# Implementation and Evaluation of a Vibrotactile Assisted Monitoring and Correction System for Partial Weight-Bearing in Lower Extremities

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***Abstract*—Accurate partial weight bearing in the foot during rehabilitation from musculoskeletal injuries in lower extremities is important to ensure successful recovery. However, it is difficult for patients to know how much to load, and many are therefore reluctant to load at all. This study presents a novel footwear concept with strain gauge based force sensors and vibrotactile feedback that enables accurate foot loading and partial weight bearing monitoring during rehabilitation from musculoskeletal injuries in the lower extremities. Four force sensors integrated in the foot-sole of a sandal measures ground reaction force, and two eccentric rotating mass motors provide vibrotactile feedback to the user when a predetermined force threshold is reached. Partial weight bearing data from the force sensors are transferred wireless using wifi communication to a remote patient monitoring dashboard, enabling decision support for health personnel. We demonstrate the use of the prototype to reduce overloading in partial weight bearing in a validation experiment (N = 16). Findings showed that the prototype significantly reduced overloading in the right foot for healthy adults ($p < 0.05$), which indicate that closed-loop force sensing footwear with vibrotactile feedback can be useful in aiding patients with musculoskeletal injuries in the lower extremities during rehabilitation.**

***Index Terms*—Force Feedback; Rehabilitation; Tactile Devices; Biomechanics**

## I. BACKGROUND

Musculoskeletal injuries in the lower extremities, such as in the knee, ankle or foot, are common in the general population. During rehabilitation it is important to accurately load the foot according to the physician's recommendations to ensure a fast and successful recovery. Vibrotactile haptic feedback has previously been used in rehabilitation [1], [2]. Footwear with integrated force sensors combined with vibrotactile feedback has the potential to provide information on the patient's partial weight bearing (PWB) capacity, as well as warn the patient when a predefined force threshold is reached.

Regardless of surgical or non-surgical treatment of lower extremities injuries, the rehabilitation period is an essential part of the treatment. Immobilization is initially achieved by using a cast or orthosis, but in many cases, the patient can start with early partial weight bearing [3]. It has been shown that commencement of weight bearing during the immobilization period may have benefits, such as improving ankle range of motion [3], and earlier return to work and sports [4], [5]. In fracture recovery, the micro-movements stimulate the formation of callus, which is essential in the healing and remodeling process. On the contrary, if too much load is applied to the bone, alignment can be affected and recovery times prolonged, as shown in Fig 1. A study showed that patients who had recently had total hip arthoplasty and received audio feedback, were able to perform PWB to a prescribed target load [6]. However, they were unable to replicate the prescribed target load when walking unsupervised. From one of the authors' experiences in outpatient practice, a large proportion of patients are afraid to overload their injured extremity and therefore end up not loading it at all.

Several smart footwear devices with force sensing capa-

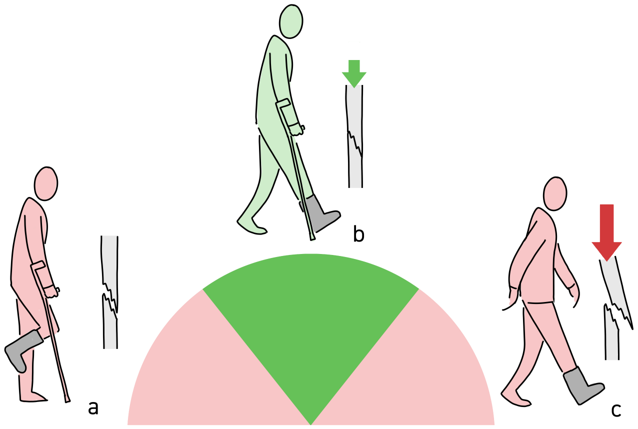

Fig. 1. Accurate weight loading is essential in recovery after injuries or surgery in the lower limbs, here demonstrated by a fracture: If the foot is not sufficiently loaded, reduced bone contact can lead to prolonged recovery or delayed union (a). Correct weight load will stimulate fracture healing (b). If the fracture is overloaded, it can be displaced and lead to incorrect union (c). Our experience is that patients are afraid to overload and, therefore, reluctant to load at all.

