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Identification of anatomical locations: its relevance for vibrotactile perception of individuals with Parkinson's disease

Ankita Raghuvanshi[1*], Priya Pallavi[1], Rahul Chhatlani[2], Jayesh Parmar[3], Manish Rana[4], Sagar Betai[5] and Uttama Lahiri[1]

*Correspondence:
ankitaraghuvanshi@iitgn.ac.in

[1] Discipline of Electrical Engineering, Indian Institute of Technology Gandhinagar, Gandhinagar, India
[2] Faculty of Physiotherapy, Marwadi University, Rajkot, India
[3] Shree KK Sheth Physiotherapy College, Rajkot, India
[4] Department of Community Medicine, GMERS Medical College, Sola, Ahmedabad, India
[5] ANSA Clinic, Ahmedabad, India

Abstract

Background: Vibrotactile input is a useful sensory cue for individuals with Parkinson's Disease (PD) to overcome freezing of gait (FoG). For this input to serve as a cue, its accurate perception is required. This needs the input to be delivered at an anatomical location where it can be perceived. This is particularly true for individuals with PD whose tactile perception differs from that of healthy individuals. Literature indicates choice of various anatomical locations e.g., Finger, Wrist, Thigh, Shin, Calf, Ankle, Achilles Tendon, Heel and torso for the application of vibrotactile stimulation. Though studies have focused on the comparison of the vibrotactile perception (based on feedback) at various anatomical locations, yet these have involved only healthy individuals. However, such exploration remains as majorly untouched for individuals with PD.

Methods: To bridge this gap, here we have conducted a study using our vibrotactile stimulation system while involving twenty-one individuals with PD to understand the choice of anatomical location with regard to vibrotactile perception. In addition, our study involved twenty-one age-matched healthy individuals to understand possible differences if any in vibrotactile perception between the two groups of participants.

Results: Our results showed that for the healthy participants, both 'Wrist' and 'Thigh' were equally strong anatomical locations with regard to vibrotactile perception that were correctly identified 100% of the time closely followed by 'Finger' for which the correct identification was 98% of the time with correct identification for all these three locations being statistically ($p < 0.05$) higher than the other locations. In contrast, for individuals with PD, the 'Thigh' emerged as a strong candidate anatomical location with regard to vibrotactile perception even for those with severity of symptoms (based on clinical measure) that was correctly identified 96% of the time followed by 'Wrist' for which the correct identification was 92% of the time with the correct identification for only the 'Thigh' being statistically ($p < 0.05$) higher than all the other locations (except 'Wrist').

Conclusion: This finding is clinically significant in deciding the right anatomical location to offer vibrotactile cues for it to be correctly perceived by one with PD, providing assistance to overcome FoG.

Keywords: Vibrotactile, Perception, Parkinson, Anatomical location

Background

The use of sensory cueing is one of the non-pharmacological approaches often employed by researchers [1, 2] to help individuals with Parkinson's Disease (PD) to overcome deficits in gait, such as freezing of gait (FoG). The FoG manifested as "brief, episodic absence or marked reduction of forward progression of the feet despite one's intention to walk" [3], is one of the most debilitating manifestations of these individuals, which might lead to falls and decrease their quality of life [4, 5]. The sensory cueing can be of various types, namely visual [6], auditory [7] and vibrotactile [8–21]. Vibration is a natural stimulus recognized by the human body, and its application serves the purpose of offering neuromuscular stimulation [22, 23] that can be perceived as a cue. Researchers have shown that among the three types of sensory cueing, vibrotactile cueing can be easily perceived in any environment by such individuals [9, 10, 18], thereby emphasizing the importance of vibrotactile stimulation and the role of tactile perception. Tactile perception begins with the activation of specialized mechanoreceptors in the skin, such as Merkel cells, Meissner's corpuscles, Pacinian corpuscles, and Ruffini endings, which detect physical pressure or movement, converting this mechanical force into electrical signals [24]. These signals are further transmitted through specialized pathways towards the central processing system. The signals then reach the thalamus, which refines and filters the sensory inputs before relaying them to the somatosensory cortices in the brain for further processing [25]. Any disturbance along this route can affect the quality of the sensory input perceived. In the elderly, tactile perception declines due to age-related changes across the somatosensory pathway. The Mechanoreceptors in the skin at various anatomical locations become less dense and sensitive, resulting in weaker signal transduction, along with reducing the speed and accuracy of sensory transmission [26]. The issues aggravate in individuals with PD for whom dopaminergic neuron degeneration leads to reduced dopamine levels, and sensory alterations that in turn disrupt normal tactile signal processing, resulting in sensory reception changes [27]. Thus, it is also essential to identify the anatomical location where the vibrotactile stimulation (quantified in terms of frequency of vibration [28]) can be applied so that the stimulation can be perceived (with the perception being the ability to interpret the stimulants received into meaningful insight [29]) by an individual.

Literature indicates the choice of various anatomical locations (belonging to the upper limb, lower limb, and torso) for the application of vibrotactile stimulation for both healthy individuals and individuals with PD (Table 1). With regard to the upper limb, vibrotactile stimulation has been offered to the Finger [11, 30–33], Wrist [12, 13, 32, 34] and Shoulder [32, 35]. The Finger having a high density of mechanoreceptors was reported to offer the highest vibrotactile acuity [32] and the Shoulder to have the least sensitivity towards vibrotactile stimulation for healthy individuals [32] among the various anatomical locations in the upper limb. With regard to the lower limb, vibrotactile stimulation has been provided to the Heel [30, 33, 36–38], Achilles Tendon [16, 39] Ankle [12, 39], Calf [38], Shin [40] and Thigh (also referred as the Knee extensor muscle) [33, 41, 42]. Unlike that for the upper limb [32], in the case of the lower limb, none of the studies have investigated variation in vibrotactile perception among the various anatomical locations, particularly for individuals with PD. For the task of understanding the perception of vibrotactile stimulation, we selected the 'Finger' and 'Wrist' locations

Table 1 Literature on Vibrotactile stimulation on different anatomical locations

Reference for the publication	Overall anatomical location	Details on anatomical location
[11, 30–33]	Upper limb	Finger
[12, 13, 32, 34]		Wrist
[32, 35]		Shoulder
[30, 33, 36–38]	Lower limb	Heel
[16, 39]		Achilles Tendon
[12, 39]		Ankle
[38]		Calf
[40]		Shin
[33, 41, 42]		Thigh
[45–47]	Torso	Abdomen
[47]		Chest

in the upper limb due to their ability to provide an intuitive guidance during movement [43] which can be beneficial as a hint to move and the high density of mechanoreceptors present in these anatomical locations [32] Additionally, we included lower limb anatomical locations as candidate locations for vibrotactile stimulation as it provides a more direct sensory link to walking, particularly relevant for future applications where vibrotactile cues can be integrated to facilitate dynamic gait activities [44]. Again, with regard to the torso, vibrotactile stimulation has been offered to the Abdomen [45–47] and the Chest [47]. However, researchers have reported lower sensitivity (for vibrotactile stimulation) of anatomical locations in the torso than that of the locations in the upper and lower limbs [42, 48] (thereby ruling out the choice of the torso for application of the vibrotactile stimulation. The choice of Abdomen for vibrotactile stimulation can lead to discomfort due to a feeling of ticklishness [49]. Though there is a rich history of literature in which researchers have selected different anatomical locations for vibrotactile stimulation with some of these comparing vibrotactile perception for the various locations (in the upper and lower limbs), these studies have involved only healthy individuals. Also, in all of these studies, the recipients of vibrotactile stimulation were in static position, with the task being focused on identifying vibrotactile stimulation provided on different anatomical locations in either sitting on a chair or standing upright. Similarly, in our study, as our aim was on understanding the comparative perception of the vibrotactile stimulation between different anatomical locations (so that these locations can be used as candidate anatomical locations for delivering vibrotactile cue) for individuals with PD, we adopted the approach of using static position of seating. In fact, while identifying the most appropriate anatomical location for vibrotactile stimulation, we wanted to eliminate possible confounds, e.g., cognitive load arising due to the task of focusing on walking that might adversely affect one's choice of anatomical location for receiving vibrotactile stimulation.

