STEPbySTEP Project: Systematic Test of Exoskeleton Products by a Stairs-based Testbed Evaluation Protocol

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***Abstract*— A recent review of the current literature on the clinical effectiveness of powered exoskeleton-assisted walking shows that most training programs and clinical studies are based on walking on flat indoor surfaces while there is a lack of data regarding the use of exoskeleton in more complex tasks such as walking outdoors, navigating obstacles, climbing stairs, and performing activities of daily living. In this framework and considering that stairs are obstacles encountered frequently in daily living, the STEPbySTEP project will develop a modular and sensorized reconfigurable staircase testbed for lower-limb exoskeletons benchmarking to be included in the EUROBENCH project main facility. Specifically, the inclination of the staircase will be easily adjustable as well as, consequently, the height of the steps. Furthermore, the staircase will be provided at the upper end with a platform adjustable in height allowing for turning. Adjustable sensorized handrails at both sides (both for safety reasons and for human subject support) will be designed, including load cells at the handrails base to measure the additional support required by the human subject executing the task. Moreover, two force platforms embedded in the stairs, a motion capture system, and a physiological-signal measurement system (*e.g.*, heart-rate and EDA measurement) will be integrated in the testbed. These measurements, along with the EMG signals from the system available at the main EUROBENCH facility, will be used to define and calculate performance metrics to evaluate the exoskeleton solutions. In addition, since benchmarking is usually based on performance indicators and/or effects on the users motor function, the STEPbySTEP project will integrate measurements from the human factors' perspective (*i.e.*, trust, cognitive workload and usability) by introducing a new standard index. The main goal of the project is, therefore, to outline a benchmarking scheme in order to compare systems and define which one is most usable for the final user.**

I. Introduction

A. Context

Lower-Limb Exoskeletons (LLEs) systems are used in different fields of application such as the industrial and the medical ones [1], [2]. In the medical field, exoskeletons are used for both rehabilitation and assistive purposes with the aim of stimulating motor recovery and enabling participation in activities of daily living [3]. Nowadays, at least three LLEs are available on the market and many others ready for testing in the clinical setting. In [4] results are compared on the use in spinal cord injury (SCI) patients of the ReWalk (ReWalk Robotics, Inc., Marlborough, MA, US), which was evaluated in eight studies, the Ekso (Ekso Bionics, Richmond, CA, US), which was evaluated in three studies, and Indego (Parker Hannifin Corp., Cleveland, OH, US), which was evaluated in two studies. Main results refer to the safety of the systems and the outcomes indicate that a powered exoskeleton uniquely facilitates independent performance of tasks relevant to the home and community settings. However, only four studies incorporated more complex activities such as walking on uneven or carpeted surfaces and grades, negotiating curbs outdoors, climbing stairs, entering/exiting of elevators, and ordering at a cafe. In conclusion, there is a lack of standardized protocols to evaluate the efficacy and the performance of LLEs in more complex activities different from walking on flat indoor surfaces. The study of more complex activities is needed to evaluate specific characteristics (*e.g.*, dependability, adaptability, configurability, *etc.*) and abilities (*e.g.*, interaction, perception, decisional, *etc.*). These are fundamental information in benchmarking of LLEs to verify how different technologies may affect system abilities and their performance. There is also a lack of understanding of the users' experience and evaluation of bipedal locomotion for rehabilitation/assistive purposes [5]. Furthermore, human-factors aspects in the interaction between users and LLEs are not sufficiently investigated.

B. Paper Contribution

Within the considered framework and the EUROBENCH project [5], the STEPbySTEP sub-project proposes the development of a modular and sensorized reconfigurable staircase testbed to validate (with a systematic procedure) the LLEs abilities, performances and the effects on the user experience during ascending/descending stairs. In fact, although stairs are obstacles encountered frequently in daily living, no comprehensive work investigated the use of LLEs in ascending/descending stairs to the knowledge of the authors. One case study [6] investigated the use of the Vanderbilt lower-limb exoskeleton during stair ascending/descending with the purpose to define joint torque and power requirements. Another study using ReWalk presented a 20-session training to enable spinal cord injury (SCI) patients