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bilities have been presented previously, but only a limited number have considered monitoring and vibrotactile feedback in combination. The largest category of smart footwear is smart soles intended for gait analysis that provides information on the foot pressure distribution [7]. This category mostly relies on thin force resistive or capacitive pressure sensors, which give a good pressure distribution map, but a lower accuracy force estimate [8]. These sensors are also known to have a limitation in terms of hysteresis, creep, and nonlinearity [9]. Some systems based on capacitive force sensors, such as Loadsol [10], [11], have achieved good ground reaction force readings, but have not been demonstrated in use for longer time periods. A study recently demonstrated the use of liquid pressure sensors in a shoe insole for recording full-body ballistocardiogram [12]. This technology could also be used for PWB monitoring, but it has limitations in terms of robustness, and it was reported that bladders were prone to leaking in the current implementation. Another study presented an orthosis using single strain-gauge based load cells for force detection, and a vibrotactile feedback belt load correction [13]. This device showed a weight sensing accuracy of $\pm 2.43$ kg in the range $2.3 - 23$ kg, which was within the reported clinical tolerance of $\pm 4.5$ kg for PWB compliance. A preliminary user study investigating the effect of vibrotactile feedback using the device was presented, but had too few participants to be conclusive. Another study presented a piezoelectric insole pressure sensor for PWB monitoring that was demonstrated for a two week period [9]. However, the size and cost of the piezoelectric sensor are not better than off-the-shelf single strain-gauge based load cells. A number of patents describing smart footwear devices which includes vibrotactile or other feedback from a predefined force threshold have been proposed previously [14]–[16], but only one commercial solution have been found to exist in the market (PedAlert, UK), and this does not provide PWB monitoring, and uses audio feedback which is less suitable for use in public spaces.

Remote patient monitoring (RPM) and remote therapeutic monitoring (RTM) allow orthopedic surgeons and physical therapists to monitor patients' recovery without physical contact. According to [17], Remote therapeutic monitoring is "…the process of collecting and evaluating non-physiological data, like musculoskeletal system status, therapy adherence, and therapy response, without direct contact with patients." A study comparing effects from feedback during a PWB learning task (concurrent feedback) and feedback provided after a PWB learning task (postresponse feedback), found that concurrent feedback was beneficial for immediate performance but that postresponse feedback was more accurate for retention [18]. In a clinical setting, the ultimate goal is to teach the patient PWB within a given force range in a short amount of time. In this setting there are two feedback loops: (i) the vibrotactile feedback loop for immediate (or concurrent) correction of PWB, and (ii) a postresponse treatment loop that considers the patient's conditional learning pattern and adjusts PWB thresholds and vibrotactile cues based on this. We argue that for (ii), PWB monitoring could enhance decision support for health personnel, as well as provide postresponse feedback to the patient. For example, if the patient keeps overloading despite of concurrent vibrotactile feedback, a conservative force threshold with frequent tactile cues could be set. Conversely, if the patient shows indications of quickly learning accurate PWB, the inclusion of vibrotactile feedback could be gradually reduced to promote independent PWB correction. This can be achieved by providing PWB data to the physician or physical therapist, which again provides a tailored PWB-program to the patient, as illustrated in Fig. 2.

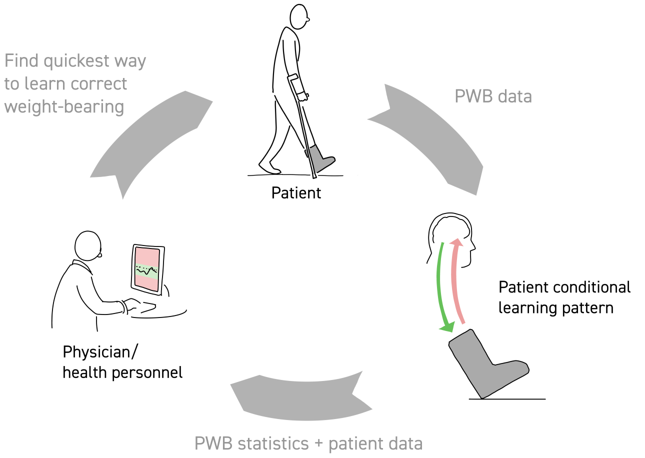


Fig. 2. Partial weight-bearing monitoring makes patient-specific weight-bearing data available for health personnel, which could enable better decision support for rehabilitation treatment.