Adding to the choice of the anatomical location for the application of vibrotactile stimulation, the frequency of vibration quantifying the stimulation is also important since this can play an essential role in vibrotactile perception [28, 45]. It has been well-established that the cutaneous mechanoreceptors within the skin can perceive a discernible vibration frequency

range, practically from 80 to 250 Hz [28]. In the context of Parkinson's disease, frequencies ranging from 180 to 250 Hz have been employed, while vibrotactile stimulation has been applied to various anatomical locations of the lower and upper limbs [9, 14, 17]. Further, in one study involving individuals with PD and age-matched healthy individuals, researchers reported 180 Hz as the threshold frequency of vibrotactile stimulation for vibrotactile perception [45] though this study did not focus on the comparative evaluation of vibrotactile perception at various anatomical locations.

Given the importance of the use of vibrotactile stimulation (while keeping a note on the frequency of vibration) for vibrotactile perception (so that the vibrotactile stimulation can serve as a cue) along with the choice of anatomical location for delivering vibrotactile stimulation and the fact that the comparative evaluation of vibrotactile perception at various anatomical locations remains as majorly unexplored, particularly for individuals with PD, in our present work, we have conducted a study involving individuals with PD to understand the choice of anatomical location (with regard to vibrotactile perception) wherein the vibrotactile stimulation can be applied. In addition, we had participation from twenty-one age-matched healthy individuals that helped us understand possible differences if any in vibrotactile perception between the two groups of participants. Also, here we chose a simple static task in which one was expected to receive vibrotactile stimulation at different anatomical locations. Given that healthy individuals and individuals with PD have differences in vibrotactile perception, we hypothesize that there will be differences in the choice and preference of anatomical location for receiving vibrotactile stimulation among individuals with PD and their healthy counterparts. Thus, the objectives of our present research are three-fold, namely (i) to understand the choice of the anatomical location for receiving the vibrotactile stimulation of each participant group, (ii) to identify the anatomical locations that can be strong candidate locations for delivering vibrotactile stimulation (that might be useful for researchers working with the individuals with PD in terms of deciding the anatomical location of delivery of the vibrotactile cue) and (iii) whether there exists any clinical relevance of identifying such anatomical locations.

Results

While the participants belonging to Group_{H} and Group_{PD} took part in our study, we acquired their responses as a part of the Identification step. In this, they indicated anatomical locations, namely 'Finger,' 'Wrist,' 'Heel,' 'Achilles Tendon,' 'Ankle,' 'Calf,' 'Shin,' and 'Thigh' wherein they felt that the vibrotactile stimulation was offered using the Vibrotactile Stimulation Routine (see "Procedure" section). Based on this data, we computed the percentage of responses that matched or did not match with the location where the vibrotactile stimulation was delivered by our system. Also, we carried out a post-study survey on vibrotactile perception and collected their verbal feedback (as a part of the Feedback step) while rating their choice of anatomical location with regard to vibrotactile perception.

Top three anatomical locations with regard to vibrotactile perception of group_{h} and group_{PD}

Based on the participant's verbal feedback in the survey on vibrotactile perception (administered by the experimenter at the end of the study (Feedback Step; "Procedure" section), our results (computed using Eq. (1); "Computation of Choice of Anatomical

Location for Receiving Stimulation during Feedback step" section) show that the 'Finger', 'Wrist' and 'Thigh' were among the top three anatomical locations being chosen by both $Group_H$ and $Group_{PD}$ with regard to vibrotactile perception, though there were differences between the two participant groups. Specifically, for $Group_H$ (Fig. 1 (i)), the 'Finger' was chosen as one of the top three anatomical locations nearly 80% of the time, closely followed by the 'Wrist', which was followed by the 'Thigh'.

In contrast, for $Group_{PD}$ (Fig. 1 (ii)),, 'Thigh' was chosen as one of the top three anatomical locations nearly 76% of the time, closely followed by the 'Wrist' and the 'Finger'.

Responses to identifying anatomical location with regard to receiving vibrotactile stimulation: intragroup comparison

While the participants took part in the Vibrotactile Stimulation Study (see "Procedure" section), their response (to the question asked by the Vibrotactile Stimulation Routine on the location where they felt that the stimulus was delivered) was subsequently analysed (Identification step; "Procedure" section). Their responses were labelled as either 'Correctly Identified', 'Misinterpreted' or 'Missed'. The 'Correctly Identified' responses were those in which the anatomical location chosen matched with the location where the vibrotactile stimulation was actually delivered by our system (as decided by the Vibrotactile Stimulation Routine). Again, the 'Misinterpreted' responses were those in which the anatomical location chosen did not match with the location where the vibrotactile stimulation was actually delivered by our system causing the participant to wrongly point to a different anatomical location. Finally, the 'Missed' responses were those in which the vibrotactile stimulation was not perceived at all. Figures 2 and 3 shows the distribution of the responses (computed in % using Eqs. (2) – (4)) that were labelled by our system as 'Correctly Identified', 'Missed' and 'Misinterpreted' for all the eight anatomical locations for both the participant groups ($Group_H$ and $Group_{PD}$). While considering the 'Correctly Identified' labels, and using Cohen's d test, we found that the effect size to be 0.68, and 0.66 on an average for the $Group_H$ and $Group_{PD}$, respectively with sample size being 21 for each participant group and the sample power being 0.90 and 0.88 for the intragroup analysis with the alpha error probability being 0.05.

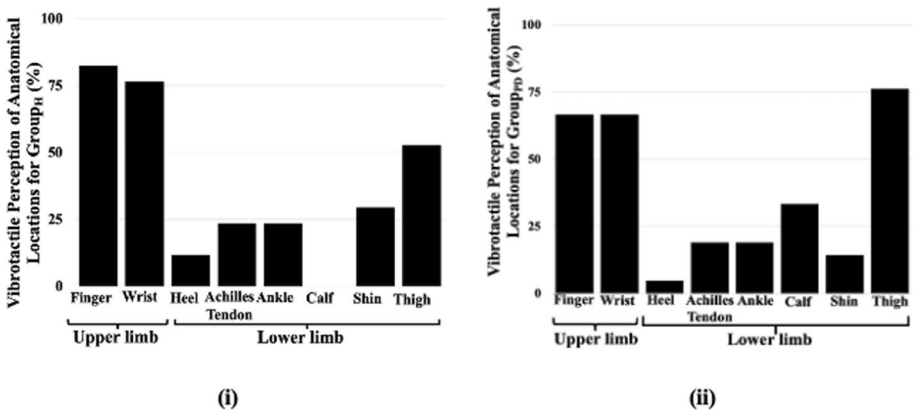

Fig. 1 Anatomical location choice based on Feedback step for (i) $Group_H$ and (ii) $Group_{PD}$. Note: '$Group_H$' indicates participant group of healthy individuals; '$Group_{PD}$' indicates participant group of individuals with PD

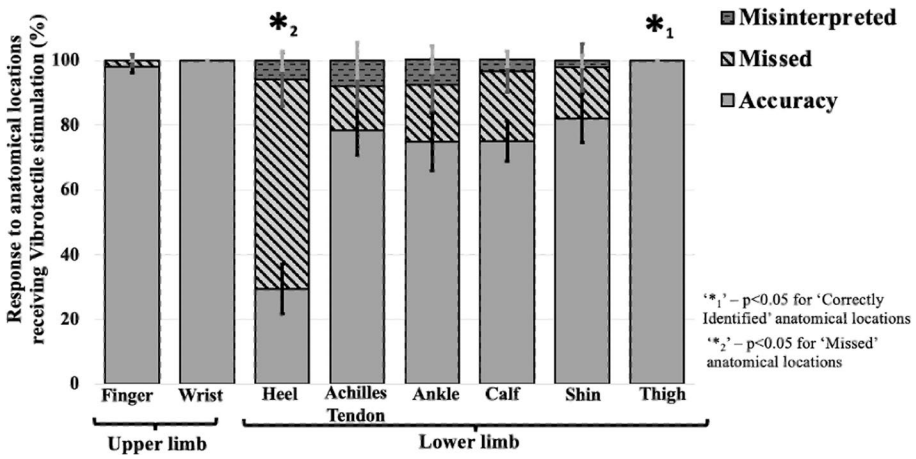

Fig. 2 Distribution of responses of the participants based on the Identification step for $Group_H$. *1 indicates $p < 0.05$ in Wilcoxon Signed-Rank test for 'Correctly Identified' anatomical locations; *2 indicates $p < 0.05$ in Wilcoxon Signed-Rank test for 'Missed' anatomical locations; $Group_H$ indicates group of healthy individuals; Error bars indicate Standard Error

