Design and Validation of a Tripping-Eliciting Platform Based on Compliant Random Obstacles

Eugenio Anselmino, Lorenzo Pittoni, Tommaso Ciapetti, Michele Piazzini, Claudio Macchi, Alberto Mazzoni, Silvestro Micera, *Fellow, IEEE*, and Arturo Forner-Cordero, *Senior Member, IEEE*

Abstract*—*Goal: **The experimental study of the stumble phenomena is essential to develop novel technological solutions to limit harmful effects in at-risk populations. A versatile platform to deliver realistic and unanticipated tripping perturbations, controllable in their strength and timing, would be beneficial for this field of study.** ***Methods:*** **We built a modular tripping-eliciting system based on multiple compliant trip blocks that deliver unanticipated tripping perturbations. The system was validated with a study with 9 healthy subjects.** ***Results:*** **The system delivered 33 out of 34 perturbations (a minimum of 3 per subject) during the desired gait phase, and 31 effectively induced a tripping event. The recovery strategies adopted after the perturbations were qualitatively consistent with the literature. The analysis of the inertial motion unit signals and the questionnaires suggests a limited adaptation to the perturbation throughout experiments.** ***Conclusions:*** **The platform succeeded in providing realistic trip perturbations, concurrently limiting subjects' adaptation. The presence of multiple compliant obstacles, tunable regarding position and perturbation strength, represents a novelty in the field, allowing the study of stumbling phenomena caused by obstacles with different levels of sturdiness. The overall system is modular and can be easily adapted for different applications.**

***Index Terms*—Falling, trip, stumble apparatus, tripping platform, stumble recovery strategies.**

***Impact Statement*— The presented system is a promising solution for the study of trip perturbations caused by compliant obstacles. The system is fully adaptable in terms of configuration and perturbation strength.**

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Eugenio Anselmino and Alberto Mazzoni are with the Department of Excellence in Robotics and AI, Scuola Superiore Sant'Anna, The BioRobotics Institute, 56127 Pisa, Italy (e-mail: eugenio.anselmino@santannapisa.it).

Lorenzo Pittoni is with the Department of Electronics, Information and Bioengineering, Politecnico di Milano, 20133 Milano, Italy.

Tommaso Ciapetti, Michele Piazzini, and Claudio Macchi are with the Institute of Recovery and Care of Scientific Character (IRCCS), Fondazione Don Carlo Gnocchi, 50143 Firenze, Italy.

Silvestro Micera is with the Department of Excellence in Robotics and AI, Scuola Superiore Sant'Anna, The BioRobotics Institute, 56127 Pisa, Italy, and also with the Bertarelli Foundation Chair in Translational Neuroengineering, EPFL, 10115 Lausanne, Switzerland.

Arturo Forner-Cordero is with the Biomechatronics Laboratory, Department of Mechatronics and Mechanical Systems, Escola Politécnica da Universidade de São Paulo (USP), São Paulo 05508-010, Brazil.

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I. Introduction

GAIT dynamics can change due to pathologies [1] and external perturbations. The latter can affect the ability to navigate the environment of an individual, especially if other health conditions are involved. Typical perturbation phenomena are trip and slip events, which respectively happen during the swing and stance phase of the perturbed leg. In this work, we focus on tripping perturbations, that are the main cause of falls among elders [2], [3], [4]. Additionally, health issues such as the presence of osteoarthritis [5], stroke [6], and lower limb amputation [7] can increase the risk of fall-related injuries.

Trip and stumble events happen during the swing phase of the gait cycle when the foot impacts an obstacle and the trip onset is strongly related to the recovery strategies adopted by the subject [8]. In healthy individuals, three recovery strategies have been reported consistently in the literature [8], [9], [10], [11]:

- *Elevating strategy*: generally chosen with early swing perturbation offsets.
- *Lowering strategy*: generally chosen with late swing perturbation offsets.
- *Delayed lowering strategy*: adopted when the elevating strategy fails.

During the mid-swing, an overlap of the recovery strategies is observed: with longer perturbations (150-300 ms) the lowering strategy is preferred, while with shorter ones the elevating strategy is adopted [11].

With pathologies such as stroke and lower limb amputations subjects suffer from an increased risk of experiencing trip-related falls [12], [13]. These individuals can adopt different recovery strategies:

- *Hopping strategy*: the subject jumps over the obstacle with both feet, this strategy is used by both prostheses wearer [14] and stroke patients [12].

