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Wireless Instrumented Crutches for Force and Tilt Monitoring in Lower Limb Rehabilitation

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Abstract

This paper describes synthetically the design, development and characterization of two wireless instrumented crutches for monitoring lower-limb rehabilitation activities. These sensorized crutches allow monitoring axial and shear forces and tilt angles in real time. Each crutch is composed of three strain-gauge bridges measuring axial and shear forces, a conditioning and transmission circuit, a tri-axial accelerometer and a battery power management circuit. The data are transmitted wirelessly via Bluetooth to a remote computer, no further readout unit is necessary. The instrumented crutches have been tested and characterized using an ad-hoc experimental setup and they have been used for the first tests on one subject. This paper shows, in a concise manner, the description of the system and the first experimental results on one crutch obtained in laboratory.

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Keywords: Rehabilitation; Strain gauges; Accelerometer; Wireless sensor; Force monitoring; Gait analysis; Tilt monitoring; Limb

1. Introduction

In the recent years, the monitoring of the rehabilitation activities at home is growing, driven by the increase of the elderly population. Therefore, the monitoring systems are having a growing interest as well. As reported in the literature, new different devices have been designed, fabricated and tested for the monitoring of rehabilitation activities in these recent years. These devices could be roughly divided in external measurement systems (wearable,

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attached, integrated into rehabilitation devices, etc.) or implanted inside the human body. For example, two wearable external devices are shown in [1-2], for monitoring the movement of the fingers [1] or for postural monitoring [2]; whereas, an implanted device for the monitoring of forces between the tibia and femur in a patient with total knee prosthesis is reported in [3]. However, implantable devices are still little used, probably because, among the various challenges, there is also the need to properly power supply these implanted devices [4]. Whereas, the external devices are growing in number and features; among the external ones, the sensorization of the rehabilitation aids seems to generate numerous benefits for both the physician and the patient. One of the most common rehabilitation aids is definitely the crutch. In fact, the use of crutches for the rehabilitation of an injury to the lower limb is often adopted in the clinical environment. The therapist usually corrects any improper use by the patient, as the incorrect balance of the weight on the two crutches or the incorrect position, only through visual observation without any quantitative analysis. However, the knowledge of the loads and inclinations is of primary importance in rehabilitation, even more through exoskeletons [5]. In the literature, a few prototypes that allow you to assist in the rehabilitation activities are reported [6] and some functions that therapists consider important are not implemented, such as the measurement of the shear forces due to the unbalance of the patient. Collaborations with therapists have allowed us to identify the main features of the sensors; the proposed wireless instrumented crutches performs the measurement of axial and shear forces and tilt angles in real time. Furthermore, the proposed crutches are easy to use, simple to configure and with a good degree of accuracy, so as to be able to reach the acceptance of patients and therapists. This paper describes the design, development and characterization of two wireless instrumented crutches for monitoring the rehabilitation of the lower limbs. These instrumented crutches allow monitoring the axial and shear forces and the antro-posterior and medio-lateral angles in real time. Each crutch is composed of three strain-gauge bridges, a conditioning circuit and transmission, a tri-axial accelerometer, and a battery management circuit. The data is transmitted wirelessly via Bluetooth to a computer, without further reading unit. The description of the wireless instrumented crutches and the preliminary experimental results are reported in the following paragraphs.

2. Description of the wireless instrumented crutches

The instrumented crutches (Fig. 1) are composed of strain gauge sensors for the measurement of axial and shear forces, a tilt sensor, a circuit for conditioning for conversion and wireless data transmission and a power management circuit (Fig. 2). The proposed crutches are developed using commercial components in order to minimize the potential cost.

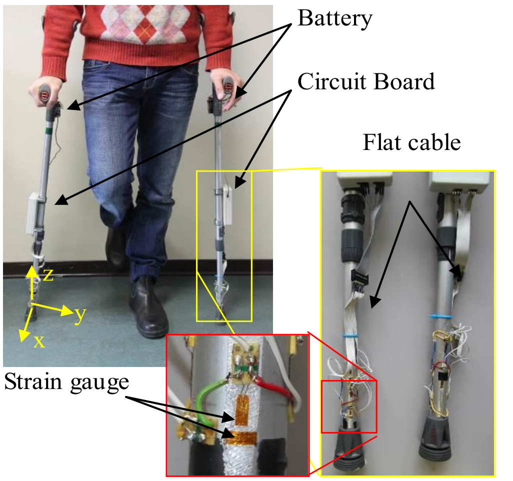

Fig. 1: Picture of the wireless instrumented crutches and zoom of the strain gauge sensors.

