Title	Vibrālign : enhancing yoga practice through haptic feedback
Sub Title	
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Publisher	慶應義塾大学大学院メディアデザイン研究科
Publication year	2025
Jtitle	
JaLC DOI	
Abstract	
Notes	修士学位論文. 2025年度メディアデザイン学 第1215号
Genre	Thesis or Dissertation
URL	https://koara.lib.keio.ac.jp/xoonips/modules/xoonips/detail.php?koara_id=KO40001001-00002025-1215

Master's Thesis
Academic Year 2025

Vibrālign: Enhancing Yoga Practice Through Haptic Feedback

Keio University
Graduate School of Media Design

Liu Feiran

A Master's Thesis
submitted to Keio University Graduate School of Media Design
in partial fulfillment of the requirements for the degree of
Master of Media Design

Liu Feiran

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Abstract of Master's Thesis of Academic Year 2025

Vibrālign: Enhancing Yoga Practice Through Haptic Feedback

Category: Design

Summary

Traditional home-yoga instruction often depends on watching a screen, encouraging practitioners to lift the head, check alignment visually, and lose touch with breath and inner sensation. To counter this outward focus, the present work proposes a deliberately low-tech, manually operated feedback kit that replaces video with a few soft audio tones and gentle vibrations delivered through a floor mat, a handheld haptic interface, and a haptic wearable kit. Across three design rounds, the haptic language was pared down to simple pulses that mark inhalations, signal weight shifts, and offer discreet "nudges" when alignment drifts. In studio trials, beginners learned the cues within minutes, reported a stronger sense of body awareness than with mirror-based practice, and preferred the tactile mode because it let them keep their gaze neutral and attention on breath. The study shows that even without complex sensing or screens, carefully choreographed audio-haptic prompts can help novices maintain inward focus, correct posture intuitively, and sustain an uninterrupted flow, pointing to a practical path for screen-free, self-guided yoga at home.

Keywords:

Embodied Haptic, Haptic Interaction, Yoga Technology, Human–Computer Interaction

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Acknowledgements

This thesis would not have been possible without the support, guidance, and encouragement of many wonderful people. I would like to express my deepest gratitude to all of you.

First and foremost, I owe my sincere thanks to Professor Kouta Minamizawa. His visionary approach to human–technology interaction, sharp academic insight, and patient mentorship kept me on track at every crossroads and taught me to see research through a broad, human-centred lens.

I am profoundly grateful to Takatoshi Yoshida Sensei, who never gave up on me. No matter the hour, he offered steadfast support and reassurance, reminding me why persistence matters whenever I felt lost.

My heartfelt thanks also go to Arata Horie Sensei, who first opened the door to the world of haptic design and guided me through its principles, and to Sohei Wakisaka Sensei, whose warm advice and infectious enthusiasm brought both clarity and joy to this project.

I would like to acknowledge my sub-supervisors, Professor Sunahara and Professor Ishido, for their rigorous feedback and constructive criticism, which greatly sharpened the structure and depth of this thesis.

Special thanks to those who offered technical support along the way: Youichi Kamiyama, Tsujita Kiryu, Kobayashi Kohei, Zhu Yufan, Shen Jiayi, and Peng Hanrui. Each troubleshooting session and hardware tweak benefited from your expertise.

I am also indebted to Xianggu for crafting the bespoke haptic-design audio that completed the experience.

To every participant who took part in my user interviews and usability tests—thank you. Your time, honesty, and engagement provided the essential data that made this study meaningful and credible.

To my friends, family, and everyone who has stood by my side over the past two years—your understanding, patience, and encouragement were my greatest source of strength. Love you all.

Finally, thank you to myself for being brave and unbreakable. May the curiosity and passion that shaped this journey continue to guide the adventures ahead.

Chapter 1
Introduction

1.1. Sedentary Lifestyles: Home-Workout Trends& Risks

Physical inactivity now represents a critical global health threat: in 2022 roughly one-third of adults (1.8 billion) fell short of World Health Organization activity guidelines—five percentage points higher than in 2010 and projected to reach 35 % by 2030 [1]. This sedentary trend is strongly associated with increased incidence of cardiovascular disease, type II diabetes, dementia, and several site-specific cancers [1]. The COVID-19 pandemic catalysed a rapid migration to home-based exercise, with the proportion of U.S. exercisers training at home rising from 24 % in 2019 to 34 % in 2020, peaking at 36 % in 2021 and sustaining 33 % in 2022; correspondingly, digital-fitness revenue (e.g., Peloton) expanded by 232 % in 2020 [2,3]. Convenience (51 %) and privacy (20 %) constituted the primary drivers of this behavioural shift [2].