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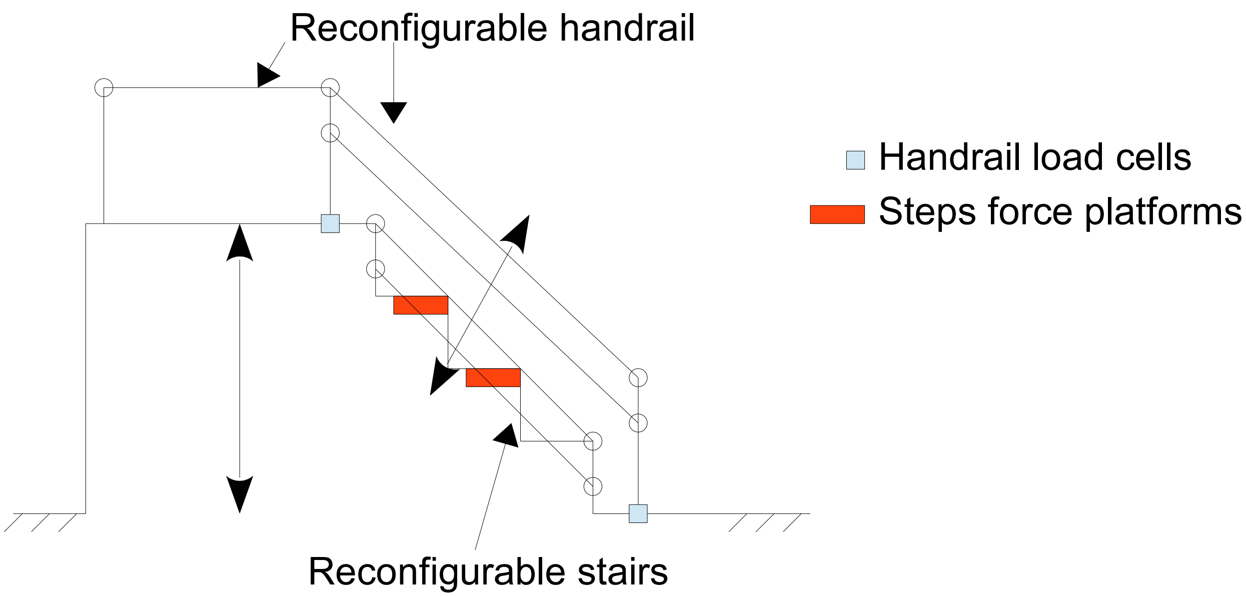

Fig. 1: Proposed reconfigurable stair testbed sensorized with load cells for handrails and force platforms for two steps.

to ascend/descend stairs [7]. Five out of ten enrolled subjects completed the training, after the training only four were able to ascend/descend stairs and no data on this task were presented. In both studies, tests were performed on a standard staircase of the building where the study was performed, not on stairs with different characteristics and in repeatable conditions. However, it is well known that the inclination of the staircase and the height of the steps on the one hand affects largely joint torque and power requirements [8], and on the other hand are important because there is an angular range where subjects do switch between a level walking and a stair walking gait pattern [9]. From here, the importance of having a staircase testbed where the inclination and the height of steps may be adjusted. Based on the rational above, the STEPbySTEP sub-project will focus on the development of a staircase testbed supplied with measurements and relative metrics to quantify LLE abilities. The STEPbySTEP team, exploiting previous experience in the field of robot design and control, movement analysis, rehabilitation, ergonomics and human factors, will work to optimize metrics aiming at quantifying the system abilities and relative effects on the physical as well as cognitive workload. Expected outcomes of the project are: i) a reconfigurable and sensorized staircase testbed, ii) physical interaction metrics, iii) ergonomics metrics, and iv) cognitive/usability metrics.

II. Outcomes of the Projects: Testbed and Metrics Design

The STEPbySTEP project aims at develop a fully sensorized staircase testbed to perform comparison and evaluation of different lower-limb exoskeletons (LLEs). The main feaures of such a testbed are therefore: i) the reconfigurable and sensorized staircase testbed, ii) the physical interaction metrics, iii) the ergonomics metrics, and iv) the cognitive/usability metrics. While i) provides the hardware and software solution aiming for testing the LLEs in different target conditions, acquiring measurements to reconstruct the bio-mechanics of the human subject, ii), iii) and iv) provide the metrics to fully evaluate the tested LLE, considering the physical interaction (*i.e.*, the effort required by the human subject to collaborate with the LLE, therefore, the transparency of the system), the physical comfort and the cognitive comfort. In the following, each component is detailed.

A. The Staircase Testbed

Patients walking with LLE assistance usually ascend/descend stairs using one crutch and the sustain of a handrail. It is therefore important to measure both the ground reaction forces and the subject/handrail interaction forces to evaluate their assistant need. The better is the LLE assistance, the less is the sustain need. In addition, from analysis of the Center of Pressure (CoP) it is possible to evaluate the ability of the subject to displace the body weight in the anterior-posterior direction and to verify the presence of possible imbalances. The proposed solution will provide a reconfigurable four-step staircase with readily adjustable inclination, provided by a handrail sensorized with load cells. Moreover, two steps will be sensorized with two digital force platforms (BTS P-6000). Two force platforms are in fact enough to evaluate a complete gait cycle. The proposed testbed in shown in Figure 1. The capability of the setup to reconfigure the inclination of the staircase and, therefore, the height of the steps is of great importance, in order to test the LLEs in different situations, evaluating their performance.