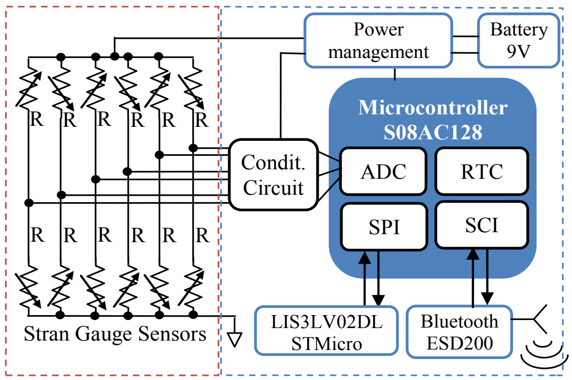

Fig. 2: Block diagram of each wireless instrumented crutch.

The axial and shear forces are measured by twelve strain gauge sensors integrated into each crutch and connected in bridge configurations, a dedicated low-power electronics allows to filter and amplify the signals. A low-power microcontroller (S08AC128-Freescale) manages the operations of conditioning, conversion and transmission. The conditioned force signals are acquires using the embedded 10-bit analog-digital converter (ADC). The wireless data communication to the host computer is obtained using a Bluetooth module (ESD200-Parani). The tilt angles are measured using a tri-axial accelerometer (LIS3LV02DL-STMicro) and the angles are calculated with the assumption that the acceleration due to gravity is predominant on the dynamic accelerations caused by a rapid change of speed, such as shocks and vibrations. In fact, in a clinical setting, patients are taught to use crutches at a slow safe speed. However, the dynamic component is minimized by the inclusion of a low-pass filter. Each sensorized crutch is powered by one 9 V battery (1.2 Ah) permitting up to 24h monitoring. Only a commercial standard Bluetooth module is required on the host computer, a standalone program developed with LabVIEW is used for recording and viewing measured data in real time.

3. Experimental Results

The preliminary results obtained testing each wireless instrumented crutch show a good accuracy of the sensors. Each crutch was connected on a manually rotating structure, and a micrometric angular screw was fixed as reference sensor for angular measurement (Fig. 3). In Fig. 3, the angles respect the vertical (crutch angle) and standard deviations (3SD) are reported; as it can be seen, the correlation with the micrometric screw is good. The accelerometer data are excellent for a measurement during static or quasi-static activities, whereas the dynamic characterization has not been considered. In Fig. 4 and Fig. 5, the crutch was mounted in a mechanical testing structure and subjected to different cycles of loading and unloading. In Fig. 4, the conditioning circuit output voltage (Vout_axial) is measured for different mechanically applied loads from about 0 to 60 kg. The data show good linearity and low standard deviations. Whereas, Fig. 5 shows the two conditioning output voltages (Vout_shear_x and Vout_shear_y) for different mechanically applied loads form 0 to 16 kg in each direction. Also in this case, the measurement data show good linearity and low standard deviations. Then, the axial and shear loads and the tilt angles were measured in real-time for a long period (Fig. 6) during the execution of a simple walking activity. In the first graph, the axial (blue squares) and shear (green crosses and red rhomboids) loads are shown; the different gait phases are clearly visible, the first peak is the contact phase (CP), then the second peak is the propulsion phase (PP), in the middle there is the midstance phase (MP). In the second graph, the tilt crutch angles are reported; the antro-posterior and the medio-lateral angles permit to monitor the crutch movements during the gait cycles. Therefore, the designed crutches allow measuring some basic parameters during use. The work is still in progress, including additional tests on more patients.