However, the widespread adoption of home workouts has introduced new challenges, most notably the increased risk of injury due to improper form in the absence of professional guidance. Common home workout injuries include sprains, muscle strains, tendinitis, and issues like lower back pain, shoulder impingement, and hip/knee pain [4]. For example, incorrect lifting posture can directly induce lower back pain, while excessive overhead movements performed incorrectly can easily damage shoulder joints [4]. Poor posture not only diminishes training effectiveness but also places undue stress on specific joints and the spine, potentially leading to long-term risks [**?**].

1.2. The Advantages of Yoga

The Corrective Advantages of Yoga, with its emphasis on mind-body connection, precise alignment, and breath control, is considered an ideal choice for addressing posture issues in home workouts. Research indicates that regular yoga practice can significantly improve functional movement patterns, enhancing metrics such as deep squat quality, shoulder mobility, and trunk stability [5]. Experienced yoga practitioners demonstrate superior joint position sense, indicating more acute proprioception (the body's awareness of its position in space) [5]. This heightened proprioception is crucial for controlling posture and coordination through complex reflex systems [5].

Furthermore, yoga activates the core, strengthens multi-muscle group collaboration, and expands joint range of motion, thereby preventing chronic strain caused by imbalances [5,6]. By engaging multiple muscle groups simultaneously and emphasizing proper muscular and skeletal alignment, yoga encourages practitioners to develop a more balanced and integrated approach to movement, effectively preventing injuries [5]. Beyond physical benefits, yoga also fosters greater body awareness, helping individuals detect physical problems earlier and take preventive action [6].

1.3. The Haptic Feedback for Yoga

The Potential of Haptic Feedback for Posture Correction In recent years, targeted vibration has been shown to rapidly signal body deviations, helping practitioners adjust their posture without relying on visual or auditory cues. Brief, localized vibratory stimuli can directly act on tendons and muscle spindles, enhancing proprioception and lower limb stability. Multiple experiments indicate that vibration training can significantly reduce balance errors and shorten correction time within weeks. For scenarios where vision is limited or attention is diverted, the accessibility of vibration cues is particularly salient.

1.4. Research Goal

Learning complex postural exercises such as yoga typically relies on visual demonstration (mirrors, videos, instructor models), which can limit learners' internal proprioceptive development. We therefore ask our **research question: how can a multimodal tactile guidance system – comprising a six-zone floor-vibration mat, a haptic wristband device, and minimal audio prompts – enhance yoga practitioners' body awareness and balance accuracy?**

Conventional yoga guidance is almost entirely visual, offering scant information on weight distribution or interoceptive cues; as a result, users struggle to monitor balance, and little work has explored how spatially distributed haptics affect whole-body control. To fill this gap, we will develop and test a multisource tactile system that couples a six-zone vibrotactile floor with a wristband actuator, a torso vest, and minimal audio beeps. In a within-subject studio study, participants will perform balance-oriented postures under audio-only versus audio-plus-tactile conditions, with postural-sway metrics and self-reported body awareness as primary outcomes. Drawing on prior evidence that vibrotactile feedback enhances motor accuracy and proprioception, we hypothesise that multimodal cues will deliver superior balance control and stronger interoceptive awareness, thereby advancing a body-centric alternative to vision-dependent instruction and highlighting the value of distributed haptics in embodied motor learning.

1.5. Thesis Structure

Chapter 1 – Introduction defines the public-health challenge of sedentary lifestyles, positions yoga and wearable haptics as a remedial avenue for at-home exercise, and states the research aim and thesis roadmap.

Chapter 2 – Literature Review synthesises scholarship on yoga's evolution and on haptic feedback in fitness, distilling outstanding gaps that motivate the present investigation.

Chapter 3 – Concept Design details user-journey insights, system architecture, and two cycles of iterative prototyping, culminating in a preliminarily validated haptic-yoga prototype.

Chapter 4 – Proof of Concept outlines the experimental protocol, data-collection instruments, and analysis plan used to evaluate the prototype, and reports the principal empirical results.

Chapter 5 – Discussion interprets the findings, recommends product and haptic refinements, considers implications for at-home fitness, acknowledges study limitations, and proposes future research directions.

Chapter 6 – Conclusion recapitulates the thesis's contributions to haptic-centred yoga guidance and underscores its significance while indicating promising avenues for subsequent work.