B. Physical Interaction Metrics

The proposed metrics rely on the use of surface electromyography (sEMG), a technique to record the electrical activity produced by muscles 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 activity of these muscles demonstrated to be suitable and sufficient to fine-tuning the gait cycle kinematic parameters of the Ekso exoskeleton in a previous study [10]. 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 and an index quantifying co-contractions between agonist and antagonist muscles. The first metric, a kind of effort index, was recently tested to verify the efficacy of a fuzzy-impedance control of a KUKA iiwa 14 robot to assist human operators in heavy industrial applications while manipulating unknown weight parts [11]. The second metric was used in a study of proprioception during robot-assisted reaching [12].

C. Ergonomics Metric

In order to have a standard criteria for evaluating a task from an ergonomic point of view, it is proposed to use the OWAS method [13] as an ergonomic standard. OWAS (Ovako Working Analysis System) method evaluates the physical workload during a job task. OWAS results provide a score not only for any individual body position but also for a set of postures within a defined task so the repetition of every postures is also considered. This ability is the main advantage of this ergonomic method. OWAS establishes 252 postures combination according to the position of the back, arms and legs. In addition, the load magnitude is also considered. Every posture is codified and a risk category is assigned [13], [14]. Using this metric, two kind of experiments will be performed in the testbed: without and with the LLE. The first one will be use as a reference in order to evaluate the behavior of the second choice in term of ergonomics.

D. Cognitive/Usability Metrics

Current LLEs for rehabilitation and assistive purposes are designed not taking into account major human-factors and human-technology interactions aspects. LLEs should require minimal user input, while fostering effective, efficient and satisfactory interactions with the user. In particular, there is currently no framework in literature that allows for an evaluation of medical LLEs usability and the impact on users cognitive workload and trust. The ascending/descending stairs use case selected in the STEPbySTEP project is particularly relevant due to the frequency it is encountered in everyday context and for the challenge that represents for physically impaired people.

The main benchmarking needs are related to the understanding of how different technologies, interfaces and design characteristics of an LLE may affect usability, trust and cognitive workload of the user . The Human Factors assessment framework developed in STEPbySTEP aims to provide a standard method to measure the performance of an LLE in terms of operational benefits, such as the capability to collaborate with the human, as well as measuring users trust, cognitive workload and system usability, allowing to distinguish between well-designed exoskeletons, which may improve cognitive performance helping the users to shift cognitive resources dedicated to physical effort to the actual activity [15].

The project will develop and test an innovative benchmarking measurement system, integrating beyond state-of-the-art techniques and tools. The following data will be gathered: users acceptability of the system [16], [17]; users' experience; users' trust towards the system; cognitive workload [18]; observation of behavioral indicators (i.e. time spent, goal achievement, movement accuracy, number of body movements); System usability; Comfort and pain; Interface design analysis.

III. Discussion

The proposed staircase testbed will be integrated in the EUROBENCH facility for the LLEs testing [5], where multiple testbed will be included in order to have a full set of scenarios for the LLEs evaluation. In such a way, the effectiveness of the tested solutions can be evaluated and compared, providing also suggestions (on the basis of the metrics and indexes of performance) for the (re)design of new LLEs. In such a way, the proposed solution is not only aiming at merely evaluate performance but allows to include such evaluation into account for the new generation of LLEs, having defined also a standardized approach for their benchmark.

A. Hardware Features

In order to achieve a flexible solution, the re-configurability of the proposed hardware plays an important role: adapting the staircase testbed it will be possible to test LLEs in different situations and under different applications conditions.

B. Software Features

The software that will be developed to acquire, manage and analyze the acquired data will be based on ROS, the most common programming framework in the robotics community [19]. In such a way, a standardized software platform will be provided, easily interfaced with the tested LLE to acquire its measurements (*e.g.*, encoders, torque/force measurements, *etc*.). Metrics calculation will be included in such a framework, making their evaluation portable also to other applications (such as industrial robotics).

C. Preliminary Staircase Testbed Evaluation

The preliminary evaluation of the proposed testbed is important in order to assess its effectiveness. The preliminary evaluation will involve firstly healthy subjects without exoskeleton using the testbed. In such a way, baseline metrics can be calculated to be used for the LLEs benchmark. Secondly, a small group of patients wearing the exoskeletons will be considered. Patients will be selected among paraplegic subject with a lesion between D4 and L1. The dimension of the group will be defined with clinicians based on the availability of patients and the duration of the tests.

IV. Conclusions

The proposed STEPbySTEP project aims to develop a staircase testbed to evaluate and compare lower-limb exoskeletons (LLEs) in the ascended-descended stairs walking scenario. Such testbed, fully sensorized, will be integrated in the EUROBENCH project facility for the complete benchmark of LLEs. Moreover, metrics will be provided to evaluate the physical interaction, the ergonomics and the cognitive/usability performance of the tested solution. In such a way, the obtained performance will be useful to compare different LLE solutions and can be used in the (re)design phase, to focus on the main arising issues.

It is important to underline that, while the proposed testbed will be used to test exoskeleton for medical purposes, the provided hardware, software and metrics can be adopted in any application area (such as industrial scenarios). The solution is highly flexible, being configurable both at hardware and software sides, providing a scalable and reproducible solution.

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