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Modified forearm crutches for load bearing measurement in exoskeleton assisted gait

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SUMMARY
This study presents a low-cost device to allow measurement of forces transferred from Lofstrand crutches to the upper body, during assisted gait with a Rewalk™ exoskeleton in patients with thoracic-level motor-complete spinal cord injury (SCI) [1].

Without modifying the aids functional structure, strain gauges were applied on the surface of each crutch, creating two 3-axis dynamometers, which were used in conjunction with a machine vision system and surface electromyography (EMG) to assess the load bearing distribution during assisted gait of a patient with complete SCI.

The patient was at the final phase of her training and already achieved the capability to use autonomously the exoskeleton for long periods, however, results displayed an asymmetric usage of crutches, which was independently pointed out by crutches orientation, muscle activations and crutches load. This fact has been considered a proof of coherence between EMG, vision system and the proposed crutches.

The authors' intent is to propose the introduction of these modified crutches to integrate training protocols for exoskeleton usage, giving both patient and therapist a feedback on the load actually supported by the upper limb, reducing excessive loading in the long term and to develop a protocol for evaluation of patients' performance.

INTRODUCTION
Patients with complete SCI suffer from different immobility-related problems therefore the ability to stand and walk is critical to limit these secondary effects [2]. Traditional HKAFO (hip knee ankle foot orthosis), intensively requires the use of crutches, that produce upper limb joint degeneration. [3]. The Rewalk™ system is a robot powered exoskeleton, designed with the aim to restore ambulatory function in individuals with complete SCI, without increasing upper limb load bearing.

The device is composed of a self-supporting 20 kg motorized structure, tied to the patient, a 3 kg backpack, containing the system batteries, and a wrist-strap remote controller. Each step is activated by a tilt sensor, which monitors upper body bending in the sagittal plane against a threshold defined on patient's characteristics (height, weight and lesion level), which is associated with the simultaneous forward movement of both crutches [4]. Given this activation mechanics, a partial load needs to be supported by the crutches before a step is initiated, therefore the patient should learn to limit this load to the minimum effectively required to avoid overstrain of the upper limbs [5].

METHODS
As shown in figure 1, on each crutch's surface 12 strain gauges were applied, near the tip, forming 3 full bridges: one measuring shear along the crutch handle direction (X axis), one measuring compression along the axial direction of the crutch (Z axis), and one measuring shear along the direction completing the right-hand coordinate system (Y axis).

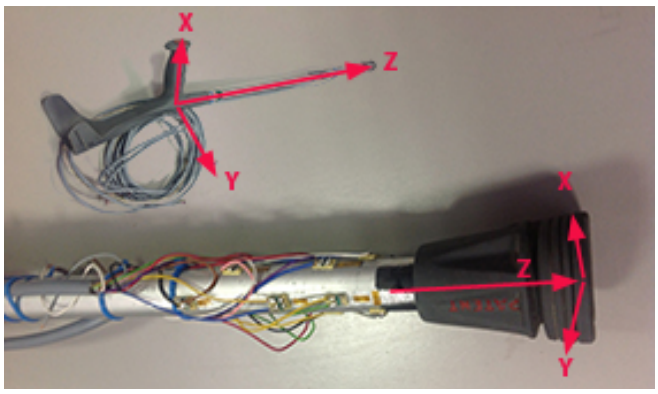

Figure 1: Strain gauges on a crutch tip (bottom, detail) and crutch (top), with relative coordinate system.

Given the ratio between longitudinal and radial dimensions of the crutches, these were treated as a cantilever beams for what concerns strain gauges configuration. Moreover, since no slipping of the tip, nor rotation of the crutch along its axis, were recorded during preliminary tests, the crutch tip was assumed to be a fixed constrain during stance [6].

To avoid false readings of longitudinal forces due to transverse sensitivity, tangential forces on the crutch tip are measured by the X and Y bridges are composed each of two couples of strain gauges aligned longitudinally (along Z) and on opposed surfaces. These two bridges are normal to X and Y respectively. The last bridge is normal to X and

composed of two gauges along the Z axis and two orthogonal to them, along Y axis, allowing the bridge to have maximum sensitivity to longitudinal compression of the crutch, while minimizing effects of bending, shear and torque [7].

Each bridge is measured using a 6 wires technique, thus reducing noise from environmental sources as well as from supply voltage, which are relevant due to the 5 m cables required to allow free movements of the patient.
The signal is acquired using a NI cDAQ 9237 at 25 kHz, than reduced to 1000 Hz using a centered running average filter to further decrease noise and improve accuracy. Acquisition program has been developed in Labview©, while post elaboration has been performed in Matlab©.