Chapter 2
Literature Review

2.1. Yoga Practice and History

2.1.1 Classical Roots and Hatha Focus

The Sanskrit verb *yuj*—"to yoke, join, concentrate"—gives yoga its name and its earliest purpose: uniting body, mind and inner self. Patañjali's Yoga Sūtra (c. 2nd century CE) systematises that aim into an eight-limbed path that moves from ethical restraint (*yama, niyama*), through breath control (*prāṇāyāma*) and meditative absorption, toward experiential stillness of thought [7]. These classical ideas place inward observation—rather than outward display—at the heart of practice, a thread that later technological discussions in this thesis will pick up.

Historical sources portray yoga not as a single technique but as a spectrum of complementary "systems of spiritual beliefs and practices". Commentators commonly group them into pathways centred on disciplined meditation (often called *Rāja*), loving devotion (*Bhakti*), selfless action (*Karma*), and philosophical insight (*Jñāna*). This overview prepares the ground for our focus on the physically oriented branch below and clarifies that posture-work is only one thread woven through a wider fabric of yogic pursuits [8, 9].

Medieval manuals such as the *Haṭha Yoga Pradīpikā* (11–15th century) introduce systematic postures (*āsana*) and breath-regulation, framing practice as a balance of solar (*ha*) and lunar (*tha*) forces. [10] Because most modern studios emphasise these posture-centred routines—often stripped of their contemplative scaffolding [10] —Hatha provides the most relevant terrain for studying weight-shift, alignment and sensory feedback. Its emphasis on bodily steadiness and energetic symmetry aligns directly with the balance-oriented cues our prototype delivers.

This thesis concentrates on novice Hatha practitioners who learn at home with limited verbal supervision. We ask how haptic guidance can restore the inward-looking ethos set out in the classics while supporting the precise weight distribution demanded by Hatha technique. By grounding the project in the lineage sketched above, the study positions haptic feedback not as a technological novelty but as a contemporary tool for reviving yoga's core promise of embodied union.

2.1.2 Modern and Home-Based Practice

Yoga has long embodied both physical discipline and spiritual cultivation, yet in the twenty-first century its primary stage of practice has shifted rapidly from traditional studios to the home. One decisive catalyst was the global COVID-19 pandemic of 2020: the temporary closure of brick-and-mortar venues drove teachers and students en masse to digital platforms, where "crisis substitutes" soon became a lasting habit. Worldwide surveys now show that roughly 67 percent of practitioners do yoga mainly at home, compared with 43 percent in gyms and 38 percent in conventional studios [11]. The "home first" pattern is visible across regions; in Japan, a nationwide poll found that about 30 percent of respondents practised via YouTube at home, far ahead of hot-yoga studios (19.3 percent) and regular studios (17.7 percent) [12]. These figures highlight the appeal of digital delivery in a time-pressed world: on-demand content eliminates commuting and dovetails with fragmented, flexible schedules.

The domestic setting has greatly broadened yoga's reach and inclusivity. Geographic barriers are eroded—people in smaller towns or rural areas can now access instruction from anywhere—and financial thresholds are lower, since many platforms use affordable subscription or pay-as-you-go models. Privacy and comfort also rise: practising at home removes social scrutiny, which is particularly attractive to those with body-image or social anxieties, while on-demand classes suit adults juggling work and family. With the explosion of online supply—from gentle Hatha to vigorous Power flows and mindfulness sessions—almost every niche is searchable, stimulating diverse, specialised demand. Practitioner numbers have surpassed 300 million [13].(Fig. 2.1)The global yoga industry was valued at roughly USD 1.071 trillion in 2023 and is projected to reach USD 2 trillion by 2030 (9.4 percent CAGR) [13]. Although offline courses still generated 74.3 percent of revenue in 2023, online offerings are growing fastest and already account for 48.5 percent of delivery in the narrower "yoga and meditation services" segment (2024) [13], signalling a structural shift toward digital income streams.

