Instrumented crutches with audio feedback to alter assisted gait

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2021 IEEE International Workshop on Metrology for Industry 4.0 & IoT (MetroInd4.0&IoT) | 978-1-6654-1980-2/21/$31.00 ©2021 IEEE | DOI: 10.1109/METROIND4.0IOT51437.2021.9488501

***Abstract*— The recruitment of Spinal Cord Injury (SCI) users to test exoskeletons for assisting gait must face the limited number of available subjects. Healthy subjects are often involved to ensure a larger sample in the validation and usability tests in preliminary phases, but the reliability of the results is limited. In this paper we propose a method based on audio feedback, driven by instrumented crutches for force measurements, to train healthy subjects to behave as exoskeletons' SCI users, to decrease the discrepancy with real case results. We analyzed 22 able-bodied subjects an exoskeleton in passive mode during a straight walk, in the presence or absence of the audio feedback controlled by the dominant-side crutch. A force threshold to activate the audio feedback before taking each step induces alterations in both the spatio-temporal parameters and the load on the crutches. Learning effects are observed in trials without feedback after brief training with it. Even if the subjects are asked to push symmetrically on the crutches, they pay more attention to the feedback than to the given instructions, causing a load unbalance.**

***Keywords*— exoskeleton, locomotion, biofeedback, instrumented crutches, asymmetry**

I. INTRODUCTION

The incidence of traumatic spinal cord injury (SCI) is 16 to 19.4 new cases per million inhabitants per year in Western European countries [1]. Technologies, like lower-limb powered exoskeletons used for gait therapy, demonstrated functional improvements and the potential to ameliorate the daily life of people with SCI [2]. In the available scientific literature, the tests in these topics are often limited to a small number of participants [3], [4], due to the acknowledged difficulties in finding subjects for exoskeleton trials. Some of the possible causes of the reduced number of subjects are logistical, social, or financial, especially when tests need to be extended for long periods. Even the inclusion/exclusion criteria could limit the sample size [5]. The difficulties related to the number of subjects, however, are also linked to physical problems. As stated in [6], the physiological demand for exoskeleton-assisted walking is 3.3 metabolic equivalents and the evaluation of perceived effort is 10 on the Borg 6-20 scale [7], comparable to the self-reported effort of a skilled person. This could make the subject fatigue easily during the tests, especially if prolonged over time. Despite the difficulties in recruiting subjects, during the early stage of development of the robot, it could be necessary to test several versions of the prototypes with a large number of subjects with heterogeneous weight, height, and gender to investigate the sensitivities of the robot and improve the performance of the device. When conducting a study with a large population, subjects with SCI will have different lesions, duration of injuries, age, and it's difficult to explore this source of heterogeneity as specified in [6]. To limit the variability due to the difference between subjects some tests are conducted with only one patient as seen in [8], [9]. These limitations could be solved using able-bodied subjects trained to behave as SCI subjects, hereinafter called pseudo-SCI-subjects. The use of pseudo-SCI-subject may speed up the proof-of-concept of the technology by performing several rounds of pilot tests with healthy subjects

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before involving SCI subjects in more advanced validation and usability tests. The advantages of conducting tests with healthy subjects are multiple. The risk of incidence of falls is 4.4% and the risk of bone fractures is 3.4% with SCI subjects [6] while, conducting a test with a subject who has full control of his/her limbs, could reduce these dangers. Additionally, conducting a study with patients requires the presence of specialized personnel able to assist them during the tests [9]; this requirement could be prevented with the use of pseudo-SCI subjects. As explained in [10], the proposed approach uses audio feedback to drive the step cadence of pseudo-SCI subjects when wearing the exoskeleton H2 [11]. The subjects are instructed to wait for a specific auditive cue in their earphones before taking each step. The audio feedback is provided when the force measured by the dominant-side instrumented crutch overcomes a given threshold. The instrumented crutches were previously developed by our group (Laboratory of Mechanical and Thermal Measurements, MMT Lab, University of Brescia) [12], [13].

II. Material and Methods

A. Instrumentation

The instrumentation used in the experiments is composed of an exoskeleton (H2, Technaid, Spain) [11], a pair of instrumented crutches (MMT Lab, University of Brescia, Italy) [12], [13], and a pair of commercial in-ears Bluetooth earphones (Taotronics TTBH026).

H2 is a lower limb exoskeleton designed for rehabilitation of adults between 1.50 and 1.95 m in height, with a maximum bodyweight of 100 kg, specifically targeted to patients following neurological insults, i.e., stroke or SCI. It is composed of six actuated joints and is designed to allow intensive over-ground gait training. In this set of tests, the exoskeleton is used in passive mode since the users are all healthy subjects with the ability to walk autonomously. Even if the exoskeleton is moved passively, it manages to accomplish its function of constraining the motion of the user's legs and forcing his walking in a specific and rigid pattern. The battery pack was also removed to avoid unbalancing the user. The exoskeleton was adjusted to fit each participant aligning the centers of anatomical and robotic joints. Participants are secured in the device with a series of straps.

