Monitoring upper limbs during exoskeleton-assisted gait outdoors

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***Abstract*—Powered exoskeleton can restore locomotion to spinal cord injury subjects but measuring their impact on the upper limbs is critical, since repeated excessive loads are strongly correlated to chronic pain at shoulder level.**

This paper presents a novel set of instrumented crutches, able to measure force exerted on the ground during walking sessions, thanks to embedded time-of-flight cameras and force sensors.

The force sensors, along with an inertial module, assess the force acting on the upper limbs, while the time-of-flight cameras detects the gait phases looking at the feet position.

The aim is to provide an affordable measuring system, without requiring a fully instrumented gait-lab, allowing the user-robot interaction to be measured in a more natural setting, closer to the foreseen working condition.

The instrumented crutches are fully independent of any other instrumentation to allow a comparison of different exoskeleton models in terms of upper limb involvement.

I. Introduction

The loss of locomotion is one of the major impairments that could result from a spinal cord injury. In recent years more and more exoskeletons are being developed with the aim to overcome this limitation [1], [2]. A few are also commercially available [3], and their efficacy and long-term health effects were investigated in different studies [4]–[6].

Most of these studies are performed in specialized gait lab, using motion capture, accelerometric data and force platforms to acquire a full kinetic and kinematic definition of the human-exoskeleton system [7]–[9].

This approach has however been limited to indoor application, in a small, constrained space, and only for a limited number of walking sessions.

To overcome this problem a set of wireless instrumented crutches has been developed, with the aim of allowing the measurement of upper limbs involvement during assisted gait in a more natural setting, and without relying on the exoskeleton specific model or capabilities.

II. Material and Methods

A set of forearm crutches were instrumented using a set of four 350 Ω strain gauges and a Bluetooth data acquisition system, as described in [10], to measure the axial force exerted by the subject.

A *Camboard Picoflexx* (PMD Technologies®) Time-of-Flight (ToF) camera was mounted on each crutch. The camera contains only the depth sensor, which makes it small and lightweight (68 x 17 x 7.25 mm only). The camera has a resolution of 224 x 171 pixels and a viewing angle of 62° x45°. The measurement range goes from 10 cm to 400 cm, and the frame rate from 5 fps to 45 fps. The Picoflexx has a USB 2.0/3.0 interface and does not require any extra power supply. The camera shows an average measurement accuracy of 37 mm, comparable with gold standard ToF cameras, such as the Microsoft Kinect v2 [11].

Fig. 1. An expert user of a Rewalk P5 device, while practing with the exoskeleton and the instrumented crutches presented in this work.

III. Results

An expert user of a Rewalk exoskeleton P5 model was measured during a walking session, using the instrumented crutches, as shown here in Fig. 1. Twenty steps were recorded and analyzed.

Preliminary results are visible in Fig. 2, were the gait events are coupled with the point clouds acquired with the ToF camera (only the right foot is represented).

IV. Discussion

Without a full kinematic and kinetic analysis of the human-robot system, an accurate assessment of the shoulder loads during assisted gait is still not possible. The load exerted on the crutches, however, strongly correlates with upper limbs joint reactions, and could be used to assess the shoulder involvement while using an exoskeleton.

An example of this data could be seen in Fig. 3, where

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forces acting on each crutch are plotted as function of the gait phase.

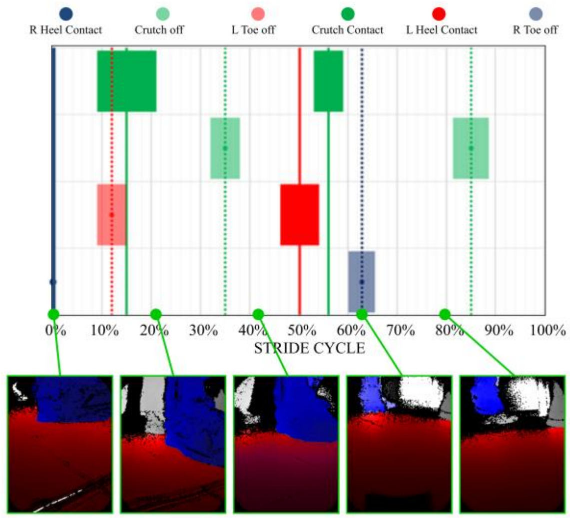

Fig. 2. Gait events recorded during 20 steps in a walking session of an expert Rewalk P5 user with synchronous crutches movement, coupled with the point clouds acquired with the ToF camera. Crutches events are in green, left foot in red and right foot in blue. In the point cloud images, the red area represents the floor while the blue area represent the right foot.

In the trade-off between the accuracy of a gait lab and easier measurements on the field, however, is critical to take into account that the exoskeleton user requires some time to adjust to the robot: limiting the evaluation to short walking tests could lead to different behaviors than found in practice.

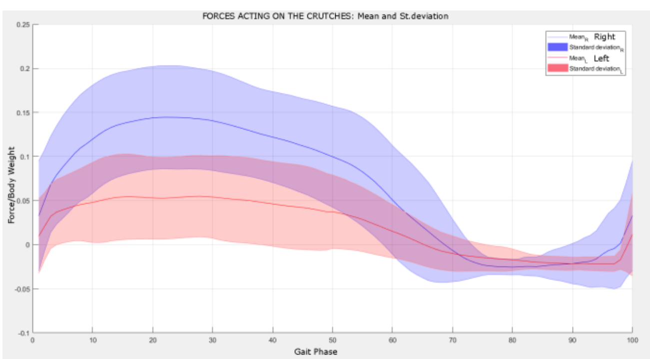

Fig. 3. Forces acting on the crutches recorded during 20 steps in a walking session of an expert Rewalk P5 user with synchronous crutches movement. Bold line is average, and the area is a 1-sigma confidence interval.

V. Conclusion

The proposed system could be used to improve the design of exoskeleton for spinal cord injury subjects, allowing a benchmarking of different robotic solutions. While simulations and experimental gait-lab analysis are the primary tools for assessing the efficacy and safety of exoskeletons, a proper evaluation should take into account an environmental setting as close as possible to everyday working conditions.

Being independent from the exoskeleton sensing system, the instrumented crutches could be considered an external validating device for the exoskeleton under testing. The lack of markers or connections, moreover, reduces the setup time for walking tests, and requires no additional instructions to the exoskeleton final user.

More subjects are currently being involved in the study, and a validation of the system by comparison with a *gold standard* in different conditions is clearly still necessary and is currently being scheduled.

Acknowledgment

We would like to thank the subjects of the study and the hospitals, Domus Salutis (Brescia, Italy) and Villa Beretta (Costa Masnaga, Italy), for their involvement and support in the project. We would also like to acknowledge the help and support provided by Paolo Gaffurini during the tests.

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