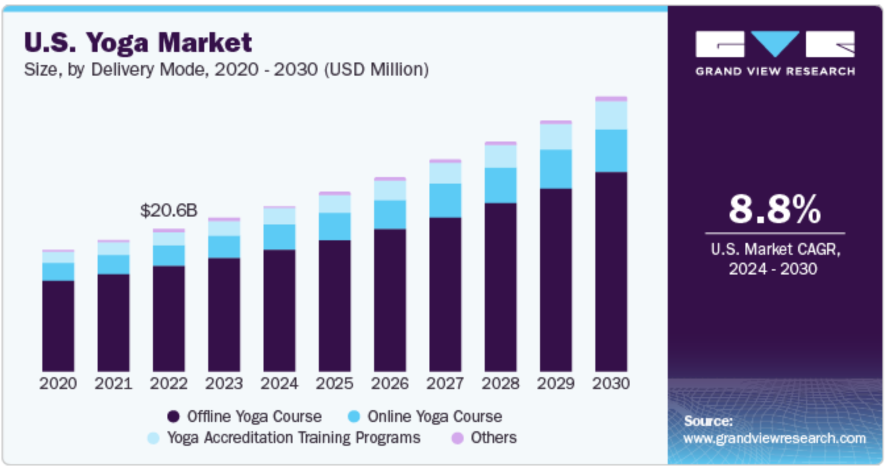


Figure 2.1 U.S Yoga Market (data from [13]).

Four factors chiefly drive the popularity of home-based yoga. First, flexibility: students can join sessions anytime, anywhere—ideal for high-intensity jobs or irregular schedules. Second, savings in time and travel: removing commutes and waiting boosts adherence. Third, affordability: online subscriptions typically cost less than studio memberships or drop-in fees. Fourth, abundant, self-directed choice: vast libraries of classes and teachers let users filter by interest, physical condition, or available time. The resulting supply-side boom has moved yoga beyond an "urban trend" toward a truly mass-participation activity, spanning teenagers to seniors and multiple cultural backgrounds.

The rise of home practice has also woven yoga more tightly into the fabric of holistic health management, transcending its traditional spiritual frame. Practitioners commonly report gains in flexibility, core strength, and posture, along with relief from anxiety, stress, chronic pain, and sleep problems. These outcomes place yoga—alongside meditation, mindful eating, and home aerobics—within the broader discipline of lifestyle medicine for preventing and managing chronic disease and improving mental health. Employers, insurers, and public-health agencies increasingly adopt online yoga as a low-cost, evidence-based intervention [14–18].

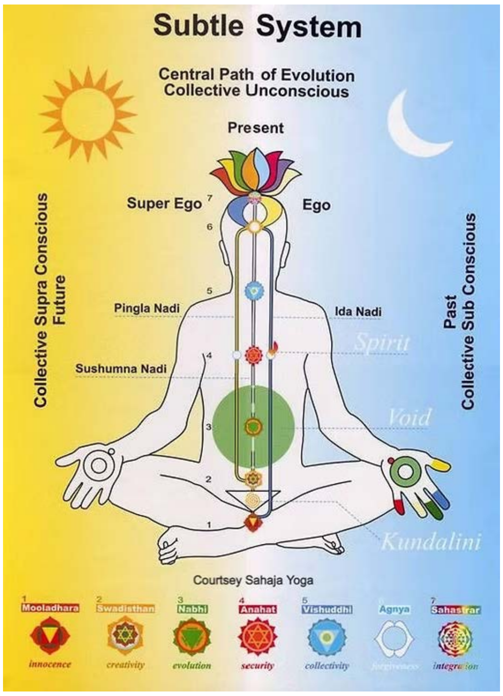
2.1.3 Embodied Sensory Experience in Hatha Yoga

Classical Hatha sources such as the *Hatha Yoga Pradīpikā* depict practice as the deliberate redirection of *prāṇa* so that it flows smoothly through the three principal*nāḍī*—*iḍā*, *piṅgalā* and *suṣumṇā*—and they treat this unimpeded energetic current as the gateway to *samādhi* [19](Fig. 2.1.3).

Contemporary neurophysiology reframes that phenomenology in terms of bodily signal integration: small-diameter lamina I afferents convey temperature, nociception, visceral pressure and cardiorespiratory information to the posterior insula, while muscle spindles and Golgi organs deliver joint-and-tension data to sensorimotor cortex; the right anterior insula then re-represents this composite map as the feeling of "how I am" in the moment [20](Fig. 2.1.3). Reviews of contemplative training report that mindfulness and yoga enhance the precision of this map—showing thicker insular cortex, stronger anterior-cingulate coupling and higher behavioural interoceptive accuracy—suggesting that the traditional "flow of prāṇa" is neurobiologically expressed as sharpened proprioceptive and interoceptive signalling.