TABLE I. The Inclusion and Exclusion Criteria.

Inclusion criteria	Exclusion criteria
Gender: any	Pregnant, lactating or postmenopausal woman;
Do not have skin problems (e.g., sores) that prevent the use of instruments	Use of an external device that supports the spine or the head, neck or torso
Must be able to follow instructions given and demonstrate learning skills	Persistent orthostatic hypotension (blood pressure drop of more than 30 mmHg with the robotic system)
Do not have any medical problem that prevents the full load or intolerance to exercise with the exoskeleton (e.g., orthopaedical disorders, pain, spasticity...)	Subjects who were hospitalized for heart attack, cardiac surgery or acute heart failure in the 3 months prior to joining the study or the presence of significant cardiovascular disease or DVT in the lower limbs (within the last 3 months)
Must be able to physically adapt to the exoskeleton	The intake of any drugs that affect bone metabolism.
Weight: lower than 100 kg without the exoskeleton	
Age: 18-75 years	
Height: 140-190 centimetres	

The instrumented crutches allow monitoring the axial forces and the anteroposterior and mediolateral orientations in real-time. As shown in Fig. 1, each crutch is composed of one strain gauge bridge, a conditioning circuit connected to a microcontroller with an AD converter. The microcontroller also manages a tri-axial accelerometer, and it sends the data with the transmitting module ESD200 via Bluetooth. The power supply is provided by a battery on each crutch. The audio feedback is handled by a virtual instrument developed in LabVIEW, which controls a Bluetooth earphone worn by the user. The virtual instrument also acquires the crutch force every 20 ms.

B. Audio feedback

Considering that the original goal of this study [10] is to reduce the cadence of the healthy subject, the proposed

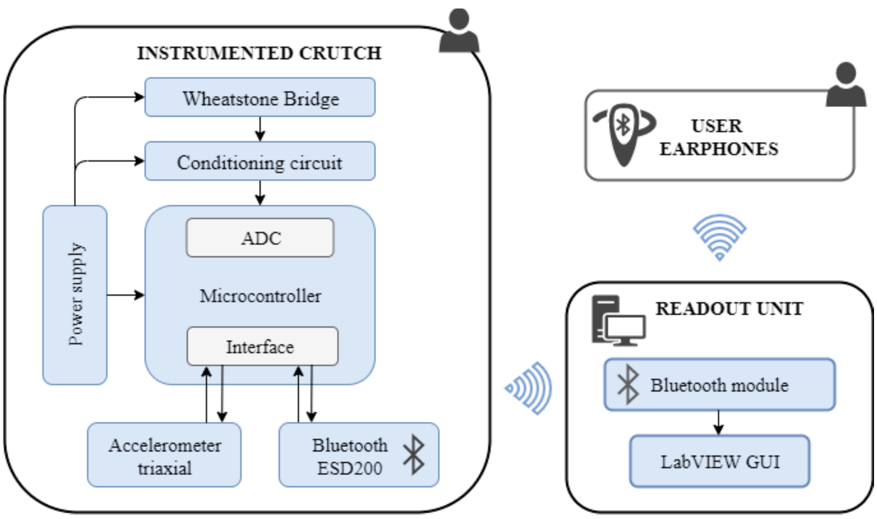

Fig. 1 - Diagram of the circuit board of each instrumented crutch, and of the feedback system.

method is based on audio feedback driven by the load measured on the dominant-side crutch, which is compared with two force thresholds. Since in [14] a case study on an expert SCI ReWalk user demonstrated average load peaks of 24% of the bodyweight on the crutches the lower force threshold is set as 20% of the body weight, instead of an auto-tuning approach (e.g., as in [15], [16]). The value of the total body weight of the subject is corrected by adding the weight of the powered exoskeleton. If the force measured by the dominant-side crutch is higher than the lower limit, the program generates a low-pitched sound, which is transmitted to the earphones; this sound is reproduced until the force value drops again below the lower threshold. Furthermore, to avoid inducing an excessive reliance on the crutches for propulsion, the upper threshold is set to 35% of the total body weight. Thus, the program generates a sound with a higher pitch if the upper limit is crossed. To avoid false feedback due to the signal noise the algorithm generates the sound when at least three force samples overtake the threshold adding a delay of 60 ms.

