FORCE MEASUREMENT DURING GAIT THERAPY ASSISTED BY A ROBOTIC TREADMILL

The Case of Lokomat®

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Abstract: The present paper deals with force measurement during gait therapy assisted by a special robotic treadmill with driven robotic orthoses that guide inferior limbs movements. The objectives, the measurement setup and the results are presented. This work has been carried out in order to gather data necessary to begin the analysis and the design of a new ankle motion device. The presented results also show how these measurements can be useful in gait parameters assessment and patient's muscle activity level.

1 INTRODUCTION

Nowadays mechanical measurements give a valid and important aid in the rehabilitation field, both for the design of specific devices and for the development of suitable data analysis techniques. Different types of sensors can be fixed on the rehabilitation machines (Comolli et al., 2005), and particular wearable sensors allow to perform the measurements directly on the patient's body, e.g. the acceleration of body segments during gait (Zijlstra, 2003). Mechanical measurements can be useful to properly set-up the rehabilitation device parameters or to evaluate the patient's conditions during rehabilitation sessions (Melis et al., 1999).

This paper deals with force measurements applied to the case of locomotion therapy assisted by a specific robotic treadmill, the Lokomat®. This is a rehabilitation device composed of a driven robotic gait orthosis that guides the patient's legs on a treadmill while a desired percentage of the body weight is sustained by a special support system. The patient is sustained while his hips, thighs, knees and legs are actively guided during the entire gait cycle, therefore reproducing a physiologic movement. The feet are instead passively pulled with a spring-belt system: consequently ankles and feet follow non "natural" trajectories and do not reproduce the actual human walking. The foot sustainment is strictly necessary to avoid the patient to stumble. Even if this eventuality wouldn't represent a danger for the patient's health because of the presence of suitable security devices, it would cause the system emergency stop to avoid the patient to fall, thus interrupting the rehabilitation session. The growing interest around this topic and the study of possible solutions are the starting point of the present work. The internal forces exchanged between the patient and the Lokomat® have been measured in order to analyze the mechanical behaviour of the utter system (human and mechanical), and to investigate the forces transmission from the suspension system to the ground and vice versa. This knowledge is the basis to upgrade the ankle motion system allowing a better control and a more physiological ankle movement. This paper describes the design of the tests, the experimental set-up and the obtained results. The analysis of the results has allowed to get information about the patient's working conditions. The achieved data have also been the inputs in order to design an innovative prototype device able to control the ankle motion (Bucca et al., 2008). The possibility of the patient's conditions evaluation and the rehabilitation parameters assessment have been therefore investigated in the paper.

Force measurements during patients' rehabilitation sessions have been performed using suitable transducers (load cells) expressly built and calibrated. These have been installed between the patient and the Lokomat® frame. The body weight sustaining force and the left/right foot pulling force have been measured during the assisted gait, both for an healthy subject and for an actual patient.

2 MEASUREMENT SETUP

This paragraph describes in detail the measurement setup, the installed sensors and the Lokomat® system.

The Lokomat® rehabilitation device (Figure 1) is essentially composed by three parts:

1. a hip support system that sustains a desired percentage of the patient's weight;
2. two electrically driven leg orthoses;
3. a passive spring-belt system that pulls and drives the feet.

Figure 1: view of Lokomat® (with the courtesy of Hokoma, from website www.hocoma.ch).

The body weight support system allows the therapist to set the counterweight that sustains the patient during the gait, accordingly to the medical directions. This parameter setup is crucial because it influences the rehabilitation session effectiveness and therefore the patient's progresses. During the gait the patient is submitted to dynamic forces, which have been measured and analyzed using suitable techniques. In order to perform this goal, a specific load cell (diameter 90 mm, thickness 5 mm, depth 30 mm, output sensitivity 7.69 mV/N) has been installed between the cable and the pin that pull the system frame (Figure 2). In the following it will be referred as the sensor N. 5.

Because of the main interest toward the feet pulling system, other transducers have been installed to measure the involved internal forces. Four load cells (diameter 45 mm, thickness 2 mm, depth 20 mm, sensitivity 20 mV/N), have been inserted between the springs and the belts that pull up the feet. Sensor N. "1" and "2" have been installed on the left side, "3" and "4" on the right one (Figure 3).

All the load cells are not commercial products but have been designed and realized for this specific application. The transducers incorporate an aluminium cell ring as the elastic element. Four strain gauges, located as shown in Figure 4, are used as sensors able to measure the strains due to the force (extension or compression) acting along a diameter.

Figure 2: sensor number 5.