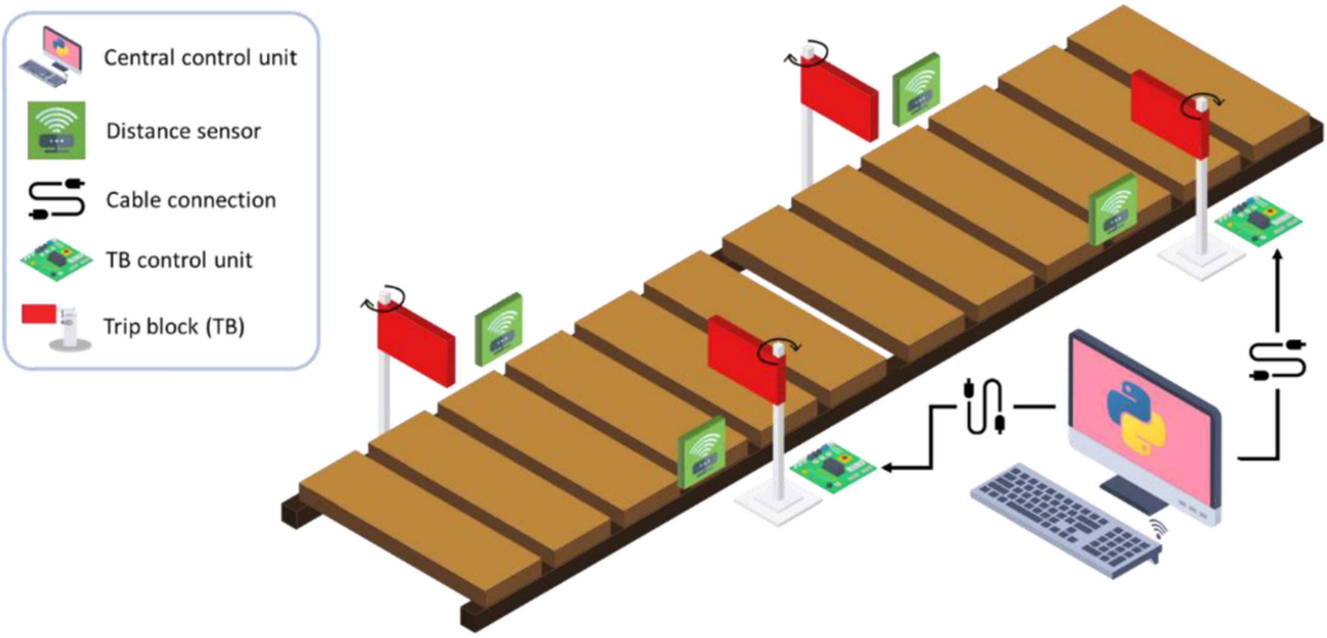

Fig. 1. Schematic representation of the trip setup. The multiple trip blocks (TBs) are visible by the subject during the experimental session.

- *Skipping strategy*: the subject takes an extra step with the perturbed foot before moving the support leg, such strategy is normally used by unilateral leg amputees [14].
- *Pivot strategy*: the subject pivots around the perturbed foot, taking multiple steps with the sound side, this strategy is generally used by stroke patients [12].

It is possible to categorize the gait perturbation setups present in the literature into three groups:

- *Tether-based setups*: tethers attached to the subject ankles can be pulled to mimic the presence of an obstacle. The perturbation can be obtained manually [15], or automatically [9], [11]. The elicited recovery strategy is comparable to the ones adopted with physical obstacles, but it is not proven if the tether and obstacle-caused accelerations match.
- *Treadmill-based setups*: they rely on sudden deceleration/acceleration of the treadmill. The perturbation can be applied during a static [16] or dynamic [17], [18], [19] task. The strategies adopted are comparable to the ones of a real-life trip [16]. The major drawback is the lack of impact with a physical object, which does not generate passive kinetic and kinematic changes in knee and ankle joints [20].
- *Obstacle-based setups*: physical objects are used to alter the trajectory of the foot. They can be divided into passive [21] (i.e., the obstacle is fixed on the ground), manual [22] (i.e., an operator moves the obstacle), and automatic [23], [24], [25]. If compared to passive solutions, manual and automatic ones lower the risks of anticipatory movements. The main advantage of obstacle-based techniques is the realism of perturbation, which guarantees realistic recovery strategies while generating passive changes in the leg.