C. *Test protocol*

22 able-bodied subjects were recruited for the study (n=22: 10 women and 12 men, aged between 21 to 41 years, with a mean age of 26.7 years). Relevant ethical approvals and informed consent is obtained before conducting the study (048/2019; CSIC Ethical Committee). Inclusion and exclusion criteria for the study are reported in Table I.

As shown in Fig. 2, all subjects perform an initial familiarization phase with the exoskeleton and the instrumented crutches. The familiarization phase consists of 5 minutes of over-ground walking at a comfortable self-selected speed, without any audio feedback. Subjects are asked to mimic the gait pattern of SCI users by moving the crutches and applying force on them before initiating the next step. After a rest interval of 10 minutes, a 10 meters Walking Test (10MWT) is performed once without audio feedback, following the same instructions given during familiarization. Then the 22 subjects are split randomly into two groups of 11 subjects each. The first group (in the top of Fig. 2) performs the tests as follows: (i) another familiarization phase, this time with the audio feedback; (ii) 10 repetitions of the 10 MWT with the audio feedback; (iii) A 10-minute rest to avoid fatigue; (iv) 10 repetitions of the 10MWT without the audio feedback. This group is called Feedback - No feedback (FN) in all results charts, because the 11 subjects start with the 10 trials with the feedback. The other group (at the bottom of Fig. 2) performs the test in the same way but exchanging the order of execution, to investigate any training effect on the results: the trials without audio feedback are carried out before the trials with audio feedback. The familiarization phase is also postponed giving the following order: (i) 10 repetitions of the 10MWT without the audio feedback; (ii) a 10-minute rest to avoid fatigue; (iii) another familiarization phase, this time with the audio feedback; (iv) 10 repetitions of the 10MWT with the audio feedback. This group is called No Feedback – Feedback (NF) in all results charts. The subject is also provided with the instructions of performing the step only after having perceived the audio feedback (in feedback tests only) and pushing on crutches with symmetrical load even if the feedback is driven only by the dominant-side force. The subjects are not informed about the side that controls the feedback.

III. Results

The forces applied on the crutches are normalized with respect to the weight of the subject and the exoskeleton, and the maximum value for each load cycle is recorded. Table II and Fig. 3 show the results for the peak value of the force applied on the crutches on both sides.

The dominant-side force increases about 9% in the group FN with respect to the baseline even when the audio feedback is removed, reaching 24% of the total weight as desired to compare it with the ReWalk expert user in [14]. Learning effects are observed in absence of feedback in group FN (left side of Fig. 3) demonstrating that the subjects, who made the feedback tests first, understand how to replicate the previous loads. Only about 20% of the total weight is observed in the non-dominant side force highlighting an asymmetrical load behavior.

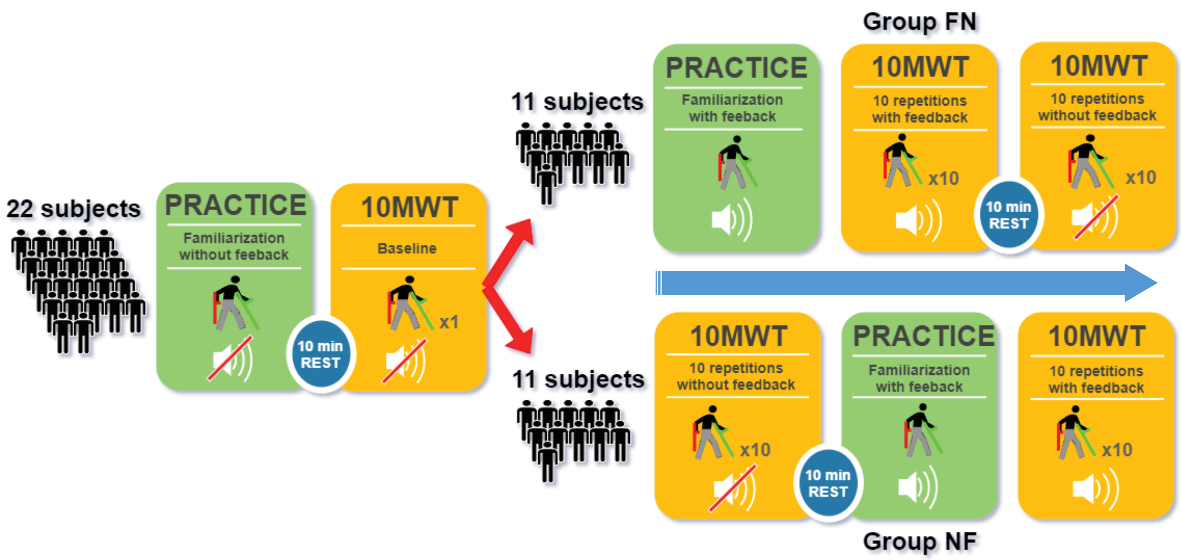

Fig. 2 - Test protocol design. After a familiarization session and a 10MWT the 22 subjects are splitted into two groups: the group FN performs the tests with feedback first and the group NF performs the tests without feedback first. A familiarization session with audio feedback is performed before the 10MWT with feedback.