This study presents a novel footwear system prototype, REHAB, enabling PWB monitoring during and shortly after the immobilization phase, and vibrotactile user feedback for accurate foot loading during rehabilitation from injuries in the lower extremities. The footwear concept utilizes robust strain gauge based force sensors, vibrotactile user feedback for PWB adjustment, and a database with wifi connection to monitor PWB capacity. This is different from previously presented smart footwear devices, because it combines PWB monitoring and vibrotactile feedback for weight-bearing adjustment. A novel conceptual RPM-dashboard is also presented, visualizing PWB data for relevant users. The contributions of this paper can be summarized as:

- Implementation of REHAB, of a novel footwear concept with strain gauge based force sensors, vibrotactile feedback, and wifi communication.
- A verification experiment demonstrating the force sensing capabilities of REHAB.
- A validation study with 16 users ($N = 16$) demonstrating that vibrotactile feedback significantly ($p < 0.05$) reduced overloading for PWB on the right foot.
- Presentation of a conceptual partial weight bearing monitoring dashboard, enabling postreponse feedback and decision support.

TABLE I

FEEDBACK MODALITY EXPERIMENT RESULTS. MODALITY PREFERENCE SCORE IS BASED ON 5-POINT LIKERT DATA WHERE 5 IS MAXIMUM.

| Feedback Modality | **Visual** | **Tactile** | **Audio** |
|---|---|---|---|
| Signals noticed (out of 10) | 3.2 | 9.3 | 9.3 |
| Modality preference score | 2.5 | 3.9 | 2.3 |

## II. FEEDBACK MODALITY EXPERIMENT

To provide decision basis for selection of feedback modality for PWB correction, an initial user experiment was conducted using a preliminary prototype with feedback actuators placed right above the ankle. The perception of audio, visual and vibrotactile feedback was studied, as well as participant preferences on feedback modality in public spaces.

### *A. Method*

A preliminary wearable prototype providing a 1 kHz audio feedback signal through a piezo speaker, visual feedback through a red 5 mm light emitting diode (LED), and vibrotactile feedback through an eccentric rotating mass motor (constant signal at 40 Hz), was developed. The feedback was remote activated manually through a web-server.

15 healthy adults in the age span 20 - 56 years old ($N = 15$) were invited to participate (10 male, 5 female). Informed consent was obtained. Participants were asked to wear the preliminary prototype on the right ankle during walking in a public space (busy campus hallway). For each modality, the participants received ten feedback signals with one second duration at random times. The order was light, vibration and audio. Participants were instructed to say "yes" when feedback was noticed. After a modality was completed, participants were asked to rate on a 5-point Likert scale in a paper survey how well they agreed with a set of statements concerning their modality preference in public spaces. A free text section asking for reasoning on preferred modality was included.

### *B. Results*

Experiment results are displayed in Table I, and show that audio and vibrotactile feedback was easier to notice than light, and that participants preferred vibrotactile feedback as modality in public spaces. In the free text section, participants reported that they preferred vibrotactile feedback because it attracted less attention than audio, and was easier to notice than visual feedback.

## III. SYSTEM DESCRIPTION

### *A. Hardware Implementation*

The REHAB prototype consists of a sandal with integrated load cells reading the ground reaction force, a control module processing the force value and communicating with an external device, eccentric rotating mass motors generating a vibrotactile haptic signal when a force threshold is reached, and a software application displaying PWB data. Vibrotactile haptic feedback was selected because it attracts less attention than audio feedback, and is easier to notice than light, as shown in section II. The force threshold can be adjusted using the external buttons on the control module, or using the software application. A sandal was selected as the base footwear to allow for flexibility for wearing immobilization measures such as a cast. An overview is shown in Fig. 3.