A second categorization can be done by dividing the existing solutions into treadmill and overground walking setups. In *treadmill setups* ([9], [11], [19], [23]), the subject's speed is forced to be constant over time, guaranteeing consistent gait cycles and recovery strategies at the expense of decreased realism. On the contrary, in *overground walking setups* ([21], [22], [25], [26]) gait speed is not forced and a greater variability among steps and recovery strategies is promoted. Both tether and obstacle-based solutions can be implemented with the subject walking overground or on a treadmill.

Here, we present a novel device to elicit realistic trip perturbations in a controlled setting. The objective is to validate a platform to investigate the biomechanics of human gait further, allowing the development of more robust stumble detection algorithms (Fig. 1). During the development process (Section II-A), we focused on having perturbations capable of eliciting subjects' reaction, concurrently limiting anticipatory behaviors and maintaining realistic experimental settings by limiting subject's movement constraints. For these reasons, we adopted a solution with multiple widely spaced compliant obstacles mounted on the side of a platform where the subject can walk freely. The ability of the system to provide multiple effective trip perturbations, limiting the subject's adaptation, is validated with a healthy 9-subjects study.

II. Materials and Methods

A. Key Design Concepts

Our device consists of i) a walking platform (WP) on which the subjects walk during the experimental session, ii) multiple trip blocks (TBs) that deliver the perturbation, and iii) the control algorithm (CA) responsible for providing the perturbation with the correct timing. A gait phase detection system (GPD) is used to synchronize the TBs activation with the subject's gait. A schematic representation of the device is shown in Fig. 1. In the current section, we will unpack the core design choices; in Section I of the Supplementary Materials we will provide details regarding the building process and materials of the WP, TBs, and the GPD system; and in Section II of the Supplementary Materials, we will present the CA.

To overcome the limitations introduced in Section I, we decided to focus on two main objectives: perturbation realism and safety. The first objective has been pursued by developing a modular device, composed of multiple TBs able to place themselves in the perturbed foot trajectory. In this way, we could exploit the realism entailed by the overground walking and obstacle-based solutions, further reducing anticipatory movements by adopting multiple TBs. Avoiding anticipatory movements is critical for simulating realistic perturbations and reducing the adaptation phenomenon, which would prevent the possibility of experimental sessions with multiple trips [24], [27]. For this reason, we adopted an elastic-based solution capable of quickly eliciting the tripping perturbation: the TB has a part fixed to the side of the WP (Fig. S1a) and a rotating part that moves to position itself on the foot trajectory when unlocked (Fig. S1b, S1c). When locked the obstacle is parallel to the WP (Fig. S1b). The obstacle deployment instant is managed by the CA, which relies on footswitches (Fig. S2) to discriminate gait phases and distance sensors to determine when the correct foot passes by the TBs (see Supplementary Materials, Section II). The adoption of an elastic-based solution simulates the case of a compliant obstacle (i.e., obstacles not fixed to the ground), which has never been considered in the literature. To avoid reducing gait variability the setup relies on a walking platform (i.e., the WP). The WP provides a structure to fix the TBs and helps the subjects maintain the correct distance from them, utilizing a guiding line drawn on the platform; such distance is essential to avoid wrong foot or missed perturbations.

Modularity and flexibility are key aspects of the tripping platform, which guarantees the setup to be adapted to different experimental needs: it is possible to lengthen and shorten the walkable area by connecting multiple WPs, and any arbitrary number of TBs can be employed, placing them in the desired configuration. The activation of the TBs is controllable both in terms of timing and force and can be randomized as needed.

The safety of the system is guaranteed by a rail-mounted safety harness and by the elastic-actuated mechanism of the TB. Unlike the elastic mechanisms present in literature, which rely on solid bars emerging from the ground [18], [28], TBs obstacles remain compliant after the deployment. Consequently, the TBs compliance can be tuned depending on the experimental requirements, avoiding excessive forces on the subject's foot.

