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DEVELOPMENT REPORT

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Development of an implicit method for directing weight shifting to the affected side in patients with stroke: a proof of concept study

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Abstract

Weight-shift training during stroke rehabilitation requires patient effort, potentially causing leg spasticity and anxiety, which disturb motor learning. The purpose of this study was (1) to devise an implicit guidance method for weight bearing that uses vibratory cues (and is therefore low exertion) and (2) to determine if the implicit guidance method is feasible. The first experiment included 12 healthy subjects. We conducted an experiment to produce a Weber's fraction capable of calculating a just-noticeable difference during a weight-shifting task. We then applied this Weber's fraction to a weight-shifting task in a patient with stroke. Using the implicit guidance method, the patient did not perceive an increase in weight bearing while weight shifting. Furthermore, the implicit guidance method appeared to reduce anxiety during training. This implicit guidance system warrants further investigation.

Keywords: Stroke, Rehabilitation, Postural control, Weight shift, Fear of falling, Human–machine interaction, Wearable device, Just-noticeable difference, Perception

Background

Reduced postural control, caused by sensory and motor impairments after stroke, impacts activities of daily life, and affects independent walking [1, 2]. Improving postural control in patients after stroke is extremely important and may help them lead independent lives, participate in society, and maintain optimum levels of health. Asymmetrical weight bearing and weight-shifting ability correlate with gait [3]. Stroke-related limitations in weight shifting manifest in the anterior–posterior (AP) and medio–lateral (ML) directions [4, 5], with marked limitations typically noted on the affected side [6, 7]. Additional limitations include reduced weight-shifting speed and accuracy [8, 9], reduced single leg support ability on the affected side [10, 11], and reduced floor reaction force on the affected side [12, 13]. Over time, patients who demonstrate these limitations form motor patterns that use only part of their support base as means of compensating for reduced postural control.

In clinical settings, these issues are often addressed through targeted weight-shifting training. Patients with stroke must expend considerable effort to weight shift, which often induces associated reactions (AR), and spasticity [14, 15]. One example of AR is where muscular strain in the paretic upper limb temporarily increases, upon exertion of the lower limb. Spasticity involves increased muscular strain caused by motor paralysis, and is exacerbated by muscle extension and exertion [14, 15].

Weight-shifting tasks can cause anxiety. Previous research into the relationships between emotional changes and postural control found that maintaining a standing position on an elevated surface causes "stiffness behavior" where the leg muscles display excessive tension [16, 17]. This phenomenon helps maintain postural stability during standing [18], whereas in complex, everyday environments it impedes trouble-free movement, increasing the risk of falls [19]. In patients with a history of stroke and hemiplegia, increased leg muscle tension exacerbates spasticity in the paretic limb, thereby impeding left–right symmetrical gait.

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One means of engineering support for limited weight-shifting is through the use of visual or auditory biofeedback (BF). Previous studies examined foot center of pressure movement in a visual display [20–23], the use of visual cues for recognizing asymmetry [24], or visual and auditory feedback [23, 25, 26]. These methods enable the perception of foot pressure and weight asymmetry, thereby allowing the conscious modification of movement and weight shifting. Mostly, visual BF is used in clinical practice; however, patients are highly dependent on vision in the early period following the initial onset of stroke [27, 28]. In detail, Marigold et al. reported that patients with stroke tend to more heavily rely on visual input to maintain frontal plane (mediolateral) sway [29]; thus, sensory supplementation, particularly in the form of tactile BF, may help avoid inadequate sensory integration. Furthermore, review articles concluded that visual or auditory BF does not improve functional balance ability [30, 31]. Several cases have used visual BF up until now during balance training; however, this training method has not been sufficiently effective and could also reinforce visual reliance.

In a clinical trial, vibrotactile BF improved body sway during quiet standing in patients with vestibular disorders and Parkinson disease [32–36], and we recently found that the immediate beneficial effects on postural stability in patients with stroke [37]. In addition, several studies used haptic feedback as a navigation for weight-shifting [38, 39]. A study of Parkinson disease reported that weight induction by stimulus of visual and haptic feedback combined led to immediate increases in the anteroposterior and left–right limits of stability (LOS) [39]. However, no studies have applied haptic BF to weight shifting of the paretic leg in stroke patients. Further, no system has been devised to reduce the aforementioned AR, and the anxiety experienced, which are typical in stroke patients.

Thus, the purpose of this study was to devise a method of implicit weight-bearing guidance, using haptic stimulation. A secondary objective was to examine the feasibility of implicit guidance in patients with stroke, and verify the validity of the technique in advance of future, large-scale investigations.