The force was measured using four low-profile SEN-10245 single strain gauge load cells. The maximum load limit for each sensor was 50 kg. Low profile force resistive and capacitive pressure sensors were prototyped, but discarded due to lack of accuracy and robustness. The four load cells were positioned below the heel and mid foot. They were integrated in the sole between two 3D-printed plastic plates to get an even force distribution between the load cells. The four load cells were connected to a HX711 load cell amplifier by a four-wire Wheatstone bridge. A 24 bit analog to digital converter of the HX711 allowed for reading the force signal serially using a microcontroller. The HX711 was connected to an Arduino MKR WIFI 1010 microcontroller, and handled in the software using the HX711 Arduino library. The load cells were calibrated using an external scale.

Vibrotactile haptic feedback was supplied by two Vybronics VC0825B002F eccentric rotating mass motors. The motors were sewn into the strap attaching the control module to the foot. Preliminary user experiments during implementation verified that the vibrotactile signal from the motors was suitable for use on-clothes and sufficient to be felt through chalk and fiberglass casts. The vibrotactile signal was actuated during overload as a constant continuous signal at approximately 225 Hz, which is near the peak sensitivity of pacinian corpuscles [19].

The force range was displayed using a 1.3" organic light emitting diode (OLED) screen (Adafruit 938). A real time clock (RTC) module (Adafruit DS3231) was included to keep time when the module was powered off. A micro secure digital (SD) card was used to store data when the system was offline. The built-in wifi module on the Arduino MKR WIFI was used to communicate with an external computer.

### *B. Software System*

The software system consists of three parts: a web server running on the Arduino microcontroller, a client running on a desktop computer, and a web-based PWB monitoring dashboard. The web server was responsible for reading the force from the force sensors, storing the force data, controlling the vibrotactile haptic signal, and setting the force threshold. Communication with the client was done using the HTTP protocol.

The client was developed in Python, and was responsible for reading PWB data from the server and calculating PWB statistics. A graphical user interface (GUI) was developed in Python using the tkinter library. This allowed for loading data from the server and displaying statistics in text format.

A conceptual PWB monitoring dashboard was then created using Grafana (New York, United States), and was responsible for displaying PWB data to patients and health personnel. PWB data from REHAB were imported into Google Sheets and connected with Grafana using the Google Cloud API. The dashboard shows information on force threshold, step

Fig. 3. Left: REHAB hardware overview, with load cells integrated in foot-sole, control module and vibration motor location. Bottom right: Load cell implementation and control module components. Top right: Partial weight-bearing monitoring dashboard that connects to the REHAB prototype with wifi, and displays partial weight-bearing history for users.

count, number of steps where the upper force threshold was exceeded, average PWB force and maximum PWB force for a selected time period. A partial weight bearing history graph displaying force per step in the selected time range was also included. Finally, a status bar showing elapsed time since surgery/injury relative to the estimated recovery time was shown. The dashboard is shown in Fig. 3.

## IV. FORCE SENSING VERIFICATION

The force sensing repeatability of the REHAB system was verified experimentally in the range 15–25 kg. This range was selected because it represents the relevant load range in the first few weeks after a musculoskeletal injury in the lower extremities. An ATI Nano 25 load cell with a load resolution of 0.125 N in the Z-direction was used for the verification. The load cell was placed under the heel of the sandal. The sandal was carefully loaded ten times until vibrotactile feedback was noticed, first to 15 kg, then to 20 kg and finally to 25 kg.

Results from the test showed that the user was able to load within ±3 kg of the target load for ten loading cycles, which is within the reported clinical tolerance of ±4.5 kg [13]. The results are shown in Fig. 4.