B. Experimental Validation

To validate the device a healthy 9-subject study was conducted at Fondazione Don Carlo Gnocchi (Florence, Italy), analyzing the adopted recovery strategies and the timing of the elicited perturbations. The experimental protocols were approved by the Comitato Etico Regione Toscana - Area Vasta Centro (protocol number: 25493_spe), and all subjects gave their written informed consent. The enrollment strategy aimed to recruit a homogeneous sample of subjects to ensure repeatable biomechanical responses. Nevertheless, a subject above the normative range of height and weight (Subject 2) was included to assess the robustness of the proposed platform. Information regarding the enrolled subjects is presented in Table I.

TABLE I
SUBJECTS INFORMATION

Subject	Gender	Age	Height	Weight
1	Male	27	174 cm	76 Kg
2	Male	30	192 cm	93 Kg
3	Male	27	185 cm	85 Kg
4	Male	28	185 cm	73 Kg
5	Female	26	159 cm	55 Kg
6	Female	29	165 cm	62 Kg
7	Female	28	155 cm	54 Kg
8	Male	25	173 cm	70 Kg
9	Male	33	178 cm	80 Kg

All subjects were in healthy conditions at the moment of the experimental session.

Fig. 2. Positions of the IMU sensors.

1) Experimental Setup: For this study, a system configuration with a 6 m long WP and four TBs was used, and the swing threshold was set to 67% of the swing duration to elicit perturbations in the early and mid-swing phases of the gait [29]. To perform kinematic measurements the right leg of the subjects was instrumented with three Inertial Motion Units (IMUs) (Xsens wireless Motion Tracker Awinda system [30]) placed on the dorsum of the foot, in the proximal part of the leg, external part; and in the middle of the thigh, external part (Fig. 2). One IMU has been placed in the center of the posterior part of each one of the obstacles, to identify the exact instant of the foot perturbation. IMU signals have been acquired with a sampling frequency of 100 Hz.

2) Experimental Protocol: The experimental protocol consisted of the following steps:

1) The subject is instrumented with FSRs and IMUs (Fig. 2).
2) The subject stands still until the reproduction of an acoustic tone, after which he/she starts walking back and forth on the WP following the guiding lines.
3) In the first trial, the subject is asked to reach the end of the WP and stop after two minutes; this is done to allow the subject to familiarize with the setup and to acquire baseline gait data. In the subsequent trials, the end is determined by the activation of the TBs.
4) After a perturbation event, the subject is asked to fill out a questionnaire regarding the elicited perturbation (see Section II-B3)).

Every subject was asked to perform at least four trials in a 1-hour time slot. If at the end of the four trials time was still available, additional trials with perturbations were performed.

3) Questionnaire: At the end of each trial, the subject was asked to compile a form with the following questions:

1) How much were you surprised by the obstacle activation?
2) How close to a real-life stumble was your impact on the obstacle?
3) Do you feel that your reaction to the stumble was natural?
4) Did you feel any discomfort upon impacting the obstacle?

Answers were provided on a scale from 1 to 5. The questionnaire's goal was to have the subject's opinions and to analyze their changes during the experimental session, monitoring possible adaptation phenomena.

4) Data Processing: IMU data are upsampled to 1 kHz. The footswitches and IMU data synchronization are performed by lining the first toe-off computed on the footswitch signals with the first instant of the maximum angle between the foot and the transversal plane [31], extracted from IMU signals.

The obstacle-foot impact instant is identified using the signal of the IMU placed on the rotating obstacle. The average and standard deviation of the anteroposterior acceleration (i.e., the acceleration tangential to the obstacle rotation) for activations without impact were computed before the experiments and compared to the activations with impact. The instant of impact is identified when the signals diverge by a value greater than the standard deviation. The recovery strategy adopted is identified using the video recordings, according to the definitions presented in Section I.

A database containing normal, perturbed, and recovery steps has been created by resampling the swing and stance phases, respectively to 800 and 1200 samples to maintain the typical proportions of the gait cycle. The original durations have been saved together with the tripping instant, the trial and subject identifiers, and the class.