Empirical evidence supports the link. A systematic review located three controlled studies in which 6–12 weeks of Hatha-based programmes (45–90 min, two or three times weekly) reduced absolute joint-position error in older adults, Parkinson's patients and congenitally blind children, with effect sizes up to 0.9 [22]. Parallel imaging and biomarker work shows that posture–breath–attention combinations raise vagal tone, elevate GABA and reinforce insula–ACC–prefrontal connectivity while engaging cerebello-basal-ganglia loops that refine sensorimotor prediction, giving a physiological route by which practice amplifies body-state awareness.

This sensorial chain is easily disrupted in the home environment. Qualitative analyses of online Hatha communities note that constant screen-gazing shifts attention outward; without tactile adjustment or spatial anchoring from a teacher, participants report "completing the pose but not feeling it" [23], and classic flow elements such as immediate feedback and loss of self-consciousness become rare. Survey modelling in studio settings likewise shows that serious engagement improves quality of life only when it passes through the mediators of flow and leisure benefit—pathways that weaken when feedback is poor—underlining the need for



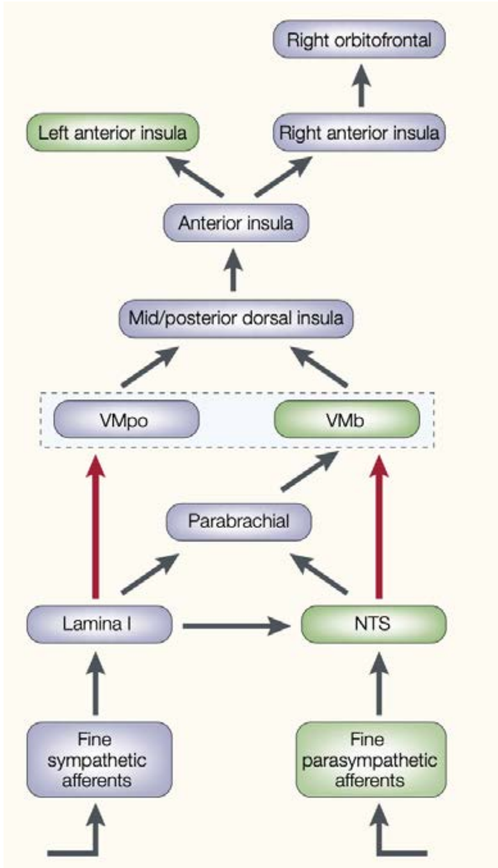


Figure 2.2 A classical Hatha-Yoga diagram of the subtle energy system, showing prāṇa moving through the central *suṣumṇā* and the paired *iḍā/piṅgalā nāḍīs* [21].

Figure 2.3 Craig's organizational chart for interoception, tracing sympathetic and parasympathetic afferents from lamina I and the NTS up through thalamic relays to graded maps in the insula and right orbitofrontal cortex [20]. Placed side by side, the two images mirror each other: the first expresses the yogic conception of energy circulation, while the second depicts the corresponding pathways identified by modern physiology.

richer sensory input [24].

2.1.4 Summary and Research Opportunity

Across the three sections above, the literature converges on a single through-line: yoga was conceived as an inward-facing discipline that refines bodily awareness, but the modern migration to home practice has weakened precisely those sensory channels that make such awareness possible. Classical texts cast prāṇa as a continuous current running through the nāḍīs, emphasising subtle perception over outer form [19]. Contemporary neuroscience translates that metaphor into the language of proprioceptive and interoceptive signalling, centred on lamina-I afferents, the insula and fronto-cingulate hubs [20]. Experimental trials confirm that structured Hatha routines can tighten joint-position accuracy and modulate vagal and GABAergic tone, physiologically sharpening the very sense of "inner flow" the classics describe [22]. Yet ethnographic and survey work shows that when guidance is delivered through flat screens and disembodied voice-overs, practitioners often "go through the motions" without perceiving the intended energetic or kinaesthetic effects; flow and quality-of-life gains collapse when immediate feedback is missing [23].

These gaps point to an actionable design space: augment home-based Hatha with multimodal cues that restore inward attention while remaining low-friction for novices. Audio instruction can handle macro-level instruction—timing, direction, sequence—freeing the eyes from constant screen-checking. Layered beneath, gentle multi-site haptic patterns can re-instantiate the felt continuity of prāṇa by (i) entraining breathing tempo, (ii) mapping stretch amplitude, and (iii) signalling weight shift in real time. Such an audio-haptic pairing directly targets the interoceptive and proprioceptive circuits highlighted in Section 2.1.3, promising to close the feedback loop that yoga practice currently lacks. The next chapter therefore reviews the state of haptic feedback technologies and distils principles for embedding them into a digitally mediated, yet somatically rich, Hatha-yoga experience.