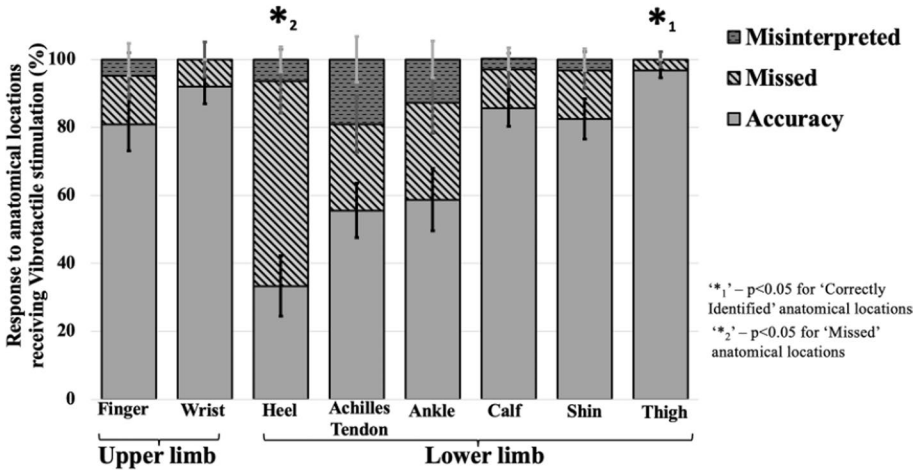

Fig. 3 Distribution of responses of the participants based on the Identification step for $Group_{PD}$. *1 indicates $p < 0.05$ in Wilcoxon Signed-Rank test for 'Correctly Identified' anatomical locations; *2 indicates $p < 0.05$ in Wilcoxon Signed-Rank test for 'Missed' anatomical locations; $Group_{PD}$ indicates group of individuals with PD; Error bars indicate Standard Error

For healthy group ($Group_H$)

With regard to the 'Correctly Identified' cases, for $Group_H$, we find that the stimulation delivered to the 'Thigh' and 'Wrist' anatomical locations were correctly identified all the time, closely followed by the 'Finger'. Based on the dependent sample statistical test (see "Statistical analysis" section) for $Group_H$, we found that the number of instances of correct identification of the 'Thigh', 'Wrist' and 'Finger' anatomical locations receiving stimulation (that were not statistically different among themselves) was statistically higher (with p-values of $p = 0.043$, 0.005, 0.028, 0.028, 0.001 for 'Wrist' and 'Thigh' both, vs. 'Shin', 'Calf', 'Ankle', 'Achilles Tendon' and 'Heel', respectively, and $p = 0.043$, 0.008, 0.028, 0.03, 0.001 for 'Finger' vs. 'Shin', 'Calf', 'Ankle', 'Achilles Tendon' and 'Heel', respectively.) than all the other anatomical locations. With regard to 'Missed' cases, for $Group_H$, we

find that the 'Heel' had the largest number of misses along with statistical significance (with p-values of p = 0.001, 0.002, 0.01, 0.002, 0.001,0.001 and 0.001 for 'Heel', vs. 'Achilles Tendon', 'Ankle', 'Calf', 'Shin', 'Thigh', 'Wrist' and 'Finger', respectively) while comparing the instances of 'Missed' for the other anatomical locations, possibly attributed to the 'Heel' being the most distal location (having reduced vibrotactile perception [29]) as far as the lower limb was concerned. Finally, with regard to the 'Misinterpreted' cases, for $Group_H$, we find that in all cases there were instances of the anatomical location being misinterpreted (with respondents confusing the anatomical location, namely 'Heel', 'Achilles Tendon' and 'Ankle' on the one hand and 'Calf' and 'Shin' on the other hand, receiving the vibrotactile stimulation), except for the 'Thigh', 'Finger' and the 'Wrist' with the 'Thigh' and 'Wrist' being correctly identified all the time unlike the 'Finger'.

In short, the strong candidate anatomical locations with regard to vibrotactile perception for $Group_H$ along with their ability to correctly identify the anatomical location receiving vibrotactile stimulation were the 'Thigh' and 'Wrist'.

For group with individuals with Parkinson's disease ($Group_{PD}$)

While both 'Thigh' and 'Wrist' emerged as strong candidate anatomical locations for delivering vibrotactile stimulation for $Group_H$, we see a different scenario for the $Group_{PD}$. Specifically, with regard to the 'Correctly Identified' anatomical locations for $Group_{PD}$, we find that the stimulation delivered to the 'Thigh' was 'Correctly Identified' the maximum number of times followed by the 'Wrist' for which our results showed 3.2% and 8%, respectively of 'Missed' instances, unlike that of the $Group_H$. Also, we found that the number of instances of correct identification of the 'Thigh' receiving stimulation was statistically higher (with p = 0.000 (< 0.0001), 0.000 (< 0.0001), 0.002, 0.043, 0.028, and 0.043 for 'Thigh', vs. 'Heel', 'Achilles Tendon', 'Ankle', 'Calf', 'Shin', and 'Finger', respectively) than that for all the other anatomical locations, except for the 'Wrist'. Again, with regard to the 'Missed' cases for $Group_{PD}$, we find that for the stimulation delivered to 'Heel','Heel' had the largest number of misses along with statistical significance (with p-values of p = 0.005, 0.003, 0.000 (< 0.0001), 0.001, 0.000 (< 0.0001),0.001 and 0.001 for 'Heel', vs. 'Achilles Tendon', 'Ankle', 'Calf', 'Shin', 'Thigh', 'Wrist' and 'Finger', respectively) while minimum instances of 'Missed' labels were attributed to the 'Thigh' location, similar to that for the $Group_H$.

In short, based on our observations while taking into account the statistical significance, instances of 'Correctly Identified' versus the 'Missed' and 'Misinterpreted' along with the choice of the anatomical locations with regard to vibrotactile perception (as expressed by the participants; "Procedure" section), for the $Group_{PD}$, the 'Thigh' possibly stands as a strong candidate anatomical location (out of all the anatomical locations) for receiving the stimulation as an external cue.

Having seen that the identification of anatomical locations receiving vibrotactile stimulation of the $Group_{PD}$ (having 62% and 38% of individuals with Mild and Moderate PD, respectively) and GroupH were differentiated, we were interested to understand whether the variations in the severity of PD symptoms contributed to such differentiation.

Responses to identifying anatomical location with regard to receiving vibrotactile stimulation: intergroup comparison along with understanding the clinical significance

To understand the role of the variation in the severity of PD symptoms quantified in terms of MDS-UPDRS-III Scores (see "Participant characteristics" section) vis-à-vis their healthy counterparts, we conducted an intergroup analysis of the percentage of responses (labelled as 'Correctly Identified', 'Missed' and 'Misinterpreted') to vibrotactile stimulation on various anatomical locations across different participant groups i.e., Healthy elderly ($Group_H$), those with mild PD with MDS-UPDRS Scores < 32 [50] i.e., $Group_{PD\_MILD}$ and those with moderate PD having MDS-UPDRS-III Scores lying within 33 and 59 ($33 \leq scores \leq 59$ [50]) i.e., $Group_{PD\_MOD}$. The idea was to identify specific anatomical locations where perception may remain intact (as in healthy elderly) or become compromised as PD progresses. While considering the 'Correctly Identified' labels and using Cohen's d test, we found that the effect size to be 0.6, 1. 2 and 1.4 on an average considering intergroup statistical analysis between $Group_H$ and $Group_{PD\_MILD}$ (sample size being 21 and 13, respectively); $Group_H$ and $Group_{PD\_MOD}$ (sample size being 21 and 8, respectively); and $Group_{PD\_MILD}$ and $Group_{PD\_MOD}$ (sample size being 13 and 8, respectively), respectively and the sample power being 0.3 (with the low sample power possibly inferring that the $Group_H$ and $Group_{PD\_MILD}$ had no significant difference with regard to choice of anatomical locations while receiving the vibrotactile stimulation), 0.8 and 0.8, respectively with the alpha error probability as 0.05.