III. Results

During the experimental session, the device delivered 34 perturbations: 33 during the desired gate phases (i.e., early and mid-swing), and one during the late swing phase; for a total of 97% of perturbations delivered with correct timing. The recovery strategies observed for the 9 subjects were qualitatively consistent with the literature concerning healthy individuals, except for the presence of the lowering strategy during the early-swing trials, although only in one case. As shown in Fig. 3(left), during the early swing phase the subjects adopted 16 times an elevating strategy, 2 times a delayed lowering strategy, and 1 time the lowering strategy; while during the mid-swing the elevating strategy was adopted 4 times, the delayed lowering 3 and the lowering 5. In two cases it has not been possible to identify the adopted recovery strategy, since the subject did not modify the trajectory of the foot. All the unsuccessful trials occurred with Subject 2. Fig. 3(right) shows the relation between the recovery strategy adopted and both the perturbation instant and the average stride duration of the trial. The delayed lowering and lowering strategies are favored with late perturbation onsets, while no strong relations are present between stride duration and strategy adoption.

The impact with the obstacle generated noticeable variations in the linear accelerations and angular velocities measured, that deviate from the average values acquired during unperturbed walking (Fig. 4), confirming the ability of the device to effectively elicit trip perturbations. To investigate the consistency of the reactions, we selected for each subject a portion of the foot IMU signals (the 30% of the swing phase following the foot-obstacle impact) belonging to trials with the same perturbation phase and recovery strategy, and we computed the correlation coefficient. Due to the randomness of the experiment, the presence of multiple perturbations provided in the same gait phase and with the same recovery strategy for each subject was not guaranteed; nevertheless, we found signals that satisfied the requirements for 6 out of the 9 subjects. The foot IMU signals were selected for the analysis due to the bigger magnitude of the perturbation. The normalized correlation coefficient for the population is 0.68 ± 0.16 (mean $\pm$ standard deviation), suggesting that the subjects adopted consistent strategies throughout the experimental session. Accordingly, Fig. 5 shows the average variation of stride, swing, and stance durations throughout the experiment, normalized for each subject with respect to their first trial. The mean fluctuations are less than 10% of the initial condition with standard deviations of the same magnitude, suggesting the absence of a clear adaptation trend.

The questionnaire results show a perceived realism of the perturbation ranging from 3 to 5 across the experimental session (Fig. 6, top left). The recovery naturalness has been perceived as generally high throughout the experiments, with answers above or equal to 4 except for 3 trials (Fig. 6, top right). For both parameters, the answers showed minimal subject-wise variations. The activation surprise level remained high across trials, with values around 4. Minimal variations were observed (Fig. 6, bottom left). Only one subject reported a consistently high level of discomfort during the experiments, while the answer provided by the rest of the population stood around 2 (Fig. 6 bottom right). No noticeable variations are present in the discomfort level throughout the session.

IV. Discussion

The platform presented was capable of eliciting realistic trip perturbations, forcing the subject to adopt previously reported

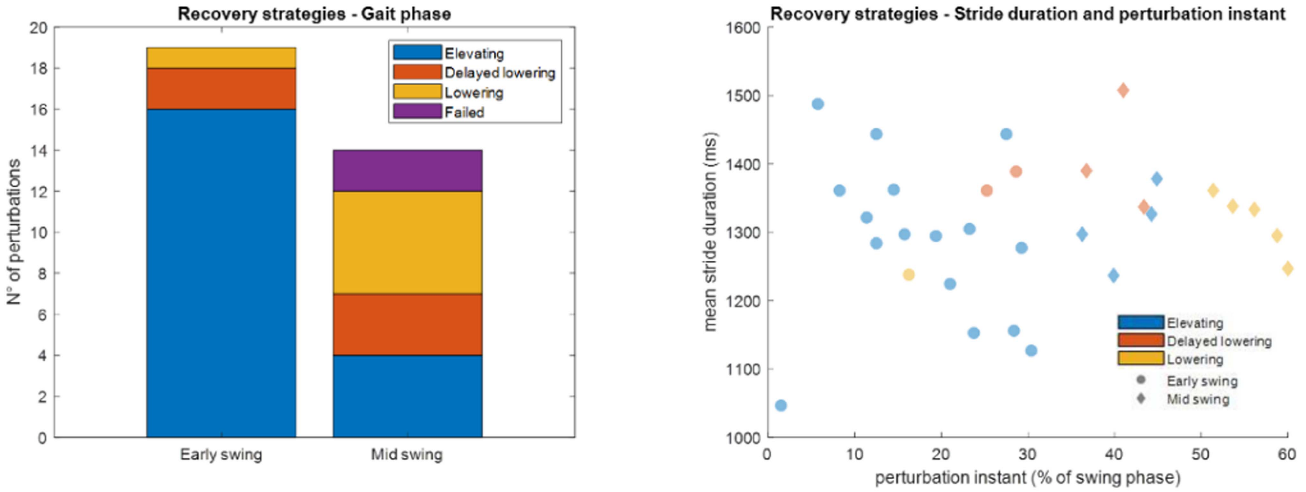

Fig. 3. Recovery strategies adopted with respect to swing phase (left) average stride duration of the trial and perturbation instant (expressed in percentage of the swing phase) (right).

