

# Adaptive Locomotor Training on an End-Effector Gait Robot

Evaluation of the ground reaction forces in different training conditions

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**Abstract**— The main goal of robotic gait rehabilitation is the restoration of independent gait. To achieve this goal different and specific patterns have to be practiced intensively in order to stimulate the learning process of the central nervous system. The gait robot G-EO Systems was designed to allow the repetitive practice of floor walking, stair climbing and stair descending. A novel control strategy allows training in adaptive mode. The force interactions between the foot and the ground were analyzed on 8 healthy volunteers in three different conditions: real floor walking on a treadmill, floor walking on the gait robot in passive mode, floor walking on the gait robot in adaptive mode. The ground reaction forces were measured by a Computer Dyno Graphy (CDG) analysis system. The results show different intensities of the ground reaction force across all of the three conditions. The intensities of force interactions during the adaptive training mode are comparable to the real walking on the treadmill. Slight deviations still occur in regard to the timing pattern of the forces. The adaptive control strategy comes closer to the physiological swing phase than the passive mode and seems to be a promising option for the treatment of gait disorders. Clinical trials will validate the efficacy of this new option in locomotor therapy on the patients.

**Keywords**- gait rehabilitation; adaptive control; robotics; computer dyno graphy

## I. INTRODUCTION

Gait rehabilitation aims at the restoration of independent gait and at the improvement of walking functions. Modern concepts of motor rehabilitation favor a task-specific repetitive training, i.e. who wants to relearn walking, has to walk [1].

The strategy of gait rehabilitation is based on stimulating the central nervous system by activating the muscles during the training. A high training intensity and the specificity of movement patterns are the fundamental factors which affect the outcome of the rehabilitation treatment [2]. To reach this high training intensity gait machines have been developed, either following the end-effector [3] or the exoskeleton design principle [4]. The clinical feasibility and efficacy of repetitive task specific locomotor training has been proved for different kinds of neurologic gait disorders for both design principles, e.g. stroke [5], [6], spinal cord injury [7], [8] and infantile

cerebral palsy [9], [10]. Several robotic devices intended for locomotor therapy followed for the end effector and for the exoskeleton principle [11]-[14]. This gait machines offer the possibility to practice up to 1.000 steps per therapy session, but are limited only to walking on the floor. Stair climbing, and descending, however, is an integral part of everyday mobility [15].

The Haptic Walker was the first rehabilitation robot, which allowed the repetitive practice not only of floor walking, but also of stair climbing and stair descending, by means of fully programmable foot plates [16]. Subsequently other end-effector gait rehabilitation robots with fully programmable foot plates were developed: the G-EO Systems [17] and the 6 Degrees of Freedom (DoF) Gait Rehabilitation Robot [18].

A frequent objection to the end-effector gait rehabilitation robots is the lack of a true swing phase during the gait cycle. To allow a physiological swing phase without end-effector support to the foot, a series of different adaptive control algorithms were developed [19].

The aim of the present work is to analyze the ground reaction forces in three different conditions: real walking on a treadmill, passive walking on the gait robot and adaptive walking on the gait robot. The analysis of the ground reaction forces should show the forces applied during the whole gait cycle, allowing therefore a quantitative and qualitative evaluation of the effective support given by the robotic end-effector during both, the stance phase and the swing phase.

## II. METHODS

### A. Gait Robot

The device chosen was the G-EO Systems rehabilitation robot (Reha Technologies, Italy). It allowed to secure the subjects with a harness while they stood on the foot plates of the machine. The foot plates had 3 DoF each, allowing to control the length and the height of the steps and the foot plate angles. The maximum step length corresponded to 550 mm, the maximum achievable height of the steps was 400 mm, the maximum angles were  $\pm 90^\circ$ . The maximum speed of the foot plates was 2,3 km/h.



Figure 1. The G-EO Systems gait robot.

A safety binding ensured the safety of the subjects under test: the binding opened and the machine stopped immediately for wrong trajectory settings

Two further DoF controlled the body weight support system and the lateral displacement of the hip. The graphic user interface (GUI) showed the actual trajectory, so that the therapists were able to control and to correct it. Changes could be made for step length, step height, the terminal stance and the initial contact inclination angles of the feet, the vertical and the lateral excursions of the CoM, and for the relative position of the suspension point with respect to the foot plates. The computer saved the trajectory settings.

