



# Development of Proprioceptive and Vibrotactile Training Modes for BALANSens Platform

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**Abstract**—Recent studies have shown that training plantar tactile perception (vibrotactile sensation) and ankle joint position awareness (proprioceptive sensation) can substantially improve balance and gait rehabilitation. Building on these findings, we developed two training modes for the BALANSens robotic platform, a 3-RPS lower-limb rehabilitation manipulator designed in alignment with the Integrated Balance Rehabilitation (I-BaR) framework. In the proprioceptive training mode, the robot guides the subject's ankle to a target position and back, after which the subject reproduces the movement without visual feedback. In the vibrotactile training mode, one of the motors stimulating the plantar surface is randomly activated, and the subject identifies the stimulated region. This paper presents the design and functional evaluation of these training modes with healthy subjects. Results indicate that angular deviation (with and without VR) in proprioceptive training, along with accuracy and response times in vibrotactile training, serve as reliable quantitative performance metrics. Clinical trials are planned to further solidify this claim of potential of sensory feedback-based interventions for rehabilitation.

**Index Terms**—Proprioception, multi-modal sensory feedback, virtual reality environment, robotic rehabilitation

## I. INTRODUCTION

Postural stability and walking balance rely heavily on accurate sensory feedback from the feet and ankle proprioception. Among chronic stroke patients, ankle proprioception is among the strongest predictors of balance impairment [1]. The cutaneous afferent system of the plantar surface provides critical information for maintaining upright stance and coordinating gait, influencing both static and dynamic stability. Disruption of this sensory input, whether due to neurological injury, ageing, or disease (such as Parkinson's or multiple sclerosis), can significantly impair balance control and increase fall risk.

Proprioceptive training, aimed at enhancing the body's awareness of limb position and movement, has been shown through meta-analyses of randomized controlled trials to markedly improve balance performance, gait speed, trunk

control, and functional mobility in individuals recovering from stroke [2], [3]. In fact, even a single session of proprioceptive training with feedback has shown to improve movement accuracy and to induce functional connectivity changes in the brains of chronic stroke patients [4].

Among various sensory enhancement strategies, vibrotactile stimulation has emerged as a promising method for augmenting feedback during rehabilitation. Systematic reviews indicate that vibrotactile cues, delivered to areas including the plantar surface, can enhance both static and dynamic postural performance by supplementing the central nervous system's sensory input; however, more high-quality randomized controlled trials are needed to ascertain efficacy [5].

Alongside these sensory-based interventions, robotic rehabilitation systems have gained popularity for their ability to deliver precise, repeatable, and adaptable therapy. Lower-limb robotic devices, including those based on 3-DOF parallel manipulators, have been developed to support targeted ankle rehabilitation by enabling controlled multi-axis movement. Within the broader field of rehabilitation robotics, evidence continues to support the integration of robotic platforms into therapy programs to promote neuroplasticity and enhance sensorimotor recovery [6].

Although many systems have investigated the efficacy of these three aspects individually (i.e. proprioceptive [7], plantar vibrotactile and robot-based training), but no system, to the best of our knowledge, has incorporated these modes within a single device. This limits the potential benefits of a multi-modal approach. I-BaR framework [8], [9] provides a structured approach for combining different modes of balance-related rehabilitation in robotic platforms. In addition to the aforementioned modes it also proposes engaging visual feedback in the form of a serious Virtual Reality (VR) game. This has been shown to be significantly effective in improving rehabilitation efficacy among people with Parkinson's Disease [10]. As a result many commercially available rehabilitation

robots utilize VR in some form [6]. Examples include Lokomat and Hunova. Addressing these gaps could enable more comprehensive rehabilitation strategies that improve both balance and gait.

In light of the aforementioned discussion, a critical gap persists in the current state of the art: only a limited number of systems incorporate plantar vibrotactile stimulation, ankle proprioceptive training, and virtual reality within a unified robotic platform. Addressing this gap presents a unique opportunity to advance a synergistic rehabilitation paradigm that simultaneously augments sensory feedback and actively engages the neuromuscular system through precise, robot-assisted motor execution. This work introduces such an integrated approach, implemented on the BALANSens platform, which incorporates multiple rehabilitation modalities [11].

## II. METHODS

### A. System Description

The BALANSens robotic platform is a rehabilitation device developed in accordance with the I-BaR framework [8]. It is structured around three sequential stages to provide comprehensive balance and gait rehabilitation: (i) ankle preparation, (ii) balance training, and (iii) stepping rehabilitation.