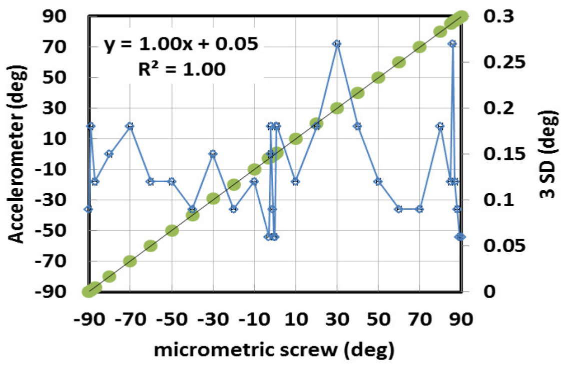

Fig. 3: Antro-posterior angle tests, mean (green dots) and standard deviation - 3SD (blue squares) for the Left Crutch.

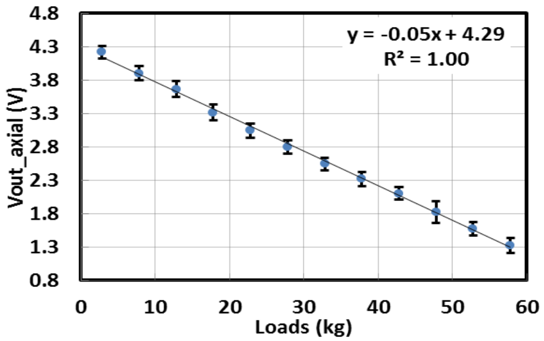

Fig. 4: Axial force tests, cond. circ. output voltages vs. mechanically applied loads (mean and 3SD) - Left Crutch.

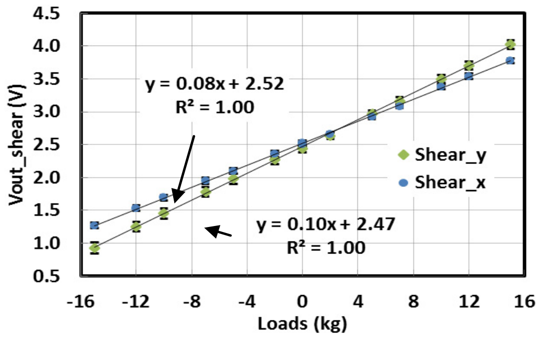

Fig. 5: Shear force tests, cond. circ. output voltages vs. mechanically applied loads (mean and 3SD) - Left Crutch.

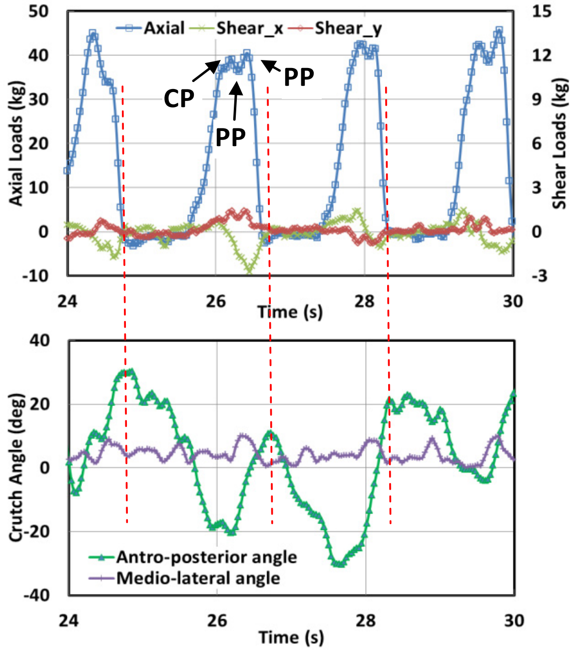

Fig. 6: Axial and shear loads and tilt angles monitored in real-time during tests of one person – Left Crutch.

4. Conclusions

In this paper, two wireless instrumented crutches are described and the preliminary results reported. Crutches allow measuring the axial and shear forces, and the antro-posterior and medio-lateral angles. The results of characterization show good linearity and a low standard deviation obtained on multiple tests. Further work is underway to improve the response of the accelerometer in order to reduce the problems associated with dynamic accelerations. Moreover, further tests are in progress to assess the possibility to monitor the unbalanced weight of the subject during rehabilitation walking activities.

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