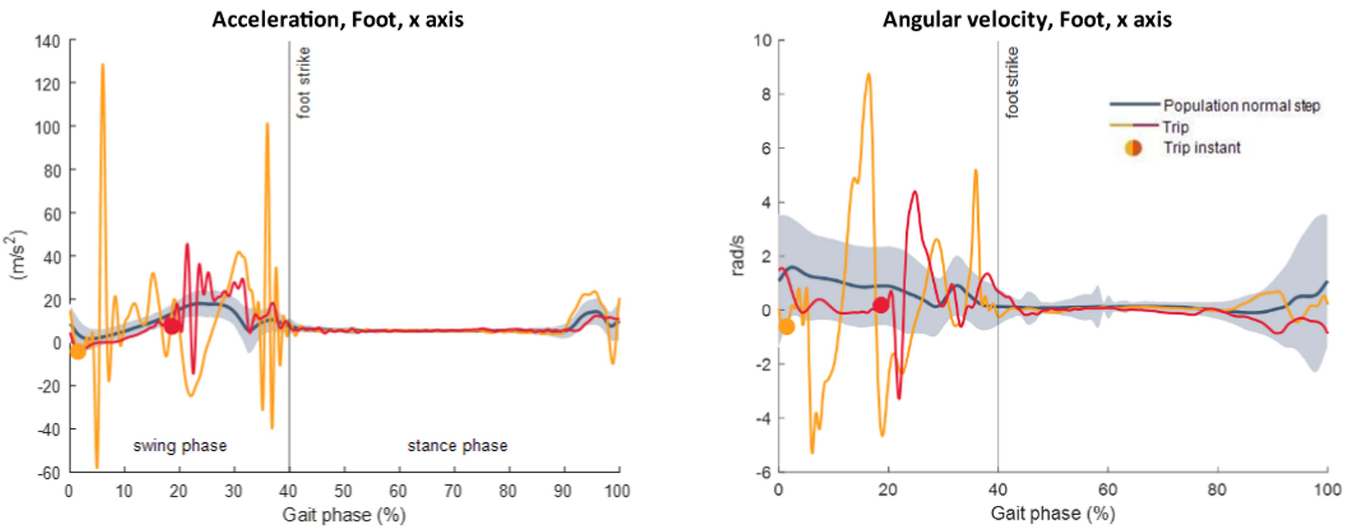

Fig. 4. Example plots showing the differences between normal and perturbed steps from the point of view of accelerometers (left) and gyroscopes (right) data.

recovery strategies. The device can deliver repeated perturbations at the desired gait phase, early and mid-swing for these experiments but potentially across the entire swing duration.

We could not find any adaptation from a subjective point of view (unlike previous research [32]), with limited variation of the surprise level, and in terms of measured gait parameters (i.e., stride, swing, and stance durations). Gait parameters showed limited and inconsistent variations across subjects, in agreement with previous results [33]. The absence of adaptation phenomena is supported by the consistencies present in the IMU signals of the foot following the trip perturbation (see Section III), with a mean correlation coefficient of 0.68 $\pm$ 0.16 (mean $\pm$ standard deviation) between trials with the same perturbation phase and recovery strategy. These results suggest that the setup limited subjects' adaptation, allowing the delivery of effective subsequent perturbations.