2.2. Haptic Applications for Fitness

Recent work in human-computer interaction and wearable technology has explored haptic feedback as a tool to enrich yoga practice and similar embodied movement disciplines (e.g. tai chi, Pilates). By providing tactile cues – from gentle vibrations to pressure or stretch sensations – these systems aim to guide posture, synchronize breathing, and heighten practitioners' proprioceptive awareness. Below, we review examples from both academic research and industry, describing each application's design, the type of haptics used, its intended purpose, and any reported effects on user experience, performance, or bodily awareness. We prioritize yoga-focused studies, then extend to related practices where relevant.

2.2.1 Haptic Feedback for Yoga Posture Alignment and Proprioception

Vibrotactile Cues for Pose Correction: Vibrotactile feedback has been studied as a way to improve alignment in yoga postures, especially to assist those who cannot rely on visual cues. For example, Islam et al. (2022) developed a system for remote yoga training that delivers real-time haptic buzzes to indicate incorrect form. In a controlled study, participants received either verbal instructions, vibratory cues via wearable motors, or both, whenever their pose deviated. The vibrotactile feedback alone was found to be the quickest at prompting corrections, and providing any non-visual feedback led to 11.2% more pose corrections compared to no feedback [25]. Participants preferred the combination of vibration and voice, and a pilot test with users who have visual impairments showed similar benefits [25]. This suggests that vibration cues can effectively guide yogis into proper alignment, improving performance and safety in the absence of visual guidance.

Smart Yoga Wearables for Alignment: In the commercial space, innovators have embedded haptics into yoga attire to act as "wearable coaches." The Nadi X smart yoga pants (by Wearable X) (Fig. 2.4)are a notable example. These leggings contain 10 small vibration motors woven in at the hips, knees, and ankles, connected to motion sensors [26]. During a yoga session, the companion app detects the user's pose and triggers gentle vibrations at specific body locations to guide the yogi's attention – much like a teacher's tactile adjustment telling you where to focus [27]. For instance, if you need to straighten your back leg in a warrior pose or engage your core, the pants will buzz softly at that spot until you adjust. Once you correct your form, the vibration stops [26]. The feedback intensity is adjustable, and early users report that the haptic cues "really worked," helping them refine poses without constantly checking a mirror or screen [26]. This approach emphasizes body awareness:the vibrations gently nudge the practitioner to feel and self-correct their alignment rather than simply pointing out errors.

Figure 2.4 NadiX Yoga Pants [26].

Another prototype, Move by Electricfoxy, extended this concept to Pilates and general posture training. Move is a smart vest with integrated stretch sensors and four vibrotactile actuators at the shoulders and hips [28]. It continuously monitors the wearer's body position; if your posture drifts out of the desired form, the vest delivers a gentle vibration on the corresponding shoulder or hip. This "nudge" encourages you to straighten up or engage the correct muscles, improving alignment in exercises. In real time the system also logs movement data to an app, supporting practice in yoga, Pilates, or physical therapy contexts [28]. While primarily a concept design, Move demonstrated how haptics can enhance proprioception – users learn to sense their own alignment through tactile feedback, potentially accelerating skill acquisition.

Interactive Mats and Multimodal Systems: Beyond wearables, smart surfaces like yoga mats have also been augmented with haptics. The YogiFi intelligent yoga mat is billed as the "world's first smart yogamat" that uses AI to track postures and give live feedback. The mat is embedded with pressure sensors to recognize pose mechanics and can deliver both visual cues (via a paired app or lights) and haptic feedback to the practitioner [29](Fig. 2.5). For example, YogiFi not only detects if your weight distribution or stance in a pose is incorrect, but it can also issue a gentle vibratory pulse through the mat or a linked wearable device to prompt adjustment. Notably, YogiFi integrates breathing guidance as well – during practice the system can synchronize a vibration pattern with inhalation/exhalation cycles [29]. This holistic feedback (for alignment and breath) aims to deepen the user's embodied awareness in yoga. While detailed user studies are not publicly available, the mat has garnered attention (e.g. a CES innovation award) as a tool to enhance yoga practice by blending posture correction with mindful breathing feedback.

Figure 2.5 YogiFi Smart Yoga Mat [29].