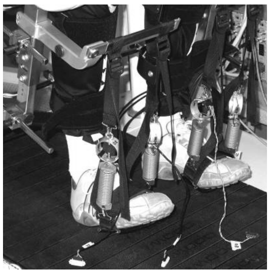

Figure 3: sensors number 1-2 (left leg), 3-4 (right leg).

The strain gauges are connected in a full Wheatstone Bridge. The arrangement allows the thermal compensation. The bandwidth is 0-20 Hz.

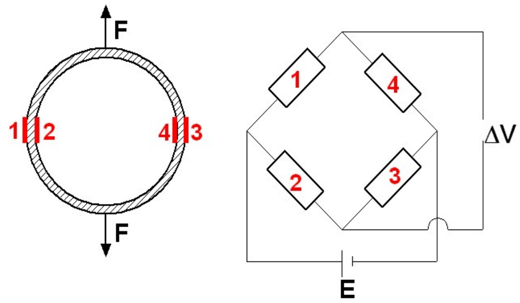

Figure 4: mechanical and electrical design of the load cells.

All the output voltage signals have been acquired with a National Instruments Acquisition System, using a 12 bit PCMCIA DAQ card and a notebook for data storing.

3 TEST DESCRIPTION

Several tests have been carried out in two different conditions:

1. during the gait of a 65 kg healthy person, with no specific pathology (it will be referred as the *"normal"* condition);
2. during the gait of a patient with a specific motor disability.

In the first case (healthy subject) different speed and counterweight conditions have been tested, and are listed below:

- gait speed of 1.5 km/h and 2 km/h;
- counterweight of 20 kg and 35 kg;
- active and passive gait: in the active session the subject was asked to walk in normal conditions, therefore using his muscles at 100% and contrasting the Lokomat® resistance; in the passive session he was asked not to use his muscles, being completely transported and guided by the Lokomat® orthoses.

In the second case (real injury condition) a Spinal Cord Injury (SCI) patient has been monitored during a usual rehabilitation session. Because of the specific pathology he was almost unable to use the left leg but not the right one. Considering that the patient used to have his gait sessions at 2 km/h with 40 kg of counterweight, two different speed parameters have been tested (1.5 km/h and 2 km/h), and he was asked to walk both passively and actively. In order to prevent negative effects on the patient's rehabilitation sessions, only the usual 40 kg counterweight has been tested.

4 RESULTS

This paragraph presents the results obtained in the most meaningful tests for both test conditions.

4.1 "Normal" Conditions

A first effective analysis can be performed analyzing the data obtained from the sensor N. 5 (the one measuring the body sustaining dynamic force).

Figure 5 shows the force time histories 30 s long, measured in the following conditions:

a) subject standing and suspended;
b) subject walking suspended;
c) subject walking leant with 35 kg counterweight;
d) subject walking with 20 kg counterweight.

The measured forces, except obviously the case of standing subject (a), present a periodic shape due to the alternate left and right foot contact.

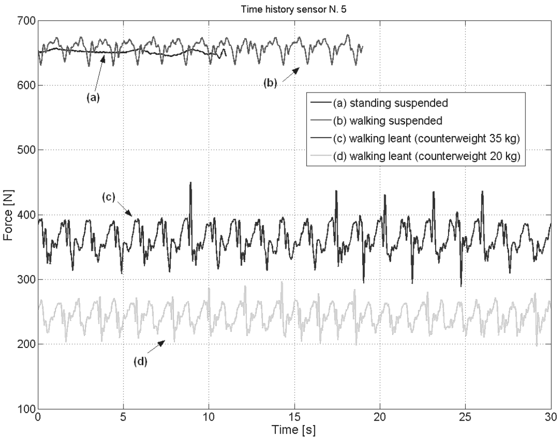

Figure 5: measured body sustaining force in different test conditions.

A characteristic force waveform can be observed in a step cycle, considering for example a 10 s long time interval, in the case of subject walking at 1.5 km/h with a counterweight of 35 kg (Figure 6).

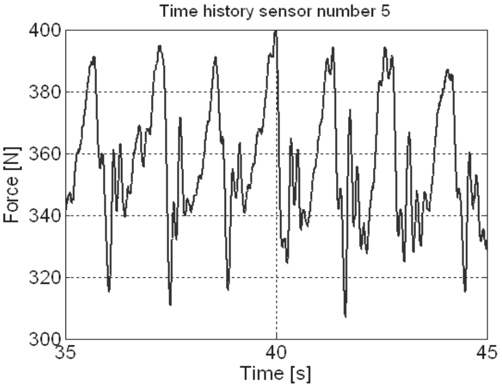

Figure 6: body sustaining force - time history.