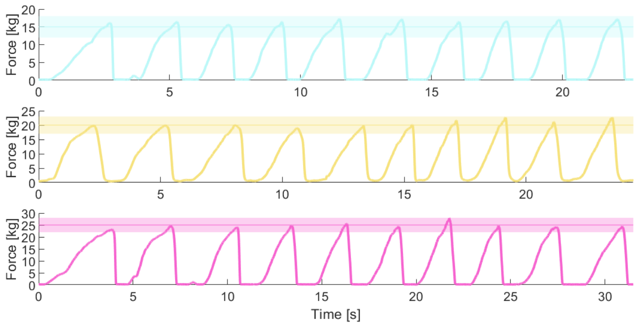


Fig. 4. Repeated loading test for target loads of 15 kg, 20 kg and 25 kg. The horizontal band shows the ±3 kg interval.

## V. USER VALIDATION EXPERIMENTS

To investigate if concurrent vibrotactile haptic feedback increased confidence in PWB accuracy for the proposed system, a user study testing PWB with and without vibrotactile feedback was set up. The following hypothesis was tested:

- **H0:** The mean ground reaction force for adults loading one foot is equal, for target forces of 15 $kg$, 20 $kg$ and 25$kg$, when no concurrent feedback is provided (condition A) and when vibrotactile force feedback is provided (condition B).
- **H1:** The mean ground reaction force for adults loading one foot is higher, for target forces of 15 kg, 20 kg and 25 kg, when no concurrent feedback is provided (condition A) than when vibrotactile force feedback is provided condition B).

### A. Method and Participants

16 healthy male and female adults in the age span $18-42$ years old, and weight $62-93$ kg, were invited to participate ($N=16$), of which 7 were female and 9 were male. The participation was voluntary. Informed consent was obtained, and consent could be withdrawn at any time. Data collection was approved by the Norwegian Center for Research Data under reference 300275.

The REHAB device shown in Fig. 3 was used without a cast. A digital bathroom scale with loading accuracy of $\pm 0.981$ N was used to verify the user load. The experimental procedure consisted of two conditions, one involving no vibrotactile or other feedback (condition A) and another including vibrotactile feedback (condition B).

For condition A, which did not involve vibrotactile feedback, the participants did not wear the REHAB device, but their original footwear. The participants were first asked to load the right foot to a target load of 15 kg. This was repeated five times. The procedure was performed with one foot on the scale, and facing away from the display of the digital scale so that the reading was hidden for the participant. No feedback was given to the participants. The maximum load for each loading cycle was saved. This procedure with five consecutive steps per target load was repeated for 20 kg and 25 kg.

For condition B, which involved vibrotactile feedback, the participants were asked to wear the REHAB device for the experiment. The participants were again asked to load the right foot to a target load of 15 kg five times. The procedure was performed with one foot on the scale, and facing away from the display of the digital display so the only feedback was a constant vibrotactile signal at 225 Hz from the REHAB device. The maximum load from each loading cycle was saved, and the procedure repeated for target loads of 20 kg and 25 kg.

### B. Results

Results from the user validation experiment showed that for condition A, i.e. no vibrotactile feedback given, participants exceeded the target loads by large amounts. This is illustrated in Fig. 5. For the 15 kg target load, participants loaded a mean of $\mu = 32.7$ kg, exceeding the target load with $118\%$ when no feedback was given. For the 20 kg target load, the mean was $\mu = 40.2$ kg, and the target was exceeded by $101\%$. For the 25 kg target load, the mean was $\mu = 42.2$ kg, and the target was exceeded by $69\%$.

For condition B, which included vibrotactile feedback, the overshoot was significantly reduced. For the 15 kg target load, the mean load was $\mu = 20.7$ kg, and the target load was exceeded by $38\%$. For the 20 kg target load, the mean load was $\mu = 21.9$ kg, and mean overshoot $9.5\%$. For the 25 kg target load, the mean load was $\mu = 25.8$ kg, and mean overshoot only $3.2\%$. The results are shown in Table II.

