIT TRAINER FOR NEUROLOGICAL REHABILITATION

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Abstract-The restoration of gait is a key goal after stroke, traumatic brain injury and spinal cord injury. Conventional training methods, e.g. treadmill training, require great physical effort from the therapists to assist the patient. After the successful development and application of a mechanised gait trainer, a new research project of constructing a sensorised robot gait trainer is under way.

The aim of this project is to build a robotic device which enables the therapist to let the machine move the patients feet, fixed on two footplates, on programmable foot trajectories (e.g. walking on the ground, stepping stairs up and down, disturbances during walking). Furthermore impedance control algorithms will be incorporated for online adaptation of the foot trajectories to the patients walking capabilities. Another important feature is the compliance control to simulate virtual ground conditions, i.e. the machine acts as a haptic foot device.

Due to the partially high dynamic foot movements during normal walking, conventional industrial robots are not suitable for this task. This paper describes development aspects and problems that have to be dealt with during the design process of the robotised gait training machine.

Keywords - gait rehabilitation, gait trainer, gait analysis, robot, compliance control

I. INTRODUCTION

Restoration of gait following stroke, traumatic brain injury and spinal cord injury is an integral part of rehabilitation and it often influences whether a patient can return home or to work. Modern concepts of motor learning favor a task specific training, i.e. to relearn walking, the patient has to walk repetitively in a correct manner [1]. Treadmill training with partial body weight support proved effective at restoring gait in chronic nonambulant subjects after spinal cord injury and stroke [2].

The major disadvantage of treadmill training is the great physical effort required by two therapists to ensure that the patient's gait is relatively normal throughout the training session of up to 25 minutes. Due to physical strain of the therapists the preciseness of the manually guided foot trajectory decreases the longer the training session lasts. Hence a robot gait training device supporting the therapists would enable longer training sessions in combination with much more precise foot trajectories, thus improving the learning success and relieve the therapists.

A first step towards a solution for this problem was the design, construction and successful application of a mechanised gait trainer by our group [3] and an exoskeleton robot gait trainer connected to a treadmill developed at the university hospital Balgrist, Switzerland [4].

One major disadvantage of treadmill training in general and also both new approaches is the limited variability of different gait parameters and possible training trajectories. In general on the treadmill the patient can only train walking on the plane ground, but not e.g. stepping staircases up and down. It is desirable to let the patient train as many walking situations as possible, he or she will be confronted with in the real world outside the rehabilitation clinic. Therefore it is also desired to be able to train not only relatively smooth walking trajectories, but also to have the possibility to train "unpredictable" but real walking situations, e.g. walking on rough surfaces or slight stumbling.

These desired features of a robotic gait training device from the medical point of view have to be translated into technical requirement specifications and lead to a new type of universal walking simulator for neurological rehabilitation. This paper describes technical insights resulting from an extensive simulation process during the design phase of the robotic gait training device and focuses on the kinematic requirements.

In addition to the foot device a separate device to support the upper body of the normally wheelchair bound patients is needed. Such a device, that must be perform controlled movements in synchronisation with the foot device is under development as well. This paper focuses on the robotic foot device.

II. GENERAL DESIGN

The aforementioned desired main features of the robotic gait trainer from the medical point of view are as follows:

- each of the patients feet shall be attached to a movable footplate. The footplate must be able to carry the patients weight (approx. 100kg) at any time, especially during the stance phase
- the robotic gait trainer shall move the patients feet on different programmable foot trajectories at walking speeds up to 5 km/h: plain ground, stairs up/down, rough ground, stumbling
- the therapists access to the patient shall not be impeded by the robotic gait trainer. The machine shall be compact so it can be easily installed in different places in a rehabilitation clinic without constructional changes, e.g. building or moving walls, grounds or ceiling
- the foot trajectory parameters shall be freely programmable by the therapist and adjustable to every patient
- the patient shall be given the feeling of free walking as he/she relearns walking. He/she shall feel hard ground during the stance phase and air during the swing phase of

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the foot in order to train independent balancing on both feet.

