Lower-Limbs Exoskeletons Benchmark Exploiting a Stairs-Based Testbed: the STEPbySTEP Project

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***Abstract*— Wearable exoskeletons can be valuable assistive robots to physically support humans in a wide variety of daily living activities. However, there is a lack of standards for the devices benchmark and evaluation. The STEPbySTEP project is developing a modular and sensorized reconfigurable staircase testbed for lower-limb exoskeletons benchmarking to be included in the main EUROBENCH project testing facility. In addition, metrics for the benchmark and evaluation of different solutions are defined, including physical interaction metrics, ergonomics metrics, and human factors metrics.**

I. Testbed description

The STEPbySTEP project proposes the development of a modular, sensorized and reconfigurable staircase testbed to be used in a systematic procedure aimed at validating lower-limbs exoskeletons (LLEs) abilities, performance and effects on user experience during ascending/descending stairs. The proposed testbed is shown in Figure 1. The capability of the setup to reconfigure the inclination of the staircase (*i.e.*, the height of the steps) is of great importance to test the LLEs in different situations. Such inclination can be set by changing the height of the landing through the *Actuator for Height Regulation*. The handrail is sensorized with load cells. In addition, two steps are sensorized with a force plate (BTS P-6000) to measure the contact forces between the subject and the steps. Two force platforms are in fact enough to evaluate a complete gait cycle.

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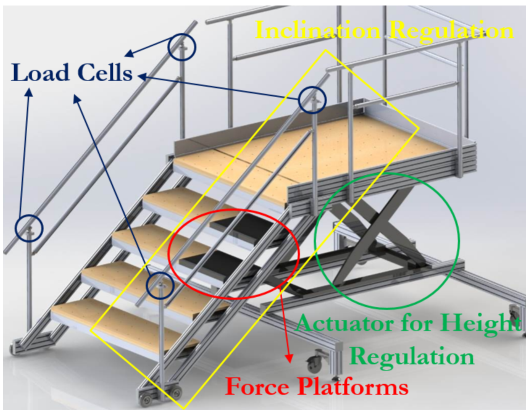

Fig. 1. Proposed reconfigurable and sensorized stair testbed.

II. Metrics definition

A. Physical interaction metrics

The proposed metrics rely on the use of surface electromyography (sEMG), a technique to record the muscles electrical activity during contraction. The stronger is the contraction, the higher is the electrical activity. The sEMG of tibialis anterior, soleus, rectus femoris, and hamstring muscles will be collected bilaterally. The selection of these muscles is a good compromise between the setup time and the quantity of information extractable from the data, but more muscles may be selected for other kinds of analyses (*e.g.*, muscle synergies). Two kind of metrics will be presented: an index quantifying the amount of activity of the i-muscle ${}_{A}EMG^{i}$, and an index quantifying the co-contractions between the i-muscle and the j-muscle $ccEMG^{ij}$). The first metric was recently tested to verify the effectiveness of a physical collaborative controller on a KUKA iiwa LBR 14 robot [1]. The second metric was used in a study of proprioception during robot-assisted reaching [2].

Each muscle signal is processed as follows: i) subtraction of the DC offset; ii) the calculation of the absolute value; iii) calculation of the signal envelope ENV^{i} using of a Hilbert transform filter (Figure 2 left panel). The index ${}_{A}EMG^{i}$ quantifying the activity of the i-muscle is defined as the area

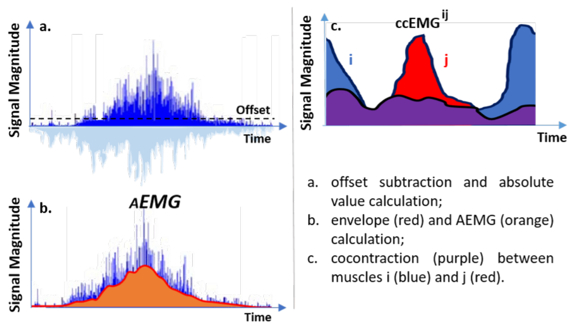

Fig. 2. EMG elaboration (left) and co-contraction index calculation (right)

underneath the signal envelope:

$$_{A}EMG^{i} = \Sigma_{k=1}^{N} ENV^{i}(k). \quad (1)$$

The index $ccEMG^{ij}$ quantifying the co-contraction between the muscle i and the muscle j (Figure 2 right panel) is:

$$ccEMG^{ij} = 2 \times \frac{\Sigma_{k=1}^{N} \min(ENV^{i}(k), ENV^{j}(k))}{_{A}EMG^{i} +_{A} EMG^{j}} \times 100\%, \quad (2)$$

where N is the number of samples and ENV^{i} the i-muscle signal envelop.