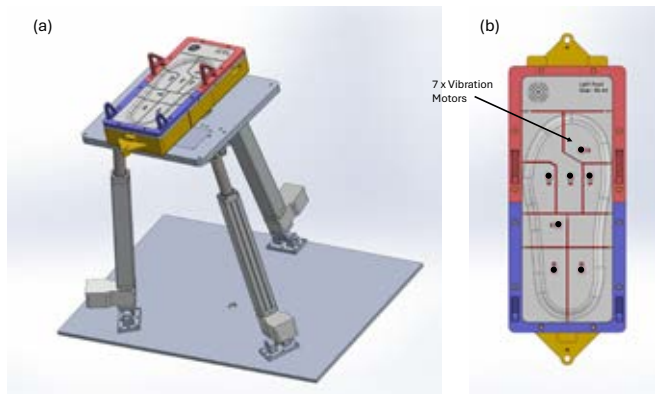


Fig. 1. The BALANSens Robotic Platform (a) For the ankle preparation phase, the 3-RPS manipulator has only one foot assembly attached to the end-effector (b) Top view of the foot assembly

In the ankle preparation phase, the 3-RPS parallel robot is mounted with one foot assembly as shown in Fig. 1a. The detailed design of the robotic platform and the VR system has been published elsewhere [11], [12], but it is important to restate here that the foot platform of the device is divided into 7 regions. Each region has a coin-type vibration motor (5 VDC, 8 mm diameter) mounted on rubber pads in it. This motor is protruding very slightly (1-2 mm) above the surface of the foot platform. This gap ensures that when the subject places his foot on top of the foot platform, the vibration motors will be in direct contact with the desired plantar regions. This construction enables the incorporation of proprioceptive and vibrotactile training into the same product.

### B. Proprioceptive Training

The proprioception mode operates in two phases. In the first phase, the robotic platform moves the subject's ankle joint to a predefined position. This target position, entered by the user through the interface (Fig. 2a), is specified by two parameters: the inversion-eversion angle ( $\alpha$ ) and the dorsiflexion-plantarflexion angle ( $\beta$ ). Afterwards, the foot is returned to the neutral position, marking the start of the second phase. In this phase, impedance control is activated, rendering the manipulator effectively "transparent." When forces are applied to any of the seven regions of the foot platform, the corresponding torques in the  $\alpha$  (inversion-eversion) and  $\beta$  (dorsiflexion-plantarflexion) directions are computed. These forces are simultaneously visualized on the lower-left corner of the user interface as a blue-yellow-red color map. The manipulator then moves according to the calculated torque, allowing the subject to perceive the platform as following the natural motion of the foot with minimal resistance. The details of the torque computation and impedance control scheme are provided in an earlier publication [13].

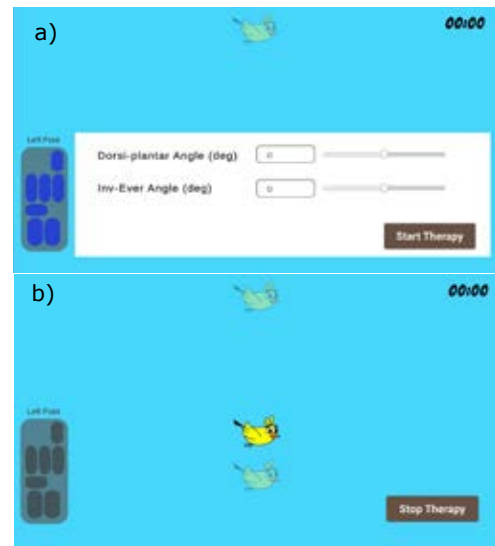


Fig. 2. VR Interface for the Proprioceptive Training Mode. (a) The user can input the desired target position. The input menu is hidden when training starts. (b) A faded image of the bird is shown at the initial zero position and at the 20-degree dorsiflexion position.

The BALANSens platform uses a serious VR game to complement the training. A bird avatar is shown in the game that follows the position of the foot in the 2D plane (Fig. 2); It moves up-down for dorsi-plantar motion and left-right for inversion-eversion motion.

### C. Vibrotactile Training

In the vibration sensing mode the goal is to enhance the subject's sense of touch on the sole of his foot. So, for subjects with severely compromised tactile sensation, vibration therapy is provided first. In this therapy all 7 vibration motors turn on at the same time as per the on/off time durations and intensity specified by the user (Fig. 3a). This procedure can enable the

subject to develop new neurological pathways, associating the vibration with the felt sensation.