Methods

Overview of the haptic-based weight-shift system

The system consists of a Wii balance board (Wiiboard, Nintendo, Japan) for capturing center of foot pressure (CoP) data. The subject was fitted with a vibration unit, with four vibrators worn around the pelvic girdle, which displayed CoP motion, coupled with a personal computer (PC) (Fig. 1). We measured CoP using a Wii balance board (WBB), with signals relayed to a PC by Bluetooth. CoP measurements (sampling) were taken every 20 ms, and the transmission period was 20 ms. The software screen displayed CoP and target weight bearing in real time (Fig. 2). The target weight-shift length can be set at any position from 0 to 1vibration motors (Z7AL2B169208200% of body weight by inputting the subject's weight. Vibrations were transmitted to a vibration unit (i.e., pelvic belt) using a USB connection wireless module (nRF24LE1-F16Q32, Nordic, Norway). The communication cycle is 20 ms. The frequency bandwidth of the module ranges from 2400 to 2525 MHz.

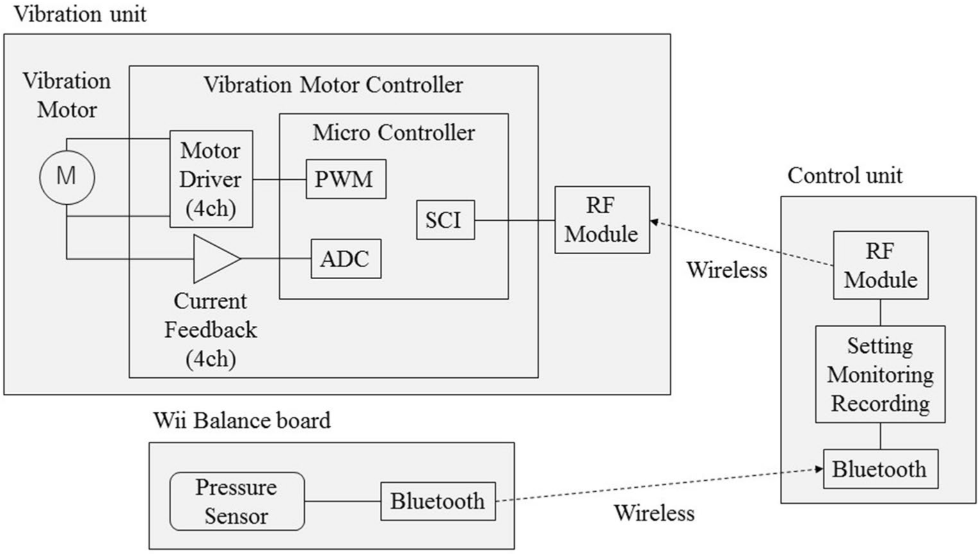

Fig. 1 Configuration diagram

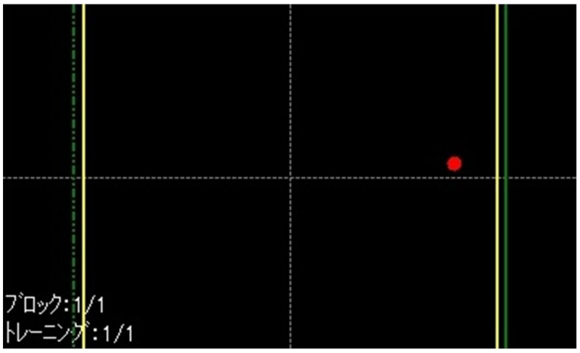

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Fig. 2 Screen shot of the software. On the software screen, the CoP and target weight bearing could be displayed in real time

The vibration unit includes four built-in , KOTL, China). Vibration motors are mapped on a bony ridge (i.e., the bilateral anterior and posterior superior iliac spines) to efficiently convey vibrotactile stimulation (Fig. 3b). The rate of the vibration motor speed is 12,000 ± 2500 rpm. The intensity of vibrations can be changed by PC according to the degree of patient paralysis. Until the CoP position reaches the target weight-shift length, the device will continue to vibrate. Vibrations cease once the subject reaches the target weight-shift length.