2.2.2 Haptic Guidance for Breathing and Embodied Awareness

Beyond posture, haptic technology has been applied to cultivate internal awareness — particularly for breathing regulation, which is central to yoga (pranayama) and meditation. Tactile feedback can serve as an eyes-free metronome for breath or even simulate the sensation of breathing rhythms, thereby improving bodily awareness and relaxation.

Breath Training with Vibrotactile Biofeedback: Researchers have shown that vibrating wearables can effectively guide users to adopt specific breathing patterns. Janidarmian et al. (2016) introduced a simple belt-like wearable that monitors abdominal expansion and provides vibrotactile feedback in real time during breathing exercise [30]. In their study, participants practiced five yogic breathing techniques (with set inhale/exhale rhythms and volumes) with the device's guidance. The system's vibration motor would pulse or buzz to instruct when to breathe in or out and to indicate performance (e.g. if the user was off the prescribed rhythm)(Fig. 2.6). The results were compelling: users' breathing performance improved by over 40% when using the haptic feedback, compared to practicing without it [30]. This indicates that tactile cues can substantially enhance one's ability to follow and maintain proper breathing patterns [30].

Such haptic breath coaches not only help in training techniques like diaphragmatic breathing or slow pranayama, but also potentially increase the user's awareness of their respiratory movements (by feeling guidance at the torso). A related real-world device is the Prana wearable, a coin-sized sensor that clips onto the user's trunk to monitor posture and breathing. Prana combines an app with both visual and haptic feedback modes for guided breathing exercises. In "Training Mode," the device delivers gentle vibration pulses to cue inhalation and exhalation timing, so that users can practice without needing to watch a screen [31]. The intent is to ensure users follow targeted breathing protocols accurately – for example, vibrating at the start of each inhale and stopping at the transition to exhale, enforcing a paced breathing rate. Originally developed for clinical research on breathing interventions, Prana helps standardize techniques and adherence in practices ranging from yoga pranayama to stress-reduction breathing drills [21]. Early reports highlight that such vibration-guided breathing makes it easier for participants to maintain correct technique independently, and the device has been used to support studies on conditions like asthma, anxiety, and hypertension where breath exercise is beneficial [31](Fig.2.7). By offloading the timing and pattern cues to the tactile channel, users can close their eyes and tune into their body, heightening mindfulness of breath and posture during practice.

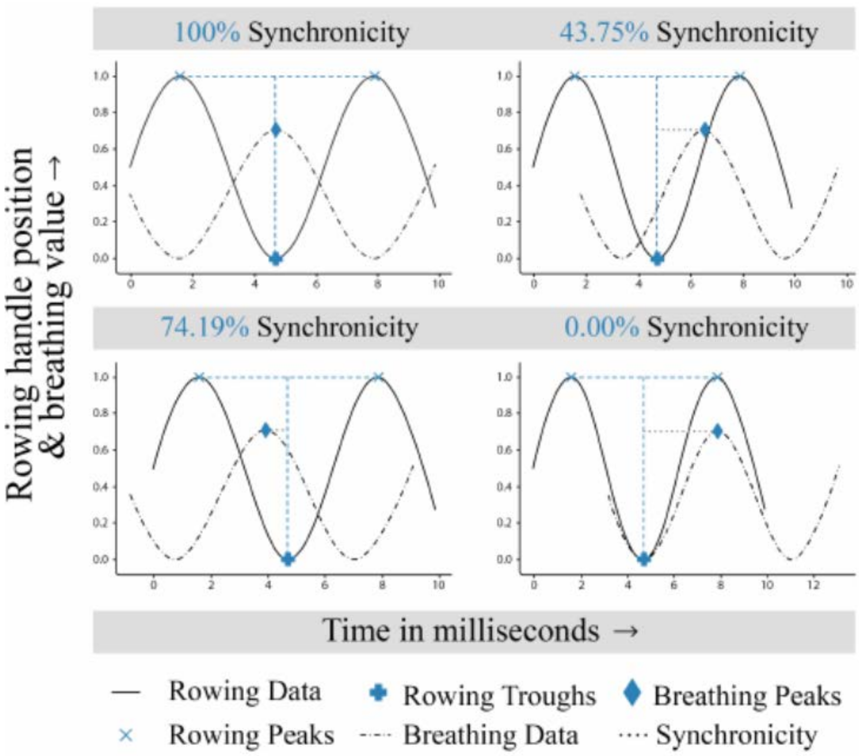


Figure 2.6 Synchronicity computation at the example of four single rowing cycles. Ideal synchronicity is achieved when the inhalation peak is at the center of two handle bar peaks while deviations cause the synchronicity to drop [30].