If the subject's sensation is in an improved state then Vibrotactile training is employed by turning only one vibration motor on at random. The subject then has to identify which vibration motor turned on. This encourages the subject to develop a stronger mental connection with the individual plantar regions. After assessing the sensation the subject must click on the corresponding region on the screen (Fig. 3b). The regions also display the force applied by the subject on that region, in the form of a blue-yellow-red colour map. Then the next vibration motor turns on at random, and the cycle continues until the specified training time has elapsed.

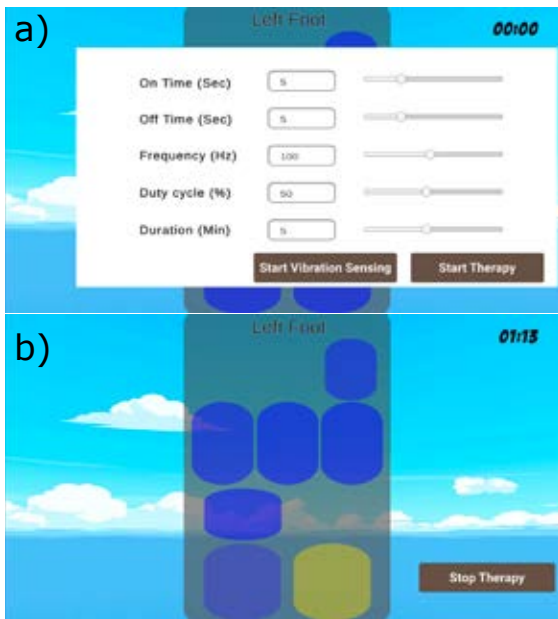


Fig. 3. Graphical User Interface for the Vibrotactile Training Mode. (a) Desired parameters are input on this screen. (b) Once the training begins, the subject may click on the corresponding plantar region shown on the screen.

At the end of the session, the subject's accuracy (the number of correctly identified iterations) and the subject's response time is displayed. This quantitative feedback acts as motivation for the subject and can encourage him to stick with the rehabilitation program. Furthermore, if the subject's results seem positive, then the intensity of the vibration motor may be reduced to increase the difficulty level of the training.

### III. FUNCTIONAL EVALUATION AND RESULTS

A series of trials is conducted on two healthy male individuals to validate the system's design and assess the suitability of the performance metrics for the two training modes. The studies involving human participants are reviewed and approved by the University Research Ethics Council of Istanbul Medipol University under the E-66291034-772.02-4494 number. The participants provided their written informed consent to participate and data sharing in this study. The age

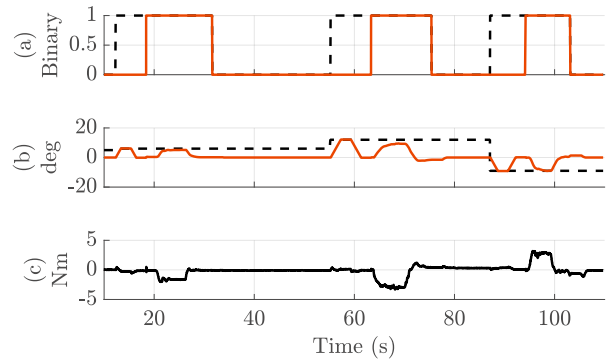


Fig. 4. Results for the proprioceptive training (Blind Trial) (a) The dashed line shows the start flag and the solid line shows the impedance flag. (b) The dashed line illustrates the target angle, and the solid line shows the angle of the manipulator. (c) The line represents the torque generated by the subject.

of the subjects are 29 and 33 years, and they do not report any history of lower limb injuries or falls.

#### A. Proprioception Training Results

The trial involving 3 repetitions is conducted, with one subject performing the training blind, while the other is allowed to look at the VR screen. The trials were conducted only in the dorsi-plantar direction for evaluation purpose. Results for the blind trial are shown in Fig. 4. At the moment that the user sets the desired target angle  $\beta$  and clicks on the start button, the start flag is set to 1 (Fig. 4a - dashed line). Consequently, the manipulator starts moving towards the target position and back, at a steady pace (Fig. 4b - solid line). Here, it can be noted that the variation in torque is minimal (Fig. 4c). Next, the impedance flag is set to 1 (Fig. 4a - solid line) and the subject applies some torque to the manipulator, as is observed in this relevant region (Fig. 4c), which in turn is responsible for enabling the motion of the manipulator.