The subject has a left (or indifferently right) foot contact in 2.7 s and therefore a foot contact in 1.35 s. The lowest force values are exhibited at the foot contact instant while the highest when the foot rises. The time-history analysis allows to evaluate the actual load variations. In this case the measured mean value is 359 N, with minimum and maximum values equal to 310 N and 400 N. It has therefore been calculated that the subject has sustained an average weight of 275 N (~28 kg), with a minimum of 235 N (~24 kg) and a maximum of 324 N (~33 kg). The analysis in the frequency domain (using DFT techniques) is useful to identify the dynamic component parameters. Figure 7 shows the force amplitude spectrum: there is a main component at 0.7 Hz (correspondent to the feet contact frequency at a speed of 1.5 km/h) and other lower multiple components.

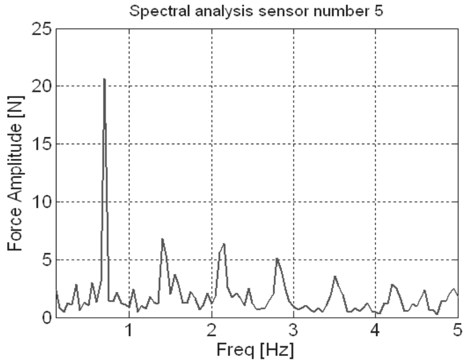

Figure 7: body sustaining force - amplitude spectrum.

Table 1 contains the numeric results for all test conditions, in terms of mean, max and min values and peak to peak amplitude.

Table 1: measured body sustaining force (mean, max, min, peak-to-peak values) for 35 kg and 20 kg counterweight.

	35 kg	**20 kg**
Mean value	359 N	242 N
Max value	400 N	265 N
Min value	310 N	215 N
Peak-to-peak	90 N	50 N

The analysis of the data acquired by the cells installed over the feet (sensors N.1 to N.4), gives some important indications about the subject's real activity during the gait. Table 2 presents the numeric results, comparing the suspended and the leant subject conditions, both for left and right leg.

Table 2: numerical results for left/right foot pulling force.

	Suspended patient		**Leant patient**	
	Right	**Left**	**Right**	**Left**
Peak-to-peak	30 N	25 N	105 N	110 N

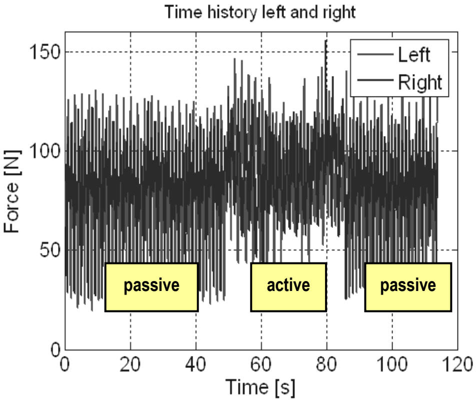

Figure 8: left and right foot pulling force (comparison between active and passive zones).

In this case the mean values are not meaningful because of their dependence on the static tension the therapist gives preparing the patient. The dynamic components are instead indices of the subject's muscle activity. The peak-to-peak value grows from 30 N to 105 N for the right leg and from 25 N to 110 N for the right, showing a strong increment of the forces needed to sustain the feet when the subject walks leant on the treadmill respect to the suspended case.

The comparison between the time histories of the active and passive sessions shows a significant difference in the measured forces, being useful for the subject's work evaluation (Figure 8).

4.2 SCI Patient Gait

The previous analyses, performed in the case of an healthy subject, have been applied to the case of a SCI patient. The considered patient is affected by an asymmetric left/right motor disability, and therefore well suits a study case.

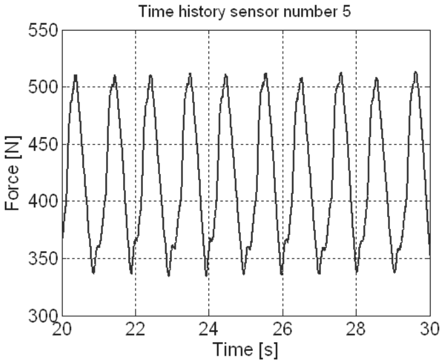

Figure 9: time history (body sustaining force).

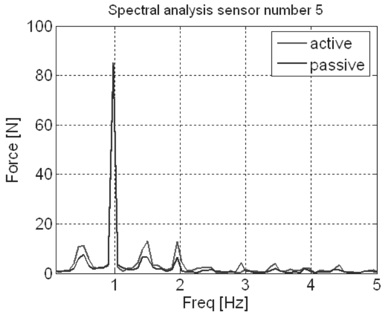

Figure 10: spectral analysis (body sustaining force).