Implicit weight-shift length-extension algorithm

Weight-shifting length is automatically determined by an implicit weight-shift length-extension. To reduce excessive voluntary movements and fear of falling, we applied Weber's Law to the sense of weight, increasing the length of weight shifting [40]. This law enables calculation of the just-noticeable difference (JND), which is the minimum amount of change that can be perceived. In the perceptual literature, JND represents the smallest detectable change by which a subject can reliably discriminate between a comparator and an original stimulus. For example, in a size-discrimination task a participant might be asked to verbally report whether the length of a visually presented line (i.e., the comparator) differs from the length of a reference line. In this context, JNDs are defined statistically with the appropriate detection of a magnitude change based on an experimentally determined criterion [41]. Equation (1) represents Weber's Law, where W is the current amount of weight bearing, K is the Weber ratio, and ΔW is the JND

$$\Delta W = K \times W \tag{1}$$

Experiment to derive the Weber ratio for weight-shift task

Because the Weber ratio for sense of weight bearing has not been used previously, we conducted an experiment with 12 young, healthy subjects to derive the Weber ratio. Subjects included 12 healthy adults who provided written consent for participation (mean age 21.25 years, SD 0.72, male 9 participants, female 3 participants). Body mass index (BMI) for each participant is shown in Table 1. The present study was performed with approval of the Ethical Review Board of Waseda University.

Subjects stood with their feet 30 cm apart, and the experimental task was repeated weight-shift task to both left and right leg (Fig. 3a). First, we instructed subjects to shift 60% of their body weight to the left side by using a vibratory cue on the left side waist (i.e., L1/2; Fig. 2). When the weight shift reached 60% of the body weight, vibrations for the left side stopped, and the vibrator activated on the right side; this process was repeated. After weight shifting once to the left and once to the right, we increased the percentage of weight shifting, based on the set Weber ratio (initial value 0.05), without communicating this change to the participants (Fig. 3c). The initial value of 0.05 was based on preliminary experiments that found a somatic sensory Weber ratio of 0.03–0.3 [42]. This procedure was repeated at 90-second intervals, and after the experiment subjects reported if they felt an increase in the amount of weight shifting, according to two conditions ("Yes" = it increased; "No" = unchanged). After performing the weight-shift task using the initial Weber ratio, the Weber ratio was either increased or decreased according to participants' responses (decreased when the participant felt an increase in the amount of weight shifting; increased if the participant did not). Once we established the point where a change of 0.01 in the Weber ratio caused a change in response, decreases were made in 0.002 increments from the noticeable value to find the Weber ratio where increases for weight shifting were unnoticeable for each participant (Fig. 4).

Table 1 Characteristic of the participants

Participants (*n* = 12)	Age	Gender	Height (cm)	Weight (kg)	BMI
Participant A	23	F	163	67	25.22
Participant B	21	F	156	54	22.19
Participant C	21	F	156	47	19.31
Participant D	20	M	176	57	18.4
Participant E	22	M	165	60	22.04
Participant F	21	M	182	90	27.17
Participant G	21	M	169	65	22.76
Participant H	21	M	174	60	19.82
Participant I	21	M	180	65	20.06
Participant J	22	M	171	63	21.55
Participant K	21	M	169	62	21.71

BMI body mass index

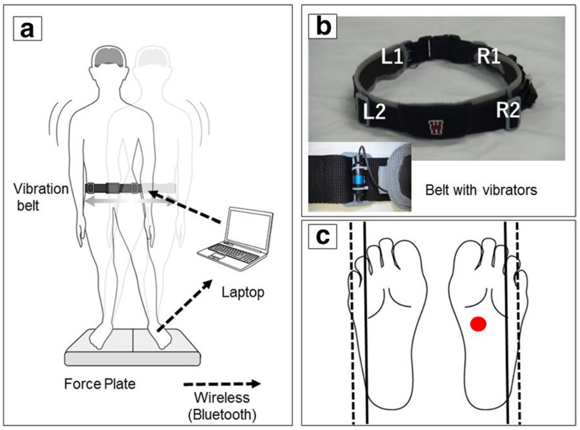

Fig. 3 Overview of the weight-shifting task and the vibration system. (Modified from Yasuda et al. [37]: The effect of a haptic biofeedback system on postural control in patients with stroke: an experimental pilot study. Somatosensory and motor research) [37]. **a** Participants were asked to stand with the feet 30 cm apart, and starting with their body weight shifted to the left side with the vibrating unit attached to the waist, and participants weight shift to the target position. Once the vibrations stopped, the activation of the vibrator was shifted to the opposite side. The time latency between users' movements and vibration was approximately 50 mm/s. **b** Vibration motors are mapped on a bony ridge (i.e., the bilateral anterior and posterior superior iliac spines) to convey vibrotactile stimulation. **c** The percentage of weight shifting was increased, based on the set Weber ratio (initial value: 0.05), without communicating this change to the participants

Results

Table 2 shows the participants' Weber ratios. The mean Weber ratio was 0.045, SD 0.0078, maximum 0.054, and minimum 0.024, with a 95% CI of 0.040–0.050.