We observed recovery strategies and timings consistent with previous literature [9], [10], [24]. Anyway, one subject performed the lowering strategy during the early swing phase, which was not expected. Despite this happening only once, it is important to analyze the possible causes. Firstly, since in our experimental setup the subject is walking overground, the participant was not forced to continue walking after the perturbation, as with treadmill setups, but was free to adopt a safer strategy, stopping the movement and restarting it once stability was regained. Secondly, the compliance of the TB allowed the subject to push through the obstacle and lay his foot on the ground, selecting a more effective recovery strategy and reducing the risk of failing an elevating strategy attempt. Indeed, the delayed lowering strategy was also adopted fewer times if compared to the lowering and elevating ones during the mid-swing. It is worth mentioning that with a compliant obstacle, the foot does not stop

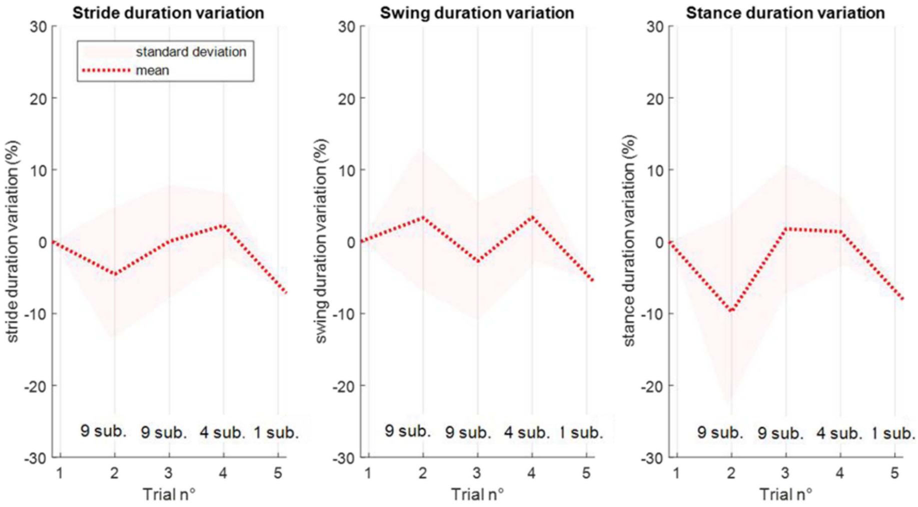

Fig. 5. Variation of the duration of stride, stance, and swing phases of the gait cycle; all the quantities are normalized with respect to the subject's first trial.