Given the different relevance of longitudinal and planar forces, a two step calibration was performed: the X and Y axis were loaded with 20 different reference force levels both in the positive and negative direction, while the Z axis was excited using a 20 s variable load (with frequency components below the transducer bandwidth) measured at 10 Hz with a second reference load cell already calibrated and in series with the longitudinal compressive load.

Following the general assumption of forces $\boldsymbol{F=[f_x\ f_y\ f_z]^t}$ being linearly related to reading of bridges $\boldsymbol{B=[b_1\ b_2\ b_3\ 1]^t}$ by direct and cross sensitivities, results of both tests were used to estimate a 3x4 calibration matrix **M** with a least squares method, minimizing the squared difference **ε** between forces computed using readings and forces actually imposed. [7]

$$F \cong MB \Rightarrow e = \left\| (F - MB) \right\|^2 \Rightarrow \hat{F} = \hat{M}\Big|_{e=\min} B$$

As a further precaution and to detect any variation in sensitivities, a second, monoaxial, load cell was used as reference during tests, to check by comparison the Z axis sensitivity at the beginning and end of each measuring session.

The following protocol was followed during each session, composed by a preliminary setup, a set of tests and a final check. During the preliminary setup phase the patient is at first equipped with the Rewalk™ exoskeleton and the portable EMG system is set in place to monitor the principal muscles of the upper limbs (medial, lateral and anterior deltoids, superior trapezoid, biceps brachii and triceps brachii). After that, 20 markers are applied to the patient following Davis protocol, and 3 marker on each modified crutch, totaling 36 markers. Modified crutches are then given to the patient, which is asked to position each tip on the reference load cell and freely apply load on it, to allow for the first sensitivity check, which is recorded.

During the test phase the patient is asked to walk in straight line for 6 m with an average stride time of 1 s, he/she is supported by therapists while inverting direction. During this phase, which is repeated up to 20 times, forces, kinematics and EMG values of the two central steps of each walk are recorded. In the last check phase each crutches is checked again, as in the setup phase. The patient is then freed by the instrumentation.

RESULTS AND DISCUSSION

Three different pairs of crutches were modified following the method described, for all them standard uncertainty after calibration resulted in less than 5N [8], with a full scale of 800N in compression for the Z axis and 200N compression-traction on X and Y axis.

Calibration also revealed a 20% transverse sensitivity of the Z bridge with respect to loads in X and Y direction, stressing the need for a full calibration matrix and a triaxial system to avoid false readings. Sensitivities of the Z axis, measured in situ before and after each session, following the protocol, were always found compatible (P=95%) with the ones estimated during calibration.

As shown in figure 2 the fraction of the patient mass supported by crutches was between 10% and 15%, while the load distribution has been found to be asymmetric. This asymmetry has been confirmed by EMG analysis, which displayed a higher activation level on the right side muscles, and by the vision system, with a constant offset between crutches orientation.

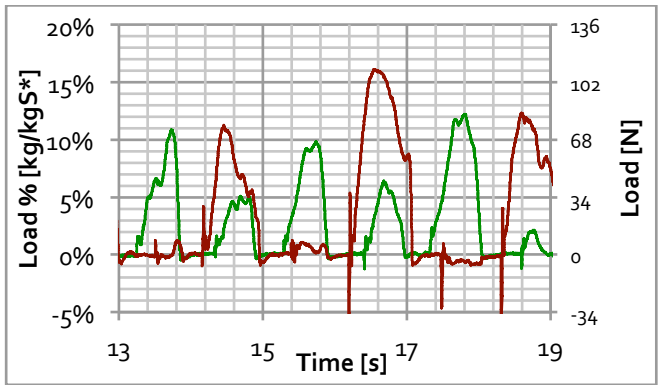

Figure 2: Axial load on crutches (left-red, right-green) as force value and as fraction of body weight during gait.

CONCLUSIONS

Rewalk™ usage is a difficult process that requires the understanding of many parameters to be mastered. Among the many monitored during training, crutches usage in term of principal load (Z) is an important factor both easily understandable and with a direct relevance for long term health of the patient. The system described presents an easy setup, a low cost, and could measure with good accuracy this parameter, while the protocol proposed could be effectively used to establish and verify targets in patient training for what concern upper limb loading limits.

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