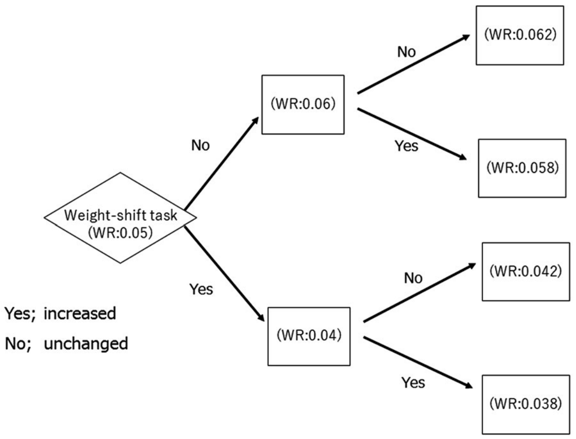

Fig. 4 Derivation process of the Weber ratio (WR). After the repeated weight-shift task, participants responded whether or not they felt an increase in the amount of weight shifting according to two conditions (response options "Yes; increased", "No; unchanged")

Table 2 Weber ratio in 60% of the weight-bearing

Participants ($n = 12$)	Weber ratio	SD	Max value	Min value	95%CI
	0.045	± 0.0078	0.054	0.024	0.040–0.050

n number of participants *SD* standard deviation *CI* confidence interval

Examination of the test validity in patients

As a preliminary step toward a large-scale clinical trial, we applied the device to one patient with stroke to examine method feasibility. In this examination, we conducted simulated weight-shift training using the derived Weber ratio, and examined the following variables: (1) perception of vibratory stimuli: whether or not vibration cues could be perceived on the paretic side, (2) perception of increased weight bearing: whether or not the patient could perceive increases in weight bearing, (3) anxiety: anxiety during the task, and referent data on the influence of training, (4) weight-bearing dose on the paretic side was measured before and after intervention, and comparisons made.

Table 3 shows patient characteristics. Our patient was a 73-year-old man with left hemiplegia (Brunstrom's recovery stage; see Appendix [43]), caused by right cerebral infarction. The patient was able to walk independently, and had no cognitive or mental disorders (i.e., Mini-Mental State Examination score above 23 [44]; no dementia).

We familiarized the patient with the weight-bearing guidance by vibration device. (At this point, the patient was not informed that the amount of weight bearing would increase.) For the weight-shift task, the patient assumed a left–right symmetrical standing position, with feet 30 cm apart on the WBB, with eyes open. In these conditions, the patient focused on a marker placed approximately 2 m in front of him. In the pretest,

Table 3 Characteristic of the patient

Patient: F.M ($n = 1$)	
Age	73
Gender	Male
Paralyzed side	Left
Days from onset	90
Superficial sensation	Moderate
Pain sensation	Normal
Vibratory sensation	Moderate
Proprioception	Moderate
Motor impairment	Brs; LE/VI
MMSE	28/30

Brs Brunstrom's recovery stage, *LE* Lower extremity, *MMSE* Mini mental state examination the patient performed the task of weight shifting to the paretic limb five times in order to evaluate baseline weight-shift ability. After the pre-testing, a continuous weight-shift tasks of both left and right sides was repeated over 70 s × 4 sessions with one-min rest intervals. During the weight-shift task, when the vibrations for one side stopped, he shifted his weight to the other side. The target weight-bearing dose was set at pre-test value (baseline) × 0.8. In doing so, the amount of weight bearing was increased for each session based on the Weber ratio. Lastly, we performed a post-test of the weight-shift task identical to the pre-test (i.e., weight shifting to the paretic limb five times to evaluate weight-shift ability).

The patient was questioned about his perception of vibratory stimuli applied from the left and right, and his perception of increased weight bearing in each session after completion of the post-test. We used a visual analog scale (VAS) to measure anxiety after the pre-test, and after the weight-shift training [45]. The VAS is frequently used to measure pain intensity. The pain VAS is a continuous scale comprised of a horizontal (HVAS) or vertical (VVAS) line, usually 10 cm (100 mm) in length, anchored by two verbal descriptors, one for each symptom extreme. VAS is a valid measure of fall anxiety, according to a recent study [46]. We asked the patient to indicate his fear of falling, on a scale from 1 to 10. The amount of weight bearing in the pre- and post-test was calculated using the data obtained from the WBB. For weight bearing, variables were compared pre-and post-testing. Statistical analyses were performed using a Wilcoxon signed-rank test as a non-parametric test because of the small sample size [47]. Significance level was set at $p < 0.05$.