This results in the following technical requirement specifications:

- each of the two manipulators must be able to carry a payload of approx. 100kg during all static and dynamic phases of the foot trajectory
- each manipulator must least support 3 degrees of freedom (DOF) in order to move the feet within the sagittal plane (main DOF of the foot), with an extensibility option to 6 DOF in order to enable natural walking in 3D space (a seventh DOF is necessary to support the metatarsal joint movement). The manipulator endeffector must be equipped with highly dynamic drives, preferably direct drives, in order to achieve a high bandwidth of the endeffector movement. This is especially necessary to simulate walking on rough ground and stumbling. The manipulator arm segments must consist of rigid links with low mass and inertia.
- the kinematic design options are very much restricted, i.e. the manipulator must be located behind or beneath/under the patient. This leads to a mainly serial manipulator because of the good workspace/manipulator volume ratio. Parallel kinematic concepts, ideally suited for movement simulators with high payload and very high dynamic range, cannot or only partially be applied, due to the low workspace/manipulator volume ratio.
- the manipulator must be equipped with an advanced robotic control unit that is able to control the secure and coordinated movement of 2 manipulator arms. Security and emergency issues play an important role since the patients feet are permanently fixed to the robot manipulators during the training session. A user interface is necessary that can be operated by non-technicians, in particular the physiotherapists.
- multidimensional force sensors must be mounted under the footplates in order to detect the forces generated by the patient during all phases of gait. Based on this sensor data, force control algorithms, especially sophisticated compliance control algorithms, must be developed and implemented in order to be able to simulate virtual ground conditions. The force data in addition to the position data from the position sensors mounted on each drive can also be used for biofeedback and diagnostic purposes.

When starting the design process, first of all foot trajectories from natural walking have to be analysed in order to determine the exact kinematic and requirements for the robot manipulator. As an example the analysis of two foot trajectories is shown here: walking on the ground at a velocity of 5 km/h / cadence of 120 steps/min and walking up a staircase at 2.3 km/h / 120 steps/min.

The data for walking on the ground is taken from literature [6], the data for walking up a staircase was measured in our department using a ZEBRIS ultrasonic motion capture system.

III. FOOT TRAJECTORY ANALYSIS

A. Ground Walking

Fig. 1 shows the a parametric plot of a foot trajectory during one stride sampled with a frequency of 70 Hz starting with heel contact. The solid line shows the metatarsal trajectory.

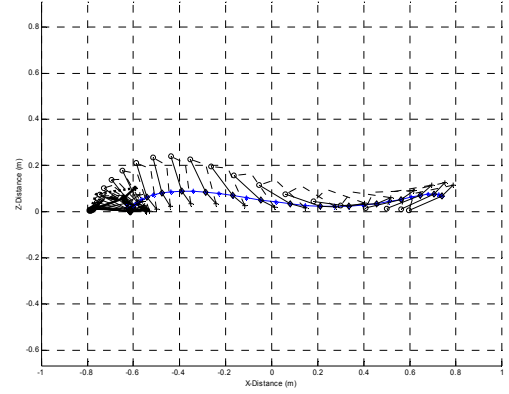


Fig. 1. Foot trajectory during one stride when walking on plane ground as seen from a fixed external observer (° = Heel, ◇ = Metatarsal, + = Toe)

On a stationary gait training machine we would have a similar situation as on a treadmill: the upper body including the hip is mainly fixed to one position in world coordinates whereas the ground moves relative to it. Fig. 2 shows a parametric plot of this relative foot trajectory. This would be the trajectory to be programmed as a reference trajectory for the robot gait trainer for training walking on the ground

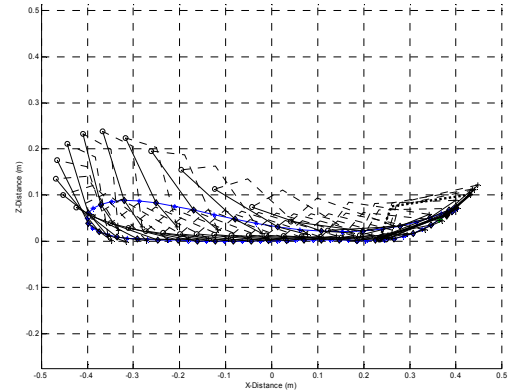


Fig. 2. Foot trajectory during one stride when walking on plane ground as seen from an external observer moving with hip velocity in X direction (° = Heel, ◇ = Metatarsal, + = Toe)

Fig. 1 and 2 show that the foot moves about two different centers of rotation during stance phase. After heel contact the first center of rotation lies in the heel and the foot moves approx. 30° about it. The second center lies in the metatarsal joint/toe region where the rotation angle is about 75°.

One aim during the design of a robot manipulator should be the minimisation of necessary joint movements during a trajectory. Hence the Tool Center Point (TCP) of the robot

manipulator carrying the footplate should lie in the Metatarsal joint. Thus the compensation movements of the other joint motors when rotating the TCP around the other center of rotation (Heel) is small.