We can see that the individuals belonging to $Group_H$ and $Group_{PD\_MILD}$ showed no significant differences in the percentage of 'Correctly Identified', 'Missed' and 'Misinterpreted' responses across all the eight anatomical locations (Fig. 4). This might infer that the perceptual accuracy of individuals with PD with mild severity does not significantly differ from that of healthy elderly.

In contrast, the percentage of 'Correctly Identified' and 'Missed' responses of $Group_{PD\_MOD}$ and $Group_H$ differed with statistical significance for each of the 'Finger', 'Ankle', 'Achilles tendon' and 'Heel' locations with p-values being 0.011, 0.002, 0.033, and 0.015, respectively for the Correctly Identified' responses and p-values being 0.026, 0.004, 0.035, and 0.018, respectively for 'Missed' responses. Also, no significant difference was found in the percentage of 'Misinterpreted' responses with regard to vibrotactile stimulation between the $Group_{PD\_MOD}$ and $Group_H$ across each of the eight anatomical locations. However, the remaining four anatomical locations, i.e., 'Thigh', 'Shin', 'Calf', and 'Wrist' showed no significant differences in the percentage of 'Correctly Identified' and 'Missed' responses with regard to the vibrotactile stimulation of $Group_H$ and $Group_{PD\_MOD}$, thereby suggesting nearly similar vibrotactile perception at these four anatomical locations of individuals with moderate PD as that of healthy elderly.

Finally, the $Group_{PD\_MOD}$ and $Group_{PD\_MILD}$ differed statistically with regard to the percentage of 'Correctly Identified' and 'Missed' responses for each of the four anatomical locations, namely 'Finger', 'Ankle', 'Achilles tendon' and 'Heel' with p-values being 0.037, 0.005, 0.035, and 0.020, respectively for the 'Correctly Identified' responses and p-values being 0.024, 0.002, 0.043, and 0.007, respectively for the 'Missed' responses with no statistical difference in the percentage of 'Correctly Identified' and 'Missed' responses for the remaining four locations, i.e., 'Thigh', 'Shin', 'Calf', and 'Wrist' ('Misinterpreted' responses showing no statistical difference for each of the eight anatomical locations).

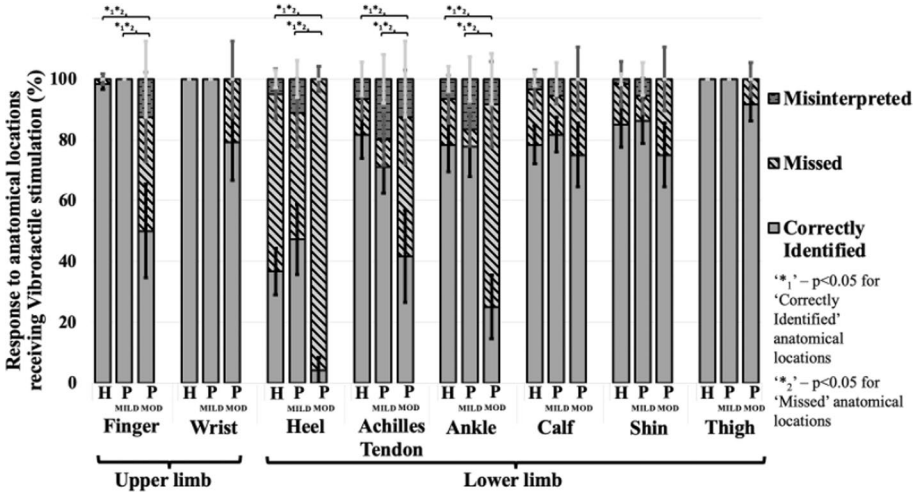

Fig. 4 Distribution of responses of the participants based on the Identification step for (i) $Group_H$ (ii) $Group_{PD\_MILD}$ and (iii) $Group_{PD\_MOD}$. Note: 'H' indicates group of healthy elderly individuals; 'P_{MILD}' indicates group of individuals with PD with 'mild' MDS-UPDRS-III Scores; 'P_{MOD}' indicates group of individuals with PD with 'moderate' MDS-UPDRS-III Scores; Error bars indicate Standard Error

In short, we could see no statistical difference in the vibrotactile perception for each of the four anatomical locations, e.g., 'Thigh', 'Shin', 'Calf', and 'Wrist' while considering the $Group_H$, $Group_{PD\_MILD}$ and $Group_{PD–MOD}$. Now, among these four anatomical locations, the 'Thigh' demonstrated the highest percentage of correctly identified responses with a minimum of Normalized Accuracy being ~ 92% in the case of $Group_{PD\_MOD}$. Such an observation might have clinical relevance thereby hinting a potent anatomical location for delivery of vibrotactile cue to individuals with PD with varying severity of the symptoms.

Discussion

This study explored the comparative evaluation of vibrotactile perception across various anatomical locations for individuals with PD. Individuals with PD often suffer from the freezing of gait (FoG) that adversely affects their mobility. External cues, such as vibrotactile stimulation (of a specific frequency, namely 180 Hz [45]) can help address issues related to FoG. For vibrotactile stimulation to be perceived as a cue, it is important to identify anatomical location where such a stimulation can be offered. Though researchers have used various anatomical locations for delivery of the vibrotactile stimulation, mostly for healthy elderly and some for individuals with PD (Table 1), the comparative evaluation of vibrotactile perception across various anatomical locations has remained as majorly unexplored, particularly for individuals with PD. In our study, we wanted to understand the effect of sensory perception on varying anatomical locations in individuals with PD and their age-matched healthy counterparts. Additionally we wanted to see whether the effect of vibrotactile simulation remains intact with the severity of the disease, as the underlying biomechanisms of tactile perception are significantly influenced by PD pathology, affecting sensory processing and perception [24, 25]. In our present work, we have conducted a study involving individuals with PD while carrying out a comparative analysis between the vibrotactile perception corresponding to 8 anatomical

locations, namely 'Finger,' 'Wrist,' 'Heel,' 'Achilles Tendon,' 'Ankle,' 'Calf,' 'Shin,' and 'Thigh' (specifically the anterior part of the Thigh). In addition, we had participation from age-matched healthy individuals to help us understand possible differences if any in vibrotactile perception between the two groups of participants.

Our results based on the participants' feedback on the vibrotactile perception (administered by the experimenter during the Feedback step (see "Procedure" section) indicate that the 'Thigh' was chosen by the $Group_{PD}$ the maximum number of times with regard to vibrotactile perception making it a strong candidate anatomical location. Such a finding can be possibly attributed to 'Thigh' constituting the proximal structure of the lower limb [51] unlike the 'Heel', 'Achilles Tendon', 'Ankle', 'Calf' and 'Shin' that constitute the distal structures of the lower limb [52]) that offer longer nerve pathways (underlying the biomechanisms), making these locations more vulnerable to slower conduction [26] and often reported to be associated with greater loss of vibrotactile acuity (than the proximal structures) in individuals with PD than their healthy counterparts [33]. Again, while considering the top three anatomical locations with regard to vibrotactile perception, the comparatively lower choice for the 'Finger' and the 'Wrist' (than the 'Thigh') by the $Group_{PD}$ might be attributed to the elevated vibrotactile perception thresholds leading to reduced vibrotactile perception at the fingertips (or the region of the hand close to the fingers, e.g., the 'Wrist') often experienced by individuals with PD [26, 53]. In contrast, for $Group_{H}$, the 'Finger' was chosen the maximum number of times that might be attributed to the improved vibrotactile acuity associated with intact mechanoreceptors at the fingertip [54] for the healthy individuals.