The body sustaining force time history (Figure 9) shows a more regular signal waveform, confirmed by the spectral analysis (Figure 10), where the main spectral component (associated to the foot contact frequency) is more marked if compared with the normal case. Comparing the active and passive session spectra, it can be observed that the secondary dynamic components tend to become lower in the passive case, but when the patient tries to walk actively a little increase appears (like the "normal" gait case, where multiple components are well marked).The analysis in the time domain has pointed out significant differences in the measured sustaining force depending on the patient's speed gait: the mean, max and min values of the aliquot part of the weight sustained by the patient himself are respectively 147 N, 59 N, 226 N for speed of 2 km/h. In the case of speed of 1.5 km/h the values are 127 N, 29 N, 226 N. The first case (2 km/h) is the usual rehabilitation condition for the patient: he seems therefore able to realize a more fluent gait supporting a higher load.

The analyses of the time histories of the feet sensors are useful to obtain indications about the patient's muscular activity (Figure 11).

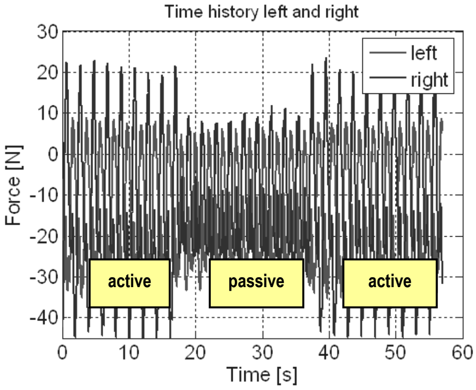

Figure 11: left and right foot pulling force (comparison between active and passive zones).

The calculation of the standard deviation of the forces, index of the dynamic forces exchanged between the patient and the orthosis, shows an increment related to the patient gait efficiency (Table 3, Table 4).

Table 3: feet pulling force values for 2 km/h speed.

2 km/h	**Passive**	**Active**	**Increment**
Right	12.3 N	19.8 N	+61%
Left	12.6 N	14.1 N	+12 %

Table 4: feet pulling force values for 1.5 km/h speed.

1.5 km/h	**Passive**	**Active**	**Increment**
Right	12.1 N	19.9 N	+64%
Left	12.8 N	16.3 N	+27 %

In agreement with the patient's pathology the results has pointed out a significant difference between active and passive sessions only for the right leg, with an increment of 61% and 64% respectively for 2 and 1.5 km/h, while 12% and 27% for the left leg.

5 DISCUSSIONS AND CONCLUSIONS

Measurement chains able to gather the forces during gait therapy assisted by a robotic treadmill have been designed and settled-up. Results have pointed out that these measurements can help doctors and therapists in the patient's assessment and the rehabilitation parameters set-up. The obtained results have also been the starting point for the study of an ankle motion system improvement.

The actual load sustained by the patient during assisted gait is a fundamental parameter. The proper value is different for each patient, depending on the physical condition and the specific pathology. A too high value may be detrimental to the patient, while a too low value may be inappropriate, raising the patient's recovery time length. The measurement of the actual load, and especially of the dynamic load variations, for sure very important to this aim, has been performed and the results analyzed.

Beside this, the knowledge of the involved internal forces can help the therapist in the rehabilitation session evaluation, allowing to properly set-up all the parameters, as the gait speed and the session time length.

The very good results obtained in the present work provide the basis for future developments aimed to the real diagnostic possibilities. Additional experimental tests will be carried out in order to consider a greater number of patiens, thus validating the obtained results and estimating the associated uncertainty levels.

The authors think that the measured internal forces are associated to the actual muscular activity of the patient. Therefore the next step in this research field will be the correlation between the measured forces and the results coming from the electromyography of lower-limb muscles during walking, in order to validate the presented results. The possibility of the patient's assessment based on force measurements is very interesting, giving a lot of advantages as low cost and ease of carrying out.

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REFERENCES

Zijlstra, W., 2003. Assessment of spatio-temporal gait parameters from trunk accelerations during human walking, *Gait and Posture* Vol. 18, 1-10.

Bucca, G., Bezzolato, A., Bruni, S., Molteni, F., 2008. A mechatronic device for the rehabilitation of ankle motion, *BIODEVICES 2008 Conference, Funchal, Madeira*.

Comolli, L., et al, 2005. Metrological characterization of a cycle-ergometer, *6th Congress of the Italian Society of Movement Analysis in Clinics*.

Melis, E.H., et al, 1999. *Analysis of assisted-gait characteristics in persons with incomplete spinal cord injury, Spinal Cord*, Vol. 37, Issue 6 pp. 430-439.