Results

The patient perceived the vibratory stimulation, applied from the left and right, on both the paretic and non-paretic side. Perception could therefore be used as a signal for weight shifting. The patient did not notice the increase in weight-shift between sessions. The VAS for anxiety was 5 (moderate) in the pre-test weight-shifting task, but 0 during the weight-shifting task. Compared with the pre-test, the amount of weight bearing was significantly increased from 67.34 (66.92–67.36) kg to 68.45 (68.44–69.24) kg in the post-test ($p = 0.0431$) with a medium effect size ($r = 0.30$) [48].

Discussion

In the present study, we applied a method of implicit weight-bearing guidance using vibratory cues. We calculated the Weber ratio during a weight-shift task, performed by young healthy individuals. In the range of 60% weight bearing, the Weber ratio was 0.045 (SD 0.0076). We applied a repeated weight-shift task with vibratory cues, using the calculated Weber ratio, to a patient with stroke. The patient did not notice any increase in weight bearing during the task. This investigation had no control conditions, therefore due care should be exercised during interpretation. The patient's perceived level of anxiety was less during this task, compared with previous weight-shift tasks. Use of a weight-bearing guidance system, using vibratory stimulation, was feasible for use in a patient with stroke. Additional studies are needed to apply this system to larger cohorts of patients.

This was the first study to examine an implicit weight-bearing guidance system, using haptic-based feedback. It is also the first study to examine the feasibility of applying this system to patients with stroke. During the weight-shift task, the participant did not perceive subtle increases in the amount of weight bearing. Although the underlying mechanisms are unclear, we can postulate that sensory information is collected and maintained in the prefrontal cortex and in primary sensory cortices. This information is later collated with new sensory information. By applying the Weber ratio to the amount of weight bearing, subliminal sensory information may input into memory centers, enabling implicit weight-bearing guidance.

From a clinical perspective, providing visual information is a common training strategy for patients with stroke. Traditionally, this training involves checking postural swaying and the state of left–right leg weight bearing [20]. However visual BF appears ineffective for weight-bearing training [30, 31]. Furthermore, during high effort tasks, AR and spasticity temporarily increase, often causing anxiety, potentially reducing motivation to train [16, 17]. Future application of this system for enabling implicit weight shifting, through haptic-based feedback, may assist patients with stroke.

Furthermore, the positive effect described in this study may represent a reliable basis for future applications (e.g., turning the device from a training equipment into something that can be worn in daily life, using an insole-type pressure sensor). Our device does not interfere with other sensory modalities (i.e., visual or auditory); hence, we expect that patients and physical therapists alike will appreciate the potential of the device use in clinical setting or activities of daily life.

This experiment examined one stroke patient; therefore, future studies should examine patients with varying degrees of stroke symptom severity. Furthermore, observed effects require clarification in terms of the influences of spasticity, AR, and anxiety. There were no control conditions for the behavioral indices in the present experiment, and the impact of a potential placebo or learning effect cannot be entirely ruled out. Future studies should compare the implicit weight-bearing guidance system with conventional weight-shifting methods, in a patient population.

Conclusions

In the present study, we derived a Weber ratio during a weight-shifting task in young healthy subjects. Based on the derived Weber ratio, we applied a method of implicit weight-bearing training using vibratory cues in a stroke patient, to examine the feasibility of the method. The patient used vibratory cues to shift weight bearing to the left or right. The patient did not notice increases in weight bearing during training. Furthermore, this implicit method reduced anxiety during the weight-shifting task. Future studies should examine the effectiveness of this method, from different perspectives, in a cohort of patients with stroke in clinical settings.

Appendix

Brunnstrom's recovery stages [43].

Lower extremity function.

Stage I	Flaccidity.
Stage II	Minimal voluntary movements.
Stage III	Hip flexion, knee flexion, and ankle dorsiflexion performed as a combined motion in sitting and standing.
Stage IV	In sitting: knee flexion beyond 90°; ankle dorsiflexion with the heel on the floor.
Stage V	In standing: isolated knee flexion with hip extended; isolated ankle dorsiflexion with knee extended.
Stage V	Almost normal movement but declining movement speed.

Abbreviations

BF: biofeedback; PC: personal computer; CoP: center of foot pressure; AR: associated reaction; WBB: Wii balance board; VAS: visual analog scale.

Authors' contributions

KY and HI constructed the study concept and design. KS and YK collected and analyzed data. KY prepared the draft manuscript. All members verified the content of their contributions. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

Consent for publication

Written informed consent for publication of their clinical details and/or clinical images was obtained from the patient.

Ethics approval and consent to participate

Ethical approval was granted by the Ethics Committee of Waseda University.

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