The adaptive control was applied only to both of the 3 DoF intended to control the legs. The remaining 2 DoF for the control of the centre of mass were excluded from being master in the adaptive mode. The device provided different kinds of adaptive control, the following one, called Force Level, was chosen: The necessary force for moving the foot plates along the selected trajectory settings was set by a Force Level slider in the GUI. Raising the required Force Level value raised the mechanical resistance to movement of foot plates, lowering the Force Level slider to zero put the footplates and the mechanics of the G-EO Systems to virtual zero friction. Once the intended Force Level was reached, there could be amplification to the movement, according to the value of the Amplification Level selected in the GUI. The Amplification Level provided for additional acceleration while executing the movement of the foot plates along the selected trajectory. By adding acceleration to the necessary force for moving the foot plates lowered. This provided a smooth and continuous movement of the foot plates.

### B. Treadmill

The treadmill used was a TRAC 60 E slat-belt treadmill for locomotion therapy, which allowed to control up to extremely slow speeds (Sprintex, Germany). It had a display for speed, time distance and pulse. Furthermore the treadmill had a body weight support system and a harness.

### C. Measures

The Ultraflex CDG analysis system consisted in a pair of two overshoes containing each 8 capacitive sensors (Infotronic, The Netherlands). The overshoes were connected to the data logger of the CDG analysis system. The CDG analysis system was able to record the vertical ground reaction forces for every sensor in both overshoes during the whole gait cycle for the whole test period. The sensors did not provide data of horizontal forces. After the acquisition, the recorded data were downloaded to a computer, where the software of the CDG analysis system did all the data elaboration. The software provided the temporal parameters for the various phases of the gait, like stance phase, swing phase and single /double support duration, velocity, gait cycle duration, cadence, gait symmetry. The dimensions of interest for the analysis were defined as follows:

- **Force Threshold:** the software allowed for setting the value of the force threshold for determination between the stance and the swing phase. A high value of the Force Threshold occurs if the stance phase is not easily distinguishable from the swing phase, e.g. if there is a residual bias of the capacitive sensors or if there is a continuous contact of the feet to the ground or foot plate of an end effector gait robot. A low value indicates an easily detection of stance and swing phase, i.e. there is only few or no contact at all with the real/virtual ground. The Force Threshold value was chosen considering to reach the best gait symmetry value displayed by the software. By changing the value of the Force Threshold, the gait symmetry value also increased or decreased. The Force Threshold value was changed until the gait symmetry value displayed by the gait analysis software was as close as possible to a gait symmetry value of 100%. This was made as the gait robot has perfect gait symmetry and should induce a perfect symmetry on the subjects under test.
- **Mean Force Graphics:** This metric represents the mean of all gait cycles of the vertical reaction forces, summed over all sensors of one foot, displayed as a function of time. It only represents the stance phase as forces can only be measured during the stance phase. The CDG Force analysis of the swing phase was not possible for there were ideally no forces to represent during the real and the robotic swing phase. In case of bias or permanent contact to the footplate, the . The values of the Mean Force Graphics were computed automatically by the CDG software.

### D. Subjects under Test

Eight healthy volunteers participated. None of them had neither orthopedic diseases impairing their gait ability, nor cognitive or communicative disorders. All of them understood the purpose of the present work and gave their written informed consent for participation. Before starting the Test Protocol, they had a session on the treadmill and on the gait robot to get acquainted to the devices and the different conditions of the test.

TABLE I. DEMOGRAPHIC DATA AND TEST RESULTS

Subject	Data				
	Gender	Age [years]	Treadmill [N]	Passive [N]	Adaptive [N]
1	Male	28	12	54	27
2	Male	25	15	58	30
3	Female	30	18	60	25
4	Male	27	14	72	31
5	Male	28	20	48	28
6	Male	30	13	63	29
7	Female	24	11	78	32
8	Female	26	16	52	27
<b>Mean</b>	3 <sup>a</sup>	27,25	14,87	60,62	28,62
<b>Standard Deviation</b>	5 <sup>b</sup>	2,18	3,04	10,15	2,32

a. Value is not a mean, but the total number of female participants

b. Value is not a standard Deviation, but the total number of male participants

### E. Test Protocol

The volunteers were analyzed in the following three conditions:

- Floor walking on the treadmill: The subjects walked on the treadmill at a velocity of 2,3 km/h. A metronome helped for pacing correctly a cadence of 70 steps/min. There was no body weight support; the harness was put on for safety reasons only. While walking at the given speed on the treadmill the CDG analysis system recorded 30 seconds of gait.
- Passive floor walking: The subjects walked on the gait robot in Passive Mode. The selected trajectory was floor walking at a velocity of 2,3 km/h and a cadence of 70 steps/min. There were no modifications made to the standard gait trajectory [17]. There was no body weight support; the harness was put on for safety reasons only. The volunteers were told to let themselves be guided by the gait robot, without applying any resistance on the foot plates. While walking with the given settings the CDG analysis system recorded 30 seconds of gait.
- Adaptive floor walking: The subjects walked on the gait robot with the Adaptive Mode set on Force Level. The Force Level was set to 0, so that there was no mechanical resistance at all to the movement of the volunteers along the given trajectory. The Amplification Level was set to 0. The selected trajectory was floor walking with the same step length as for passive floor walking. A metronome helped for pacing correctly a cadence of 70 steps/min, so that the resulting gait velocity was the same as in the two other conditions. There were no modifications made to the standard gait trajectory. There was no body weight support, the harness was put on for safety reasons only. The volunteers were told to walk the gait robot by themselves. While walking with the given trajectory settings the CDG analysis system recorded 30 seconds of gait.

TABLE II. MEAN FORCE GRAPHICS DATA

Subject	Initial response		
	Treadmill [N]	Passive [N]	Adaptive [N]
1	596	530	603
2	626	500	623
3	726	450	693
4	745	602	723
5	636	503	613
6	736	569	723
7	784	489	792
8	656	532	667
	Mid Stance		
	Treadmill [N]	Passive [N]	Adaptive [N]
1	536	493	530
2	566	463	553
3	670	413	637
4	685	565	653
5	600	466	577
6	676	532	653
7	724	452	722
8	596	495	597
	Terminal Stance		
	Treadmill [N]	Passive [N]	Adaptive [N]
1	591	502	538
2	621	492	528
3	711	450	558
4	740	534	598
5	641	475	548
6	758	542	547
7	779	482	527
8	656	526	562

### F. Data Analysis

The collected data of the three Test Conditions of the variables under analysis were compared using a 1-way analysis of variance (ANOVA) with p-value set lower than 0.05. A Post-Hoc analysis was carried out by the Tukey HSD Test.

## III. RESULTS

Table 1 shows the demographic data and the values of the Force Thresholds which had resulted in the best gait symmetry. The test enrolled a total of eight volunteers, three of them were female, and five of them were male. Their mean age was 27,25 years, the deviation from the standard age was 2,18 years.

The values of the Force Threshold varied across the subjects

for the same test condition and across the different training conditions. For the floor walking on the treadmill the mean force Threshold was of 14,87 N, with a standard deviation (SD) of 3,04 N. On the gait robot the passive floor walking condition had a mean value of 60,62N, with SD of 10,15 N, while the adaptive mode had a mean Force Threshold of 28,62 N and SD of 2,32 N. The ANOVA showed a  $p < 0.0001$ , The Tukey HSD Test revealed the group comparisons as significant with  $P < 0.01$  for all the three group comparisons.

Figure 2 shows the mean gait forces during the gait cycle for one of the subjects under test. A qualitative analysis of the gait forces evidenced the same differences in force application patterns between the three walking conditions for all the volunteers. For the floor walking on the treadmill condition the ground reaction force increased rapidly with a small overshoot at loading response, remained constant during the whole stance phase and decreased rapidly after the terminal stance. For the passive floor walking condition the ground reaction force raised like in the treadmill condition, but did neither have an overshoot at loading response neither a plateau during the stance phase. The ground reaction force decreased gradually from loading response to terminal stance. At the terminal stance the decrease stopped and the force was kept constant. After the terminal stance the ground reaction force decreased rapidly like in the treadmill condition. In the adaptive mode the force increased like in the passive mode. There was an overshoot at loading response and the ground reaction force stayed constant after the loading response like in the treadmill condition. The duration of the force plateau was shorter than in the treadmill condition. After this plateau the forces decreased gradually and the pattern was similar to the passive mode.

Table 2 shows the values of the Mean Force Graphics for the Initial Response, Mid Stance and Terminal Stance for all 8 subjects. The ANOVA on the Initial Response showed a  $p < 0.0001$ , the Tukey HSD Test revealed the comparisons as significant with  $p < 0.01$  for the comparison between Floor walking on the treadmill and Passive floor walking and for the comparison between Passive floor walking and Adaptive Floor Walking. The comparison between Floor walking on the treadmill and Adaptive floor walking was nonsignificant. For the Mid Stance the ANOVA showed a  $p < 0.0001$ . The Tukey HSD Test revealed the comparisons as significant with  $p < 0.01$  for the comparison between Floor walking on the treadmill and Passive floor walking and for the comparison of Passive floor walking and Adaptive Floor Walking. The comparison between Floor walking on the treadmill and Adaptive floor walking was nonsignificant. The ANOVA on the Terminal Stance showed a  $p < 0.0001$ , the Tukey HSD Test revealed the between group comparisons as significant with  $P < 0.01$  for the comparison between Floor walking on the treadmill and Passive floor walking and for the comparison between Floor walking on the treadmill and Passive floor walking. The comparison between Passive floor walking and Adaptive Floor Walking was nonsignificant.