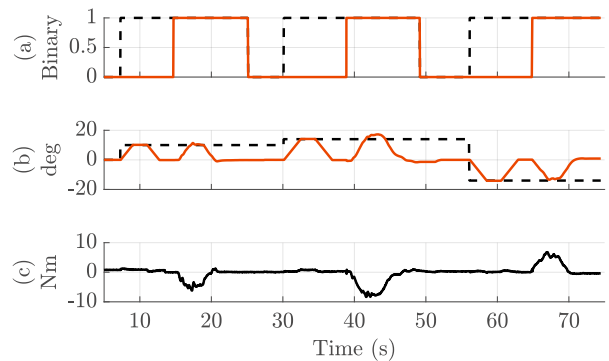


Fig. 5. Results for the proprioceptive training with VR. (a) Three iterations were conducted in this trial, like the blind trial. (b) The error between the target angle (dashed line) and observed angle (solid line) is significantly lower than in the blind trial. (c) Torque values are higher than in the blind trial, signifying calculated and confident movement.

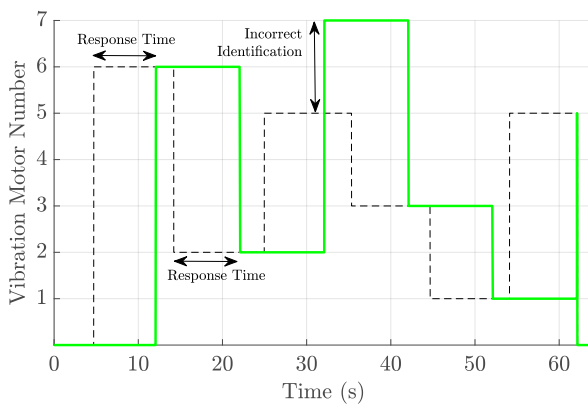


Fig. 6. Results of Vibrotactile training. The dashed line represents the motor number that is turned on, and the solid line represents the motor number chosen by the subject.

The average angular deviation from the target is observed to be 12.8% for the blind trial, whereas for the trial in which VR is used, it is 11.9% (Fig. 5). The angular deviation when returning back to the neutral position is 0.99° for the first trial and 0.82° for the second trial. Moreover, the maximum absolute torque applied by the subject is 3.3 Nm for the blind trial and 8.3 Nm in the VR trial, signifying confident and quick movement of the manipulator to the desired angle in the latter case.

### B. Vibrotactile Training Results

For this trial, the on and off times of the motors are set to 5 seconds each, and the test duration is set to 60 seconds. Therefore, the trial consists of a total of 6 on/off cycles. Both subjects play the one minute trial once, and the combined accuracy in this mode is about 91.7% (11 out of 12 correctly identified), and the average response time is 8.01 seconds and 7.44 seconds for the first and second subject, respectively (Fig. 6). It is worth noting that the duty cycle is set to 50% for the first subject and 70% for the other subject.

## IV. CONCLUSION

According to recent meta-reviews, very few lower-limb rehabilitation devices adopt a holistic approach that integrates multi-modal sensory feedback training (particularly proprioceptive and vibrotactile training) alongside traditional therapy, despite strong neurological evidence supporting their effectiveness. This work addresses this gap by developing and implementing such an integrated solution on the BALANSens robotic platform, in line with the Integrated Balance Rehabilitation (I-BaR) framework, to enable systematic clinical evaluation.

Validation tests are performed with healthy subjects to evaluate the system's readiness for patient trials. The platform computes quantitative performance metrics for both proprioceptive and vibrotactile training modes, with results monitored across multiple sessions. An important consideration in proprioceptive rehabilitation is that individuals with impaired proprioception

often rely excessively on visual feedback to determine limb position. To mitigate this, subjects are restricted from viewing their ankle during training. A serious VR game is incorporated in our implementation of the training to enhance engagement, particularly during prolonged or repetitive therapy. However, while VR can increase motivation, it may also provide indirect visual cues, potentially reducing the intended proprioceptive challenge.

Overall, the integration of proprioceptive and vibrotactile training modes within a single rehabilitation framework shows strong potential to improve balance and gait therapy outcomes. Future work includes clinical trials with participants from diverse demographics to further substantiate the benefits of this form of multi-modal therapy.

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