Our results based on the responses obtained during the Identification step (see "Procedure" section) indicated a notable strength of this study in the inclusion of age-matched healthy participants, which allowed for a clear distinction between PD-specific sensory deficits and typical age-related sensory decline. For $Group_{H}$, the 'Finger' was not 'Correctly Identified' all the time (unlike 'Thigh' and 'Wrist') in the Identification step, though the 'Finger' was chosen the maximum number of times in the Feedback step. Such an observation might be attributed to the age-related decline in vibrotactile acuity at the distal extremities in healthy elderly [55]. With regard to the $Group_{PD}$, our results indicated that the 'Thigh' was 'Correctly Identified' the maximum number of times. Such an observation can be attributed to the 'Thigh' being the proximal structure of the lower limb [51], as discussed above, thereby suggesting the 'Thigh' to be a possible strong candidate for anatomical location while considering the delivery of stimulation (which can serve as an external cue). Such a comparative approach thereby enhancing the clinical relevance of our results, revealing that distal anatomical locations are less effective for cueing in individuals with PD. Consequently, our findings underscore the potential advantages of targeting proximal locations like the 'Thigh,' for vibrotactile cueing that can have clinical significance for individuals with PD.

From a clinical perspective, the results of this study provide foundational evidence for the selection of optimal anatomical locations for vibrotactile cueing in individuals with PD having varying severity of symptoms. In fact, literature shows that there exists a relationship between one's vibrotactile perception and the severity of the disease [56] that can be quantified in terms of clinical measures, such as MDS-UPDRS. Our results based on the intergroup analysis provides valuable insights into

the impact of disease progression on sensory perception in individuals with Parkinson's disease (PD). The results indicate that Normalized Accuracy of identifying the anatomical location in individuals with mild PD closely resembled that of healthy elderly, as there were no statistically significant differences between these groups across any anatomical location. This finding suggests that sensory perception may remain largely intact in the early stages of PD, enabling comparable response accuracy to that of healthy individuals. However, as the disease progresses to a moderate stage, we could observe a significant decrease in the Normalized Accuracy for several distal anatomical locations, including the 'Finger', 'Ankle', 'Achilles tendon', and 'Heel'. However, the 'Thigh', 'Shin', 'Calf', and 'Wrist' anatomical locations demonstrated a relatively better sensory perception accuracy in the moderate PD group, with no significant differences between healthy individuals and those with moderate PD. Among these, the 'Thigh' had the highest Normalized accuracy (approximately 92%), suggesting that perception in this proximal location has a slower sensory decline with advancing disease severity. These findings underscore the potential of targeting proximal locations, such as the 'Thigh', for future intervention strategies aimed at enhancing sensory cueing in individuals with moderate severity of PD, as they offer a reliable anatomical location for delivering external cues to support gait and mobility. The identification of the 'Thigh' as a preferable location for stimulation opens promising avenues for developing wearable devices in the future that can deliver external cues to alleviate FoG, thereby supporting improved gait.

Though our results were promising, our study had certain limitations. First of all, in our present study, the data was collected when the participants were seated. We opted for a static posture in this study since our aim was to identify an appropriate anatomical location for vibrotactile stimulation (providing foundational insights valuable for future studies designed to understand the implications of such findings on one's gait performance) while eliminating possible confounds, e.g., cognitive load arising due to the task of focusing on walking that in turn might adversely affect one's choice of anatomical location for receiving vibrotactile stimulation. In future, we plan to extend our study, wherein the participants would be asked to walk while wearing our system, which would need the system to be designed as a portable system. This would require the system to be preferably wireless, unlike the existing wired system. Also, we did not consider the effect of muscle tone on one's vibrotactile perception in our study that we plan to address in the future. Again, though our data collection was done with the participants with PD being in the OFF-state, we did not account for the differences in the effect of variations in the medications and the dosages in our study that can be explored further in the future. Additionally, in our present study, while the various anatomical locations of one's dominant leg and hand in the seated posture (without any unilateral and bilateral performance measures) were considered, the vibrotactile stimulation was offered three times to each anatomical location in a randomized manner. Having found that the 'Thigh' is a strong candidate location for delivery of the stimulation, further studies will be needed to understand whether any habituation effect exists due to the vibrotactile stimulation being offered to the 'Thigh' location over repeated exposures.

Conclusion

In our present work, we have conducted a study involving individuals with PD to identify anatomical locations with regard to perception of vibrotactile stimulation so that in future these anatomical locations can be used to deliver tactile cues that has been reported as beneficial for improving gait of this target group. Given the importance of precise sensory perception for vibrotactile cues being effective, we focused on understanding differences in vibrotactile perception between PD patients and age-matched healthy individuals. Using a static, seated task, the study evaluated vibrotactile perception across eight anatomical locations along with relevant bone prominences or muscle names, such as 'Finger' (Distal Phalange of Index finger), 'Wrist' (Radial Styloid Processes), 'Heel' (below the Calcaneus), 'Achilles Tendon', 'Ankle' (Lateral Malleolus), 'Calf ' (Gastrocnemius Medialis), 'Shin' (Tibialis Anterior), and 'Thigh' (Rectus Femoris). Our results showed that the 'Thigh' (among all the eight different anatomical locations of the upper and lower limbs studied here) emerged as a strong candidate location for receiving the vibrotactile stimulation for the individuals with PD irrespective of the severity of the symptoms. This possibly suggests that the 'Thigh' can serve as the preferred location for application of vibrotactile cues having clinical significance. This preference for the 'Thigh' in PD patients may be attributed to its proximal location on the lower limb, which may retain high vibrotactile sensitivity. The 'Wrist' was also identified as a secondary viable location, though with slightly lesser consistency than the 'Thigh'. In contrast, healthy individuals demonstrated higher vibrotactile perception at the 'Thigh' and 'Wrist' followed by the 'Finger'. In summary, the choice of 'Thigh' as a strong anatomical location with regard to vibrotactile perception was found in both individuals with PD and also their age-matched healthy counterparts (for whom 'Wrist' was also found to be equally strong) emphasizing the need of further deeper investigation of the use of this anatomical location in clinical applications. Notwithstanding the limitations, our present study provides an understanding of the importance of anatomical location for receiving vibrotactile stimulation, which in turn can hold promise in clinical practice and thereby contribute to improving the quality of life of individuals with PD.

Methods

Participant characteristics

Twenty-one healthy participants (H1 to H21; $Group_H$) and twenty-one individuals with PD (P1 to P21: $Group_{PD}$) were recruited from the neighbourhood and hospitals (where they were undergoing treatment), respectively. Individuals with PD were enrolled through a clinician's referral. The inclusion/exclusion criteria for the participants were (i) age between 40 and 85 years, (ii) can understand the experimenter's instructions, and (iii) can sit at one place for around 30 min. In addition, the $Group_H$ had no neurological, musculoskeletal, or vestibular impairment (confirmed by the accompanying clinician in our team). Table 2 shows the participants' characteristics. Here, all the individuals in $Group_H$ had both right hand and right leg dominance, while, the individuals belonging to $Group_{PD}$ had 90.5% right hand dominance and 85.7% right leg dominance determined based on the Waterloo Footedness Questionnaire-Revised (WFQ-R) test [57] and Edinburgh Handedness Inventory-Writing test [58]. All the participants belonging to