Another observation from Fig. 2 is that the minimum TCP workspace for this trajectory must be approx. 80cm in X direction and approx. 10cm in Z direction at minimum for normal ground walking trajectories. The workspace length in X direction must be approx. 1.15 times half the stride length.

The following figures show velocity and acceleration profiles from Fig. 2 for one stride.

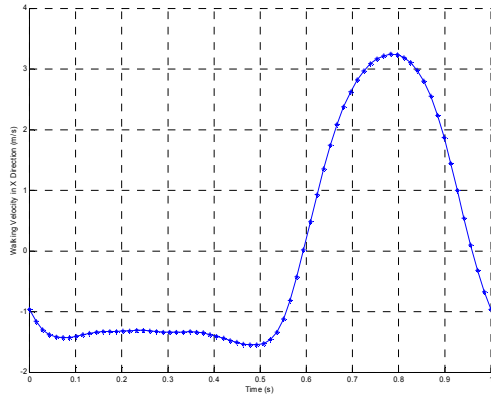


Fig. 3. Walking Velocity in X Direction vs. Time during one stride

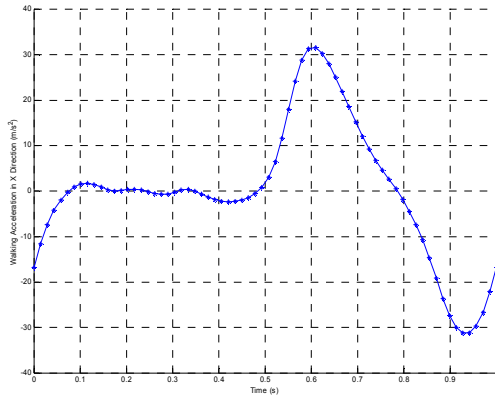


Fig. 4. Walking Acceleration in X Direction vs. Time during one stride

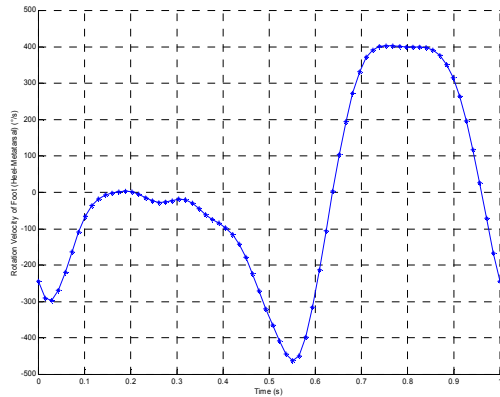


Fig. 5. Rotation Velocity of Foot (Heel-Metatarsal) vs. Time during one stride

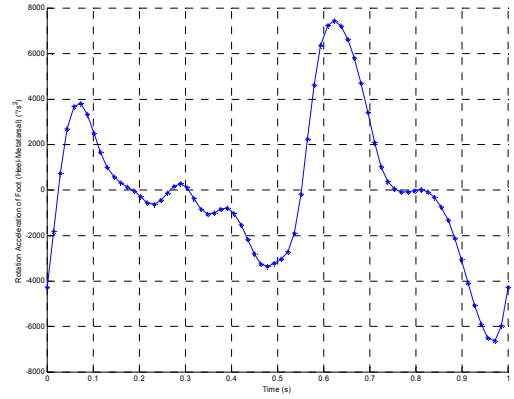


Fig. 6. Rotation Acceleration of Foot (Heel-Metatarsal) vs. Time during one stride

The peak values for translatory and rotatory TCP movements of each robot endeffector are:

$$v_{\max, \text{translatory}} = 3.25 \text{ m/s} \quad (1)$$

$$a_{\max, \text{translatory}} = 31.6 \text{ m/s}^2 = 3.22 \cdot g \text{ (} g = 9.81 \text{ m/s}^2 \text{)} \quad (2)$$

$$v_{\max, \text{rotatory}} = -462 \text{ }^\circ/\text{s} \quad (3)$$

$$a_{\max, \text{rotatory}} = 7450 \text{ }^\circ/\text{s}^2 \quad (4)$$

The velocity and acceleration peak values for the translatory movement in Z direction are lower than those in X direction.

These values match very close to measurements published in [9]. The stride length of approx. 1.4m from Fig. 1 lies in the range of values published in [7, 8].