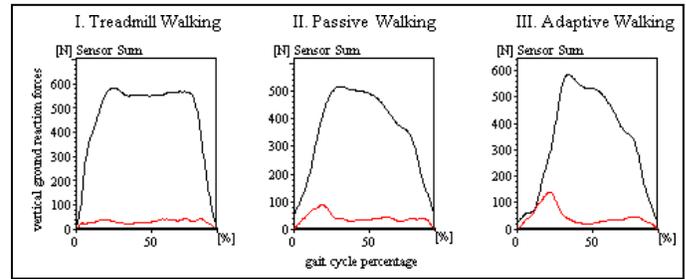


Figure 2. Representation of the mean gait forces for the three test conditions: floor walking on the treadmill (I), floor walking on the gait robot in passive mode (II) and floor walking on the gait robot in adaptive mode (III).

The vertical ground reaction force amount varied across the subjects. The values were related closely to the body weight of the volunteers, i.e. a higher body weight resulted in a higher ground reaction force. Therefore it had no sense to calculate the mean and the SD of vertical ground reaction forces of the subjects under test.

#### IV. DISCUSSION

The differences in the Force Threshold values for the three testing conditions can be explained as follows: For the treadmill condition, the feet of the volunteers were able to move freely. Therefore the threshold for the detection of the loading response was very low. The minimum value on the software is of 10 N, lower values cannot be represented by the CDG analysis system. The value chosen is not the minimum value of detection, but the value that ensures the best gait symmetry value. Therefore the value of the Force Threshold differed from the minimum detectable force value. The passive mode had the highest value of the Force Threshold and the highest SD. It follows that there is effectively a support of the leg during the swing phase. The volunteers were asked to let themselves be guided by the machine, so that the robotic device carried part of the body weight also in the swing phase. The higher SD may be due to some residual resistance of the volunteers, although they tried to stay completely passive. The Force Threshold values for the adaptive mode were twice the values of the treadmill condition and half as much as the passive condition. The support of the leg during the swing phase was therefore significantly reduced, but does still not match completely the values of real gait during the swing phase.

The qualitative and the quantitative analysis of the force graphics revealed comparable ground reaction forces and force application patterns for the treadmill condition and the adaptive condition from loading response to mid stance. From mid stance to terminal stance the adaptive condition was comparable with the passive condition. In the adaptive condition the subjects under test were able to move the leg freely like in the treadmill condition. The impact on the real and the virtual ground was harder than in the passive mode, where the leg was guided through the swing phase as well. The harder ground impact for the treadmill condition and the adaptive condition may be the cause of the comparable overshoots at loading response. After the mid stance the ground

reaction forces move towards the fore foot. As the foot plates of the gait robots lack of control of the metatarsophalangeal articulation, the intensity of the forces decreases gradually and there is no possibility of a toe clearance as in the treadmill condition. The smaller ground reaction forces measured for the passive condition can be explained again by the subjects being guided by the machine. As the machine supported the legs in both, the swing phase and the stance phase, the approach to the loading response was less hard than in the other conditions. Furthermore, as the stance leg was in mid stance, the other leg was supported by the gait robot, relieving therefore part of the body weight, which again resulted in smaller ground reaction forces for the stance leg.

The force graphics of all the three test conditions differed from the classic M-Diagram described in the literature [20]. This is due to the fact that the gait velocity of the testing conditions was lower than the physiological self selected speed of healthy subjects, but it was accepted as reasonable, as it was the maximum available speed of the gait robot.

## V. CONCLUSIONS AND FUTURE WORK

The present work introduced the adaptive mode of an end-effector based gait robot. A CDG analysis between real, passive and adaptive conditions showed differences in the Force Graphics. The causes can be due to the control mode or to design issues of the foot plate. The adaptive mode has shown to allow a ground reaction force patterns and ground reaction force intensities which are comparable to the real condition.

Future works should concentrate on the gait rehabilitation of impaired patients, as it is the intended use of the robotic gait device. A controlled trial on ambulatory patients between treadmill training with body weight support and the G-EO Systems in adaptive control mode lays on the hand.

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