Table 2 Participants' characteristics

$Group_{PD}$								$Group_{H}$				
Participant ID	**Age (gender)**	**BMI**	**MDS-UPDRS-III**	**H&Y score**	**Dominant side**		**Disease duration (Years)**	**Participant ID**	**Age (gender)**	**BMI**	**Dominant side**	
					Hand	**Foot**					**Hand**	**Foot**
P1	76(M)	21.4	22	2	Right	Left	2	H1	63(M)	19	Right	Right
P2	75(M)	30.8	23	2	Right	Left	2	H2	48(M)	17.8	Right	Right
P3	49(F)	18.8	28	2	Right	Right	4.5	H3	74(F)	29.8	Right	Right
P4	68(F)	25.9	22	3	Right	Right	2	H4	60(F)	26.2	Right	Right
P5	43(F)	25.7	24	2	Right	Right	2	H5	50(M)	21	Right	Right
P6	70(M)	29.9	35	3	Right	Right	3	H6	58(M)	19.3	Right	Right
P7	72(M)	18.9	31	3	Right	Left	7	H7	44(M)	18.9	Right	Right
P8	40(M)	29.7	30	2	Left	Left	1	H8	58(M)	26.8	Right	Right
P9	52(M)	18.5	22	2	Right	Right	4	H9	52(F)	35.9	Right	Right
P10	55(M)	24.5	47	3	Right	Right	10	H10	75(M)	28.2	Right	Right
P11	60(M)	23.5	22	2	Right	Right	9	H11	70(M)	21.4	Right	Right
P12	72(M)	23.2	35	3	Right	Right	8	H12	55(M)	25.8	Right	Right
P13	62(F)	26.5	25	2	Right	Right	7	H13	52(M)	33.3	Right	Right
P14	74(M)	27.2	47	3	Right	Right	13	H14	70(F)	28.9	Right	Right
P15	81(M)	24.3	33	3	Right	Right	7	H15	75(F)	31.2	Right	Right
P16	78(M)	20.6	51	3	Right	Right	2	H16	71(F)	33.9	Right	Right
P17	82(M)	23	21	2	Right	Right	2	H17	75(F)	19.6	Right	Right
P18	54(F)	21.4	35	2	Right	Right	3	H18	52(M)	22.1	Right	Right
P19	70(M)	24.9	53	3	Right	Right	10	H19	69(M)	24.8	Right	Right
P20	67(F)	26.2	21	2	Left	Left	4	H20	64(M)	27.7	Right	Right
P21	82(M)	26.5	27	3	Right	Right	6	H21	61(M)	26.7	Right	Right
Average (S.D)	65 (12.49)	24.25 (3.64)	31.35 (10.58)	2.45 (0.51)				Average (S.D)	62.45 (10.18)	25.58 (5.54)		

the $Group_{PD}$ were reported to have idiopathic PD, as per their clinical diagnoses. Again, scores on the MDS-Unified Parkinson's Disease Rating Scale motor part (MDS-UPDRS III) [50] of the individuals belonging to $Group_{PD}$ indicate that 62% and 38% of these participants had mild (score < 33 [50]), moderate ($33 \geq$ score < 59 [50]) symptoms of Parkinson's Disease, respectively along with Hoehn and Yahr (H&Y) Scale [59] scores ranging from 2 to 3 (Table 2). In addition, none of our participants had peripheral neuropathy as evident from the monofilament test [60]. Also, none of the participants reported any pain on any of the anatomical locations considered in our study. The two participant groups were not statistically different on age ($p > 0.05$). The study had institute ethical clearance (Approval No.: IEC/UL/2021/024).

System design

Our Vibrotactile Stimulation System comprised of four modules, namely (i) Vibrotactile Module, (ii) Microcontroller-based Central Module, (iii) Switching Module and (iv) Graphical User Interface. The Vibrotactile Module was used to offer vibrotactile stimulation at an anatomical location. The Microcontroller-based Central Module housed a Vibrotactile Stimulation Routine that was used to trigger the Vibrotactile Module via a Switching Module. The Graphical User Interface (GUI) was used to record one's responses and start the execution of the Vibrotactile Stimulation Routine. Figure 5 presents an overview of the Vibrotactile Stimulation System used in our study.

Vibrotactile module

Each Vibrotactile Module (Figs. 5 and 6) comprised of (i) an Eccentric Rotating Mass (ERM) DC Vibration motor [61] (18 mm length, 6 mm diameter; Speed:19,000 rpm; Operating voltage, 1.5–5 V) mounted on a metal steel disc (while ensuring that there is

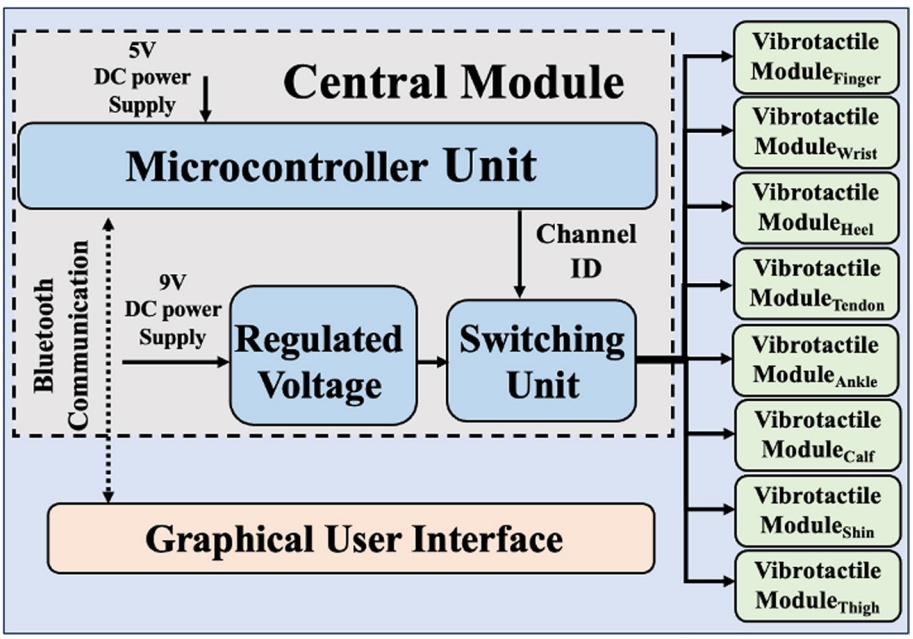

Fig. 5 Vibrotactile Stimulation System

no relative movement between the motor and the disc) housed in a casing. The casing was modelled in Autodesk Fusion 360 CAD software [62] and printed using the Raise 3D E2 FDM Printer [63] using the Polylactic Acid material [64] and (ii) an adjustable Velcro Belt for securing the casing to an anatomical location. The casing was of two types, namely Type-1 casing (Fig. 6a), i.e., circular disc 3.5 cm in diameter (having a base holder (Fig. 6b (i)) to hold the metal steel disc and a cover (Fig. 6b (ii)) with protrusions to maintain the position of the ERM Motor) and Type-2 casing i.e., half-cylindrical (Fig. 6c; 2.5 cm length, 1 cm diameter). Our system had 8 Vibrotactile Modules programmed with each module programmed to provide 180 Hz vibrotactile stimulation at each of the anatomical locations. The choice of 180 Hz was based on the existing literature [45] which included individuals with PD and healthy age matched individuals and offering stimulation only to the abdomen and reported that a frequency of 180 Hz is effective in eliciting high vibration sensitivity, for both participant groups.

Microcontroller-based central module

This Module (Fig. 5) comprised of (i) Microcontroller (ATMEGA 2560) and (ii) Bluetooth Transceiver (HC-05). The microcontroller (powered by a regulated 5 V source) housed a Vibrotactile Stimulation Routine that was used to randomly generate a channel identifier (Channel ID) which in turn was used to trigger three digital channel selector pins of the Switching Module for triggering a relevant Vibrotactile Module. The Bluetooth transceiver was used to wirelessly transmit the Channel ID to a data logger (Laptop recording the Channel ID and displaying a GUI (discussed below)) and receive an 'initiate' command from the GUI (to initiate the execution of the Vibrotactile Stimulation Routine).

Switching module

This Module (Fig. 5) comprised of (i) an 8-Channel Demultiplexer (74HC4051) based switch and (ii) a Voltage Regulator (LM317 DC-DC Adjustable Voltage Regulator Power Supply Module [65] offering regulated voltage of 3.6 V (for details on the selected voltage, please see "Calibration of Vibrotactile Module" section)). Based on the Channel ID generated by the Microcontroller-based Central Module, an output channel of the Demultiplexer integrated with a Vibrotactile Module (with options of random selection of one of the eight channels) was selected.