TABLE II
EXPERIMENT RESULTS WITH MEAN LOAD ($\mu$) AND VARIANCES ($\sigma^2$) FOR THE RESPECTIVE TARGET LOADS. RESULTS SHOW THAT INCLUDING VIBROTACTILE FEEDBACK IMPROVED LOADING ACCURACY, BY REDUCING ERROR AND VARIANCE, FOR ALL THREE TARGET LOADS. T-TESTS ($\alpha = 0.05$) COMPARING THE ACHIEVED LOADS FOR NO FEEDBACK AND VIBROTACTILE FEEDBACK, INDICATE THAT THERE WAS A SIGNIFICANT DIFFERENCE ($p < 0.05$) BETWEEN THE CONDITIONS.

| **Target Load** | **No feedback** | | **Vibrotactile feedback** | | **T-test** |
|---|---|---|---|---|---|
| | $\mu$ [kg] | $\sigma^2$ | $\mu$ [kg] | $\sigma^2$ | p-value |
| 15 kg | 32.7 | 106 | 20.7 | 55.0 | <0.05 |
| 20 kg | 40.2 | 154 | 21.9 | 15.6 | <0.05 |
| 25 kg | 42.2 | 156 | 25.8 | 26.4 | <0.05 |

To evaluate conditions A and B, three T-tests assuming unequal variances were performed for each target load using Excel. The significance level was set to 0.05 ($\alpha = 0.05$). As shown in Table II, there was a significant difference between the no feedback (condition A) and vibrotactile feedback (condition B) conditions for all three target loads ($p < 0.05$). Based on the T-tests, the null hypothesis was rejected.

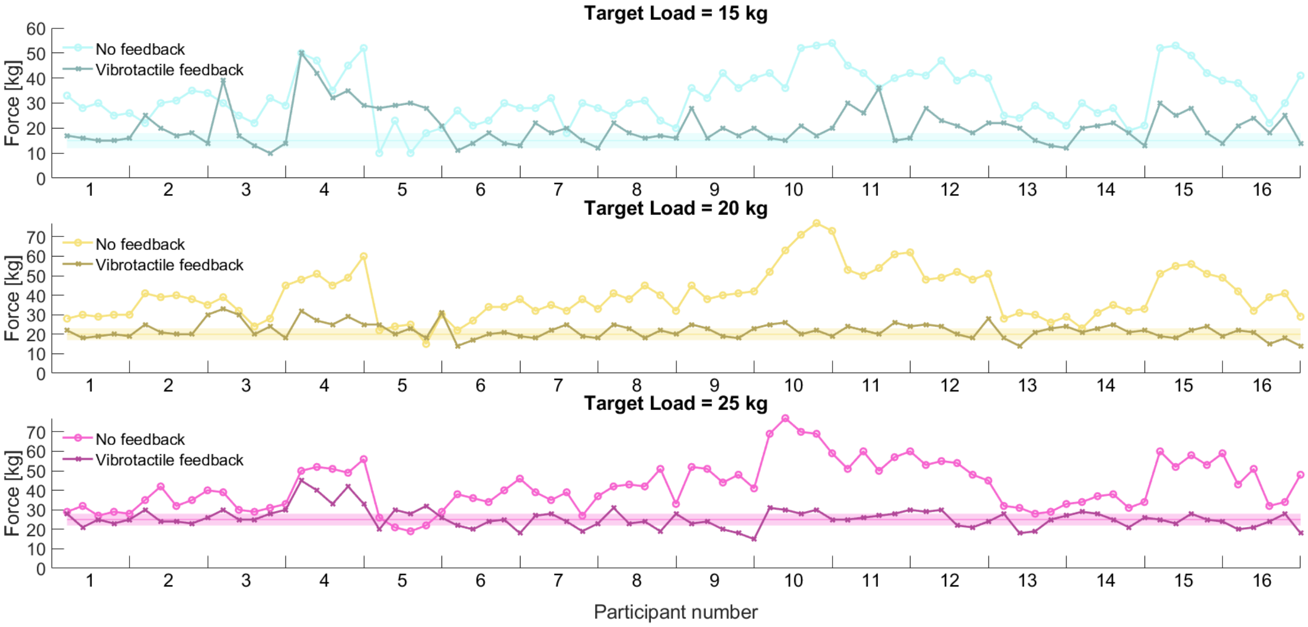
## VI. DISCUSSION

This paper has presented the implementation of a novel footwear concept with strain gauge based force sensors and vibrotactile feedback, a user validation study demonstrating its ability to reduce overloading, and a conceptual dashboard displaying PWB data from the footwear.