B. Ergonomics metrics

Stair climbing analysis is not as common as gait analysis. For gait analysis a well stablished definition for phases, subphases and events exists. However, it is not the case for stair climbing. The phases/subphases of stair ascent/descent are not well established. Figure 3 shows the approach of phases and subphases made by Harper [3].

1) Simple metrics: Simple metrics that can be measured easily in clinical setting or a motion capture lab:

- Total time to ascend the stair. Considering only ascend.
- Total time to descend the stair. Considering only descend.
- Total time to ascend and descend the stair. Considering both ascend and descend and including the time needed to turn around on the top of the stairs.

2) Complex metrics: We take into account temporal and kinematics parameters. **Temporal Parameters (Time parameters):** Subphases of stair climbing (% of gait cycle):

- Weight acceptance phase
- Pull-up phase
- Forward continuance
- Push-up
- Swing-foot clearance
- Swing-foot placement

Subphases of stair descend (% of gait cycle):

- Weight acceptance phase
- Forward continuance phase
- Controlled lowering phase

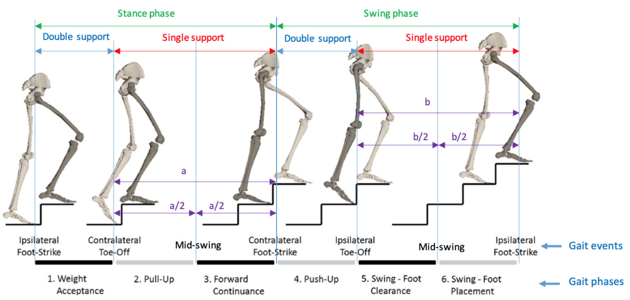

Fig. 3. Figure from [3] and modified by CEIT. The six regions of the ipsilateral (dark shaded) leg gait cycle: (1) weight acceptance (ipsilateral foot-strike to contralateral toe-off), (2) pull-up and (3) forward continuance (contralateral toe-off to contralateral foot-strike divided into two equal sections), (4) push-up (contralateral foot-strike to ipsilateral toe-off), (5) early swing and foot clearance and (6) late swing and foot placement (ipsilateral toe-off to ipsilateral foot-strike divided intro two equal sections).

- Leg pull through
- Foot placement

Kinematic parameters:

- Joint angles vs % of gait cycle.
- Peak values of angles and time occurrence (% of gait cycle) at the hip, knee and ankle joint.

C. Human factors metrics

No framework in literature allows evaluating medical LLEs' impact on users'perceptions and behaviors. The STEPbySTEP project aims to develop a Human Factors benchmarking framework based on the integration of well-accredited evaluation tools. Three types of metrics will be included. Cognitive metrics will encompass: cognitive-motor interference, measured by the Single-Dual Task Paradigm [4], perceived musculoskeletal pressure/discomfort, measured by the Local Perceived Pressure Method [5]. Psychophysiological metrics will be electrodermal activity and heart rate, measured by Empatica E4 wristband [6]. Behavioral metric will correspond to an ad-hoc observational checklist measuring user-exoskeleton interaction. The protocol will be divided in three phases. The first phase (before task, 25 minutes) entails a semi-structured interview (15 minutes) concerning user expectations about his/her experience with the exoskeleton, along with a questionnaire about age, sex, anthropometric features and expertise with assistive devices. The second phase (during task, 20 minutes) consists of climbing the staircase testbed while wearing the exoskeleton and the Empatica E4 wristband for psychophysiological measurements. In turn, two experimental conditions will be run, such as without and with cognitive-motor interefence. The third phase (after task, 30 minutes) encompasses a semi-structured interview (15 minutes) regarding user attitudes about his/her experience with the exoskeleton, along with a questionnaire about local perceived pressure.

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