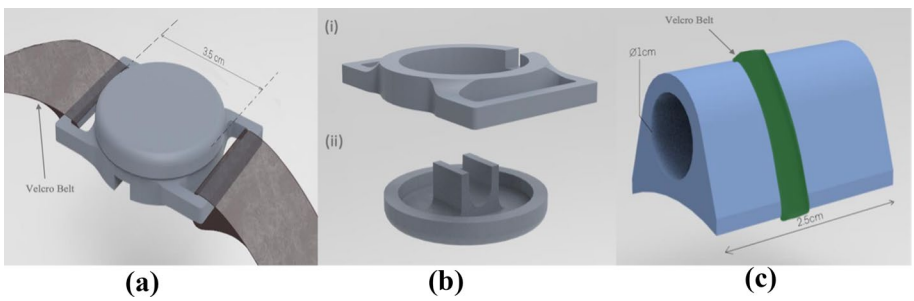

Fig. 6 **a** The Vibrotactile Module casing (circular) **b** Detailed view of the casing having (i) Base Holder and (ii) Cover, **c** The Vibrotactile Module casing (cylindrical)

Graphical user interface

The Graphical User Interface (GUI; Fig. 5) presented on a monitor of a data logger (Laptop) was used to (i) send an 'initiate' command to the Microcontroller-based Central Module to start the execution of the Vibrotactile Stimulation Routine and (ii) to log one's response on the anatomical location being stimulated.

Experimental setup

The experimental setup comprised of the (i) Vibrotactile Stimulation System having (a) eight numbers of pre-calibrated Vibrotactile Modules (Sect. 5.2.1; for details on calibration of Vibrotactile Modules, please see "Calibration of Vibrotactile Module" section), (b) eight numbers of Velcro belts with buckles and (c) Microcontroller-based Central Module, (ii) a table along with a chair and (iii) data logger (Laptop). The Velcro belts with buckles were used to hold the Vibrotactile Modules, which were applied directly on the skin. The Microcontroller-based Central Module and data logger were placed on the table in front of the chair.

Procedure

Our study required ~ 30 min of commitment from each participant. The study room had the experimental setup, an experimenter and a clinician. The experimenter was responsible for providing the instructions to the participants, preparing them for the study and registering their responses during the study. The accompanying clinician was responsible for administering all the clinical tests, signing of the consent form, collecting the demographics of the participants and identifying the relevant bone prominences or muscles as target anatomical locations for the application of vibrotactile stimulation. When the participant entered the study room, the experimenter asked him/her to sit on a chair in an upright seated pose with head over the pelvis, feet in a neutral position and supported, weight being evenly distributed between both buttocks and arm protracted forward [66]. This was followed by the experimenter showing the experimental setup to the participants and demonstrating what they were expected to do while describing the study using a visual schedule. Also, they were told that they were free to discontinue from the study at any time, if uncomfortable. In addition, they were free to ask for a break at any point during the study. The accompanying clinician administered the clinical scoring (namely MDS-UPDRS Scores [50]) while confirming the inclusion/exclusion criteria. The consent signing was administered when the participant expressed that he/she understood what was expected from him/her and was ready to take part in the study. Then the experimenter used the Velcro belts (with buckles) to position the calibrated Vibrotactile Modules (for details on the calibration of Vibrotactile Module, please see "Calibration of Vibrotactile Module" section) directly on the skin at eight anatomical locations, namely 'Finger' (Distal Phalange of Index Finger), 'Wrist' (Radial Styloid Processes), 'Heel' (below the Calcaneus), 'Achilles Tendon', 'Ankle' (Lateral Malleolus), 'Calf ' (Gastrocnemius Medialis), 'Shin' (Tibialis Anterior), and 'Thigh' (Rectus Femoris) (Fig. 7) on the dominant leg and hand of the participant ("Participant characteristics" section) while choosing Type-I casing (Fig. 6a) for all anatomical locations except for the 'Finger' location wherein we used the Type-II casing (Fig. 6c), in the presence of the accompanying clinician, while the participant was in a seated position. Following

this, the Vibrotactile stimulation was administered using the Vibrotactile Stimulation Routine (residing in the Microcontroller-based Central Module (Sect. 5.2.2)) that offered vibrotactile stimulation with each stimulation lasting for 1 s (similar to the duration being chosen in other studies, e.g., [9]) to each of the eight anatomical locations. Our system provided vibrotactile stimulation three times (i.e., during three trials) to each location in a randomized manner (to avoid ordering effects [67]), thereby offering a total of 24 numbers of vibrotactile stimulations. After each stimulation, the experimenter asked the participant to identify the anatomical location (by responding in terms of 'Yes' or 'No' that in turn was used to compute the response type as 'Correctly Identified' or 'Missed' or 'Misinterpreted' type ("Extraction of Response Type Based on Identification step" section)) receiving the vibrotactile stimulation (Identification step *henceforth*), followed by the experimenter registering the participant's response (using the GUI (Sect. 5.2.4)). Once the study was over, the experimenter administered a survey on vibrotactile perception. The experimenter collected verbal feedback (while naming the anatomical location) from the participant regarding the top three choices of anatomical locations for receiving vibrotactile stimulation (Feedback step *henceforth*).

Data processing

Computation of choice of anatomical location for receiving stimulation during feedback step

Based on the verbal feedback of the participants in the survey on vibrotactile perception, we computed the choice for anatomical location (while receiving stimulation) for each participant using Eq. (1).

$$\%Response(\mathrm{j}) = \frac{\sum_{i=1}^{N} m_i}{\sum_{i=1}^{N}\sum_{j=1}^{8} m_{ij}} * 100 \tag{1}$$

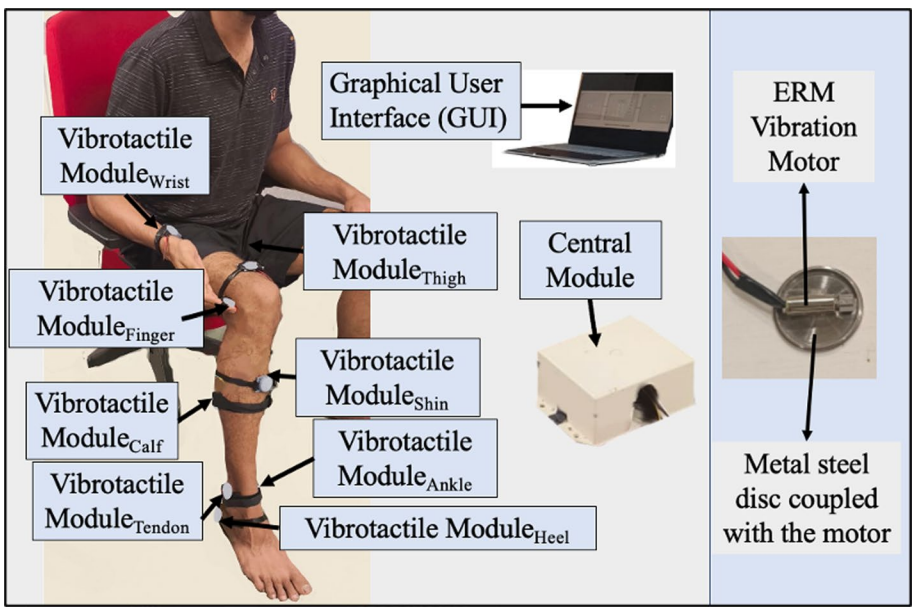

Fig. 7 Experimental Setup with anatomical locations marked for Vibrotactile modules

Here 'm' is either one (for the anatomical location being selected by the participant) or zero (for anatomical location not selected by the participant), 'i' is the participant ID, 'N' is the total number of participants in a group ($Group_H$ or $Group_{PD}$) and 'j' represents the anatomical location represented by the channel ID (Sect. 5.2.2) varying from 1 to 8, namely 'Finger,' 'Wrist,' 'Heel,' 'Achilles Tendon,' 'Ankle,' 'Calf,' 'Shin,' and 'Thigh.'