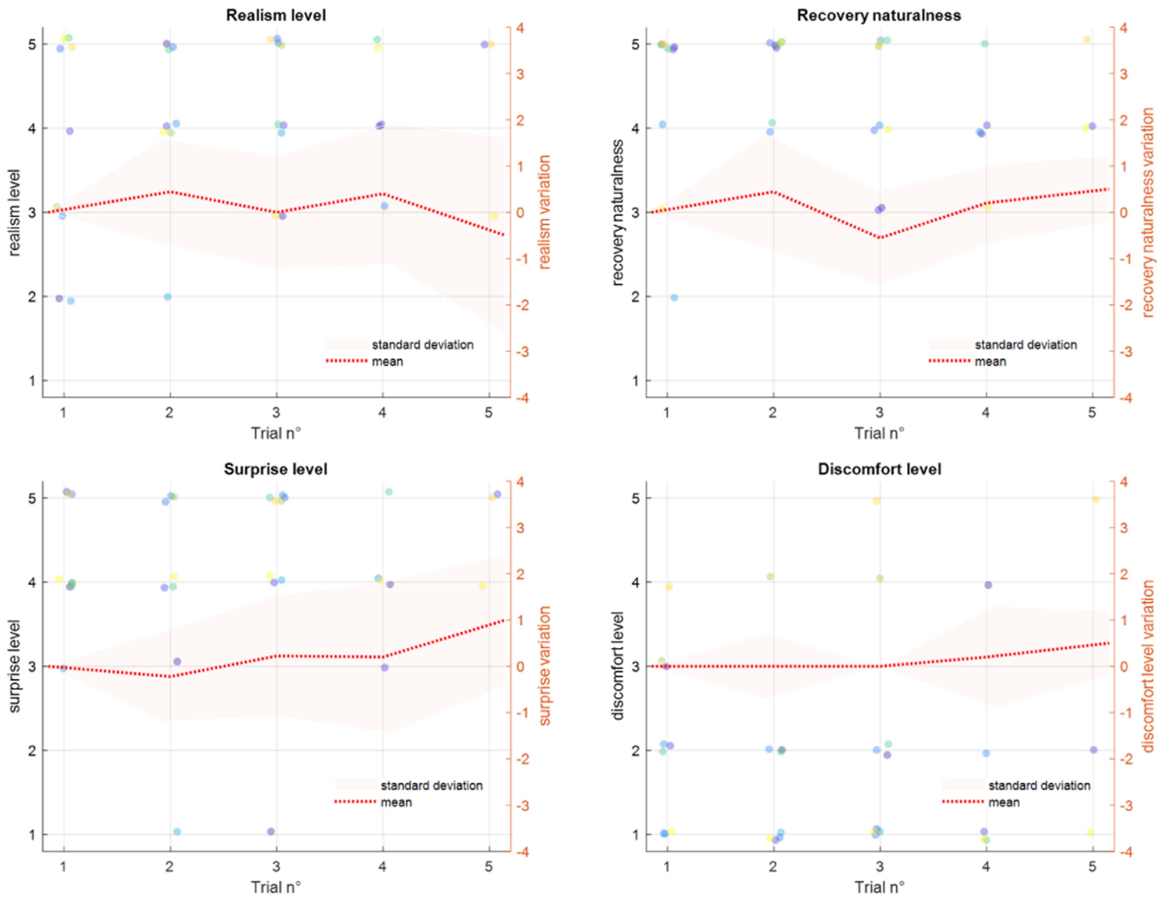

Fig. 6. Subjects' answers of the compiled forms (left axis) and mean population variation of the answers through the experimental session (right axis).

abruptly after the impact, which has two main consequences: the foot position at the instants of the subject's reaction and foot-obstacle impact is not the same (in contrast to what happens with high rigidity obstacles), causing longer perturbations which favor the adoption of the lowering strategy [33]; and the subject is less unbalanced forward, which also favors the adoption of the lowering strategy [34], [35]. The reduction of the forward unbalance is also assisted by the adoption of a non-treadmill solution. In the future, more in-depth studies will be necessary to assess the relation between the compliance of the obstacle and the selection of the recovery strategy.

During all experimental sessions, we provided 34 perturbations to 9 subjects, in line with some of the studies present in the literature [17], [21]. Only 2 of the 34 tripping perturbations provided were ineffective. Both perturbations happened with Subject 2: an outlier in terms of height (192 cm) and weight (93 Kg). In the future, we will tackle the issue by adopting elastic bands of different strengths depending on the physical characteristics of the subject. Overall, the 95% success rate of the system is in line with previous literature works that report this metric [24].

No subject perceived the perturbation and recovery as unrealistic or artificial during the whole experimental session, indicating the ability of the system to provide realistic trip perturbations consistently. The level of surprise due to the activation remained high and constant for most of the trials, demonstrating the ability of the device to prevent adaptation phenomena and preparatory movements.

V. Conclusion

The presented trip-eliciting platform proved to be a valuable solution for simulating realistic perturbations and studying recovery strategies in a controlled environment. Concerning the state-of-the-art, our system presents the possibility of using multiple widely spaced TBs, with different configurations both in terms of compliance and position, concurrently allowing a self-selected gait speed. The presence of a tunable compliant obstacle represents a novelty, allowing the study of stumbling phenomena caused by obstacles that are not fixed to the ground or with different degrees of sturdiness. Ultimately, the setup guarantees maximum flexibility and the best conditions to mimic real-life scenarios. The setup could be reconfigured and potentially used in a wide variety of gait biomechanics studies and for rehabilitation purposes, such as gait retraining in elderly and neurological patients [36], or trip-related specific training protocols [37].

In future works, we will test the system with different subject populations (e.g., lower limb amputees, parkinsonian) and use it for developing stumble detection algorithms and extracting balance-related biomarkers. The device can also be reconfigured to study the recovery strategies adopted during subsequent tripping perturbations, without allowing the subject to fully recover from the previous stumble.

Supplementary Materials

The authors provide supplementary materials. They describe in detail the hardware and software design of the presented tripping-eliciting platform.

Competing Interests

The authors declare that they have no competing interests.

Authors' Contributions

EA, LP, and AFC were the main contributors to conception and design, algorithm design, and apparatus design and construction. EA, LP, TC, and MP were the main contributors to data acquisition. EA and AFC were the main contributors to the data interpretation and drafting of the manuscripts. AM, SM, CM, and AFC contributed to the manuscript revision. SM and AM contributed to funds acquisitions.

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