Considering the implementation of REHAB prototype, there are still potential improvements with respect to robustness. Thin wires are exposed to wear and abrasion, and more rugged solutions should be developed. Considering the choice of force sensor, the strain gauge based force sensors have provided reliable readings throughout the testing period, which is in accordance with reports from [13]. The disadvantage of these sensors compared to force resistive or capacitive sensors is that they must be integrated into the sole of the shoe, requiring custom manufacturing methods. These challenges are shared with liquid-based and piezoelectric based sensors. However, as capacitive and force resistive sensors have challenges with respect to hysteresis and nonlinearities, we consider strain gauge based sensors as a reliable option for PWB monitoring and control. For vibrotactile feedback, eccentric rotating mass motors provided sufficient vibrotactile sensation for on-clothes and on-cast actuation. Other feedback modalities such as audio and light feedback were initially tested as reported in section II, but were discarded due to lack of discretion in the public space. It is possible that other vibrotactile methods and haptic cues such as skin stretching could provide more detailed feedback.

In the current implementation, vibrotactile feedback was only implemented for violation of the upper force threshold. However, as shown in Fig. 1, it is important to load above the lower force threshold as well. This could be implemented by activating vibrotactile feedback just before underload step registration. The form of the vibrotactile signal for indicating that the lower threshold has been reached should be explored.

For the user validation experiments, there was a significant difference between the means of the two conditions — indicating that force controlled vibrotactile feedback significantly influenced the participants' abilities to prevent overloading. Studying the results from the vibrotactile feedback condition,


Target Load = 15 kg

Target Load = 20 kg

Target Load = 25 kg

Fig. 5. User validation experiment results for target loads of 15 kg, 20 kg and 25 kg. The figure shows that the participants found it difficult to achieve the target load with no feedback, and that inclusion of vibrotactile feedback significantly reduced overloading ($p < 0.05$).

it is evident that overshoot was much smaller for the 20 kg and 25 kg target loads than for the 15 kg target load. Reasons for this could be (i) that the sensor accuracy was slightly poorer at 15 kg than at 20 kg and 25 kg, as seen from Fig. 4, and (ii) that there could be some bias from familiarizing with the equipment. For (ii), a different study design where the target loads were presented in a randomized order could have reduced familiarity bias.

An interesting finding observed from Table II is that although the overshoot was greatly reduced for the vibrotactile condition, there was still a small overshoot in all three target loads. This is most likely a result of human synaptic delay and reaction time. For example, [20] found that the reaction time from tactile stimuli in the right big toe was approximately 0.25 s. This means that to truly avoid overshoot of a target load, the vibrotactile feedback must be initiated somewhat earlier than the target load depending on the rate of loading.

Future work should focus on understanding conditional learning patterns for PWB with the aim of teaching patients correct PWB in a short amount of time. I.e., if it can be shown that users learn accurate PWB with a certain force threshold from vibrotactile feedback in a limited time period during the beginning of the rehabilitation, vibrotactile feedback may not be necessary later in the rehabilitation process. It should also be investigated if machine learning algorithms could be optimized to teach the patient optimal PWB based on the patient-specific conditional learning pattern.

## VII. CONCLUDING REMARKS

This study has presented implementation of REHAB, a novel footwear concept with strain gauge based force sensors and vibrotactile feedback, that enables accurate foot loading and partial weight-bearing monitoring during and shortly after the immobilization phase of rehabilitation for musculoskeletal injuries in the lower extremities. It has been shown that the REHAB system significantly ($p < 0.05$) reduced overloading on the right foot for healthy adults, which indicates that closed loop vibrotactile feedback footwear with force sensing can be useful for aiding patients in accurate foot loading in a rehabilitation setting. Conditional learning effects on patients with musculoskeletal injuries in the lower extremities should be studied further.

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