B. Walking up a staircase

Fig. 7 shows the parametric plot of a foot trajectory during one stride (= two stairs) sampled with a frequency of 50 Hz starting with Metatarsal contact. The solid line shows the metatarsal trajectory.

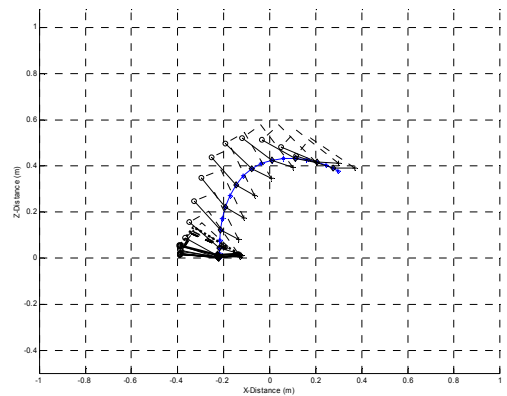


Fig. 7. Foot trajectory during one stride (= two stairs) when walking up a staircase ground as seen from a fixed external observer ($\circ$ = Heel, $\diamond$ = Metatarsal, $+$ = Toe)

For programming this trajectory on a stationary gait training machine where the patient does the training with his/her hip fixed, we need to calculate the hip relative trajectory. Then

the ground moves relative to the hip. Fig. 7 shows this trajectory.

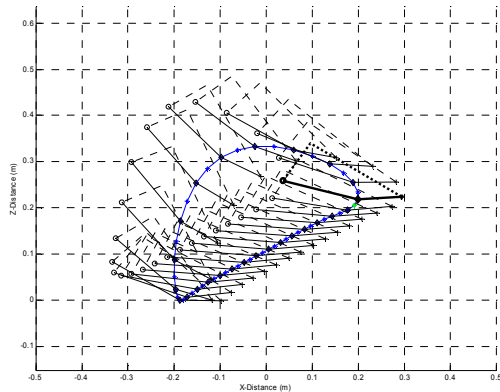


Fig. 8. Foot trajectory during one stride (= two stairs) when walking up a staircase as seen from an external observer moving with hip velocity in X and Z direction
(° = Heel, ◇ = Metatarsal, + = Toe)

Figures 7 and 8 show that the minimum TCP workspace for this trajectory must be approx. 40cm in X direction and approx. 35cm in Z direction at minimum for normal ground walking trajectories.

The velocity and acceleration peak values for the translatory movements in X and Z directions as well as for the rotatory movement are lower than those for walking on the ground.

C. Technical Specifications

The analysis of both trajectories shows that a TCP workspace of at minimum approx. 80cm in X direction and approx. 35cm in Z direction is needed for the robot gait trainer to enable training of ground level and staircase trajectories. The necessary performance values for TCP velocity and acceleration are shown in Equations (1)-(4). The TCP payload must be greater or equal than 100kg.

D. Possible Solutions

A market survey of conventional industrial robots with a payload of approx. 100kg from different manufacturers showed that none of them would fulfil the dynamic requirements of Equations (1)-(4) due to severe limitations in the joint velocities as well as accelerations. The maximum walking velocity that could be achieved with industrial robots would be approx. 1.25 km/h.

Hence there is the need to find a special kinematic design in combination with appropriate drive modules for this task.

IV. CONCLUSION

A robotised gait training machine is an ideal device to support the therapists during training sessions with neurological rehabilitation patients (after e.g. stroke, spinal cord injury). It offers the opportunity to enhance the training

duration and variability, especially the training of more real world walking situations.

On a robotised gait trainer the patients feet are fixed on two footplates, which move the feet on programmed walking trajectories (e.g. walking on plane ground, stepping stairs up/down). The footplates are moved by two separate robot manipulators. Depending on the dynamic range of the kinematic structure and joint drives, it is possible to simulate foot movements with even higher dynamics (e.g. walking on rough ground, stumbling). From the neurological point of view such perturbations are desired in order to stimulate the nervous system appropriately.

The therapist needs permanent access to the patient in order to control the training session. This imposes a number of constraints concerning the kinematic design of such a robot manipulator.

The design of this robotic device requires intensive investigation of different gait trajectories in order to determine the design parameters. In order to fulfil these requirements, a high performance robotic system is needed. Conventional 6-DOF industrial robots with a payload of approx. 100kg are not able to fulfil these performance requirements. Hence the development of a especially designed robotic system is currently under way.

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