Extraction of response type based on identification step

The participants' responses during the Identification step were categorized into three types, namely 'Correctly Identified', 'Missed' or 'Misinterpreted' Response. If the participant's indicated anatomical location matched with the location where the vibrotactile stimulation was offered by our system (as mapped from the channel ID (Sect. 5.2.2)), then the response was labelled as 'Correctly Identified' type. Alternatively, if the anatomical location indicated by the participant did not match with the location where the stimulation was offered, then the response was labelled as either 'Missed' type (in case one did not feel any stimulation) or 'Misinterpreted' type (in case one felt stimulation at a location that did not match with the location as indicated by the channel ID).

Subsequently, we computed the % Response Type for each participant group based on the 'Correctly Identified' (Eq. 2), 'Missed' (Eq. 3) or 'Misinterpreted' (Eq. 4) Responses with respect to each anatomical location.

$$\%\,''\text{Correctly identified}''\ \text{Response}(j) = \left(\frac{\sum_{i=1}^{N}\sum_{k=1}^{3} x_{ki}}{\sum_{i=1}^{N}\sum_{k=1}^{3}\left(x_{kij}+y_{kij}+z_{kij}\right)}\right) * 100 \tag{2}$$

$$\%\,''\text{Missed}''\ \text{Response}(j) = \left(\frac{\sum_{i=1}^{N}\sum_{k=1}^{3} y_{ki}}{\sum_{i=1}^{N}\sum_{k=1}^{3}(x_{kij}+y_{kij}+z_{kij})}\right) * 100 \tag{3}$$

$$\%\,''\text{Misinterpreted}''\ \text{Response}(j) = \left(\frac{\sum_{i=1}^{N}\sum_{k=1}^{3} z_{ki}}{\sum_{i=1}^{N}\sum_{k=1}^{3}(x_{kij}+y_{kij}+z_{kij})}\right) * 100 \tag{4}$$

Here, '*x*', 'y', and '*z*' are valued as either '1' or '0' and represent the 'Correctly Identified', 'Missed' or 'Misinterpreted' Responses, respectively.

For example, while considering the 'Correctly Identified' type, '*x*' will be '1' if one's response on the anatomical location wherein the vibrotactile stimulation was perceived by him / her matched with the Channel ID (as activated by our system) and '0' if one missed to perceive the vibrotactile stimulation or one's response on the anatomical location wherein the vibrotactile stimulation was perceived by him/her did not match with the Channel ID. Likewise was the case for the 'y', and '*z*'. Again, 'i' is the participant ID, 'N' is the total number of participants in each group ($Group_H$ or $Group_{PD}$) and '*j*' represents the anatomical location (i.e., 'Finger' / 'Wrist' / 'Heel' / 'Achilles Tendon' / 'Ankle' / 'Calf' / 'Shin' / 'Thigh') represented by the channel ID (Sect. 5.2.2) and '*k*' is the number of trials. In addition, we computed the percentage Normalized Accuracy (in terms of 'Correctly Identified' Responses) for each participant using Eq. (5).

$$Normalized\ Accuracy(i,j) = \frac{\left(\frac{\sum_{k=1}^{3} x_{kij}}{\sum_{k=1}^{3}(x_{kij}+y_{kij}+z_{kij})}\right)}{\sum_{j=1}^{8}\sum_{k=1}^{3}(x_{kij}+y_{kij}+z_{kij})} * 100 \quad (5)$$

Here *'x'*, 'y', and *'z'* are the same as that in Eqs. (2) – (4), *'k'* is the number of trials, 'i' is the participant ID and *'j'* represents the anatomical location ('Finger,' 'Wrist,' 'Heel,' 'Achilles Tendon,' 'Ankle,' 'Calf,' 'Shin,' and 'Thigh') represented by the channel ID (Sect. 5.2.2).

Calibration of vibrotactile module

While anatomical location that needs to be offered with vibrotactile stimulation is important, the characteristic of the stimulation is crucial particularly with regard to vibrotactile perception. Given this importance, researchers have reported use of vibrotactile stimulation frequencies ranging from 180 to 250 Hz particularly in studies involving individuals with Parkinson's Disease [9, 14, 17]. Specifically, in one of these studies, researchers have reported 180 Hz as the threshold frequency of vibrotactile stimulation for vibrotactile perception [45]. Thus, in our present study was focused on the comparative evaluation of vibrotactile perception at various anatomical locations particularly for individuals with Parkinson's Disease, we wanted to make sure that our vibrotactile system offered a vibratory stimulus of 180 Hz. To achieve this, we carried out a calibration step of our system for delivering vibratory stimulus of 180 Hz. For this, we used a Voltage Regulator (LM317 DC-DC Adjustable Voltage Regulator Power Supply Module [65]), (ii) Vibrotactile Module (Sect. 5.2.1), (iii) Piezoelectric sensor [61, 68] and (iv) a Digital Oscilloscope (as shown in Fig. 8). The Voltage Regulator (driven from a 9 V DC source) was used to regulate the input voltage to the ERM motor (Sect. 5.2.1) of the Vibrotactile Module to generate a vibrotactile stimulation output that in turn was measured using the Piezoelectric sensor (pasted to the steel disc of the casing) connected to the Digital Oscilloscope. The Voltage Regulator was adjusted to vary the voltage ranging from 0 to 4 V in steps of 0.2 Volt while driving the ERM motor along with recording the corresponding frequency of vibrotactile stimulation. We found that the frequency of vibrotactile stimulation of 180 Hz was achieved at 3.6 V.

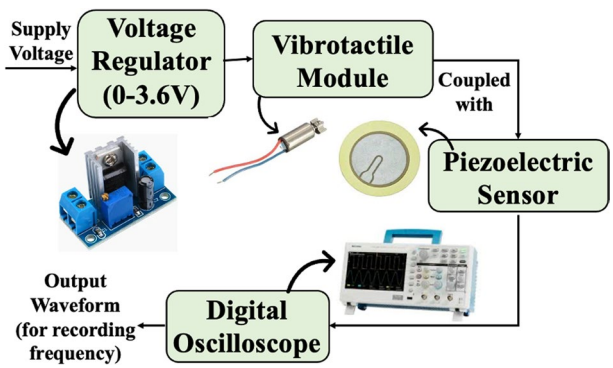

Fig. 8 Calibration Setup

Statistical analysis

We have used Statistical Package for the Social Sciences from IBM, commercially referred to as SPSS Statistics (Version 20) Software, to carry out all the statistical tests. First, the ANOVA test [69] was done on the values of Normalized Accuracy ("Extraction of Response Type Based on Identification step" section) and the % Response Type (for 'Correctly Identified', 'Missed' and 'Misinterpreted' Responses; "Extraction of Response Type Based on Identification step" section) and then the residuals were tested for normality using the Shapiro–Wilk [69]. Since this was not found to be normally distributed, we applied a non-parametric test for the statistical significance. For within-group (i.e., intra-group) analysis, we used non-parametric Friedman test followed by the Wilcoxon-signed-rank post-hoc test [69]. For across-group (i.e., inter-group) analysis, we used non-parametric Kruskal–Wallis test followed by the Mann–Whitney post-hoc test [69]. Additionally, for computing sample power, we have used Statistical Power Analysis Program (Version 3.1.9.4) commercially referred to as G*-Power (Version 3.1.9.4) software [70] to carry out the post-hoc power analysis with the observed effect size calculated using the Cohen's d test [70] and alpha error probability of 0.05 for intergroup and intragroup analysis.

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Author contributions
Ankita Raghuvanshi and Uttama Lahiri drafted the manuscript and contributed to the experiment design, experimental data collection with healthy individuals and individuals with Parkinson's, data analysis, and statistical analysis. Priya Pallavi contributed to the data collection with healthy and individuals with Parkinson's. Rahul Chhatlani, Jayesh Parmar, Manish Rana, and Sagar Betai contributed to the enrolment of individuals with Parkinson's and assessment of the clinical measures. Also, all authors had read, cor-rected/commented, and approved the final manuscript.

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Data availability
No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
The study was carried out in accordance with the recommendations of Institutional Ethics Committee (IEC), IIT Gandhinagar and Approval No.: IEC/UL/2021/024). All participants provided informed and written consent for their participation in the study.

Consent for publication
The authors affirm that human research participants provided informed consent for publication of the images in Fig. 7.

Competing interests
The authors declare no competing interests.

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