TABLE II. NORMALIZED PEAKS FORCE RESULTS.

Force peaks [% of the total weight]		Group NF		Group FN	
		Dominant	*Non-Dominant*	*Dominant*	*Non-dominant*
Baseline	**Mean**	**19.8**	**16.4**	**15.3**	**14.4**
	Std. dev.	8.5	5.8	8.1	5.2
Feedback	**Mean**	**26.7**	**18.3**	**24.2**	**19.1**
	Std. dev.	7.7	5.6	7.1	5.8
No feedback	**Mean**	**17.9**	**14.1**	**24.1**	**20.1**
		9.5	5.7	7.0	6.7

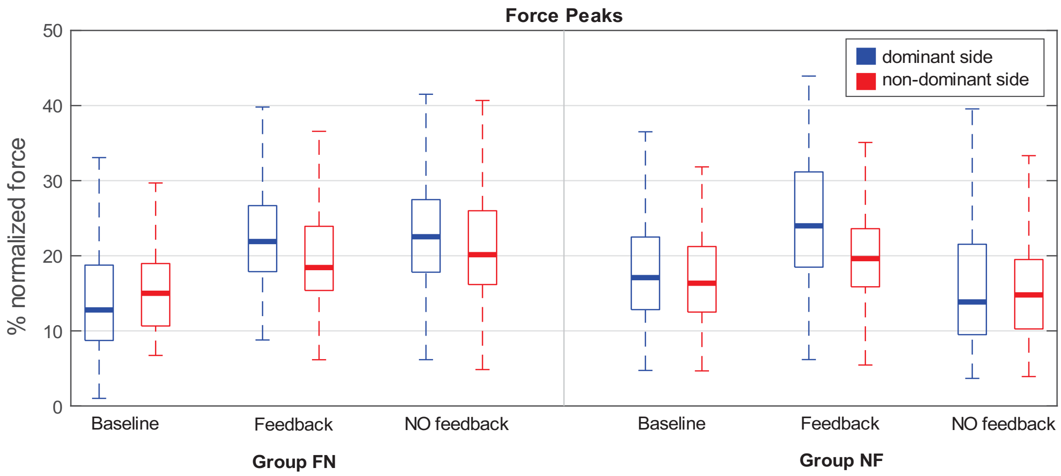

Fig. 3 - Boxplot of the normalized peaks force.

Asymmetrical load persists even in the tests with feedback of the group NF during which the peak value of the force reaches 27% on the dominant side and 18% on the non-dominant side. The presence of audio feedback, compared to the tests without it, increases the peaks of force by about 8.8% on the dominant side and only by 4.2% on the non-dominant side.

When interviewing the subjects, no one complains about the time that elapses between exceeding the lower force threshold and the generation of the sound that is supposed not perceptible.

IV. CONCLUSIONS

The method proposed, as described in [10], aims to induce changes in the gait spatiotemporal parameters in able-bodied subjects to make them as similar as possible to those of the expert exoskeleton user with spinal cord injury (SCI). While the original approach is focused on changes of the load applied on the instrumented crutches, the audio feedback has an influence on the cadence of the subjects: the median values of the cadence decrease about 29% from tests without the audio feedback to tests with the feedback [10], furthermore the normalized peaks forces on crutches increase by 8.8% in the dominant-side and by 4.2% in the non-dominant side.

The analysis of the group training with the feedback first (FN) suggests that there is a learning effect that persists even after the feedback is removed both in cadence [10] and force. This demonstrates the potential of using the training procedure to prepare subjects for tests with exoskeletons prototypes, by having them perform a short training session with the instrumented crutches.

The pseudo-SCI subjects are not informed about the side that controls the feedback but, comparing the load of the dominant and non-dominant sides, an asymmetrical behavior is identified especially in presence of the audio feedback. The subjects load more on the dominant-side crutch suggesting that they pay more attention to the audio feedback than on the instructions given to them to load symmetrically. The proposed strategy could induce load unbalance that can be (or not) a desired behavior to simulate more precisely the asymmetry of an exoskeleton's user. Aiming to improve the walking simulation, tests should be carried out to discover if an SCI user loads more on the stronger side, i.e., the dominant side.

Anyway, further experiments should investigate other strategies to include also the non-dominant side force in the audio feedback control.

Acknowledgment

The authors would thank Marcello for the preliminary and Technaid srl for the logistic support.

This article is supported by COST Action CA16116, (European Cooperation in Science and Technology) and the European project EUROBENCH (grant 779963).

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