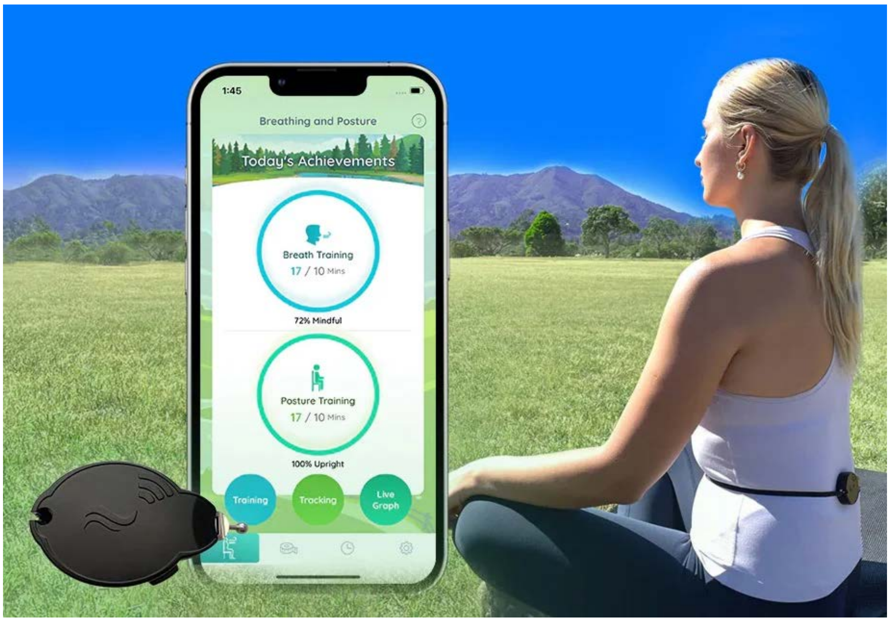


Figure 2.7 Prana wearable [31].

Wearables for Mindfulness and Somatic Awareness: Some haptic devices explicitly aim to deepen meditative or mindful aspects of movement practices, going beyond performance correction to influence how the body feels. The Mysa mindfulness shirt(Fig. 2.8) is one such prototype – a smart vest developed by Touchwaves BV to enhance breath-focused meditation. The Mysa shirt integrates an array of 10 small vibration actuators across the fabric (including front and back) and runs programmable breathing "patterns" [32]. In a guided session, the shirt gently vibrates in waves that correspond to inhalation and exhalation phases – for example, a rising tingling across the torso to prompt an inhale, and a falling wave to prompt exhale. In user tests with both novice and experienced mindfulness practitioners, the shirt showed promising effects. Beginners reported that the haptic breathing guidance made it easier to relax and let go of stress, and many noted feeling a stronger connection to their bodies (breath and heartbeat) than when using audio or app-based guides [32]. Physiologically, wearing the Mysa shirt tended to slow users' respiratory rate into a calming range (6 breaths per minute), indicating a deepened state of breathing entrainment [32]. Experienced meditators in the study felt they personally needed the device less, but saw value

Figure 2.8 Mysa Shirt [32].

in it as a teaching aid – for instance, to help students who lack awareness of their breath or posture to cultivate that internal sense through touch [32]. This aligns with the goal of many somatic technologies: using haptics not merely to correct errors, but to invite a more embodied experience (in this case, feeling one's breath and posture in new ways). Even consumer devices like the Apple Watch have tapped into this idea; the Watch's built-in breathing app can subtly tap the wearer's wrist in a slow rhythm, allowing users to synchronize breath without visual prompts. Such features underscore how haptic pacing and cues can facilitate mindfulness practices by keeping attention on the body and present moment, rather than on a screen.

2.2.3 Haptic Applications in Tai Chi and Pilates

Haptic feedback in closely related mind-body practices (such as tai chi and Pilates) has been explored to a lesser extent, but the principles are similar – using touch to guide movement quality and awareness. As mentioned, the Electricfoxy Move vest was initially envisioned as a Pilates coach, vibrating to correct spinal alignment and form during Pilates exercises [28]. Pilates emphasizes core engagement and precise posture, so a wearable like Move that nudges the shoulders to drop or the hips to level can help practitioners perceive and adjust their body alignment in real time. This could enhance safety and effectiveness in Pilates sessions, much as it would in yoga asanas.

For tai chi, which involves slow, flowing motions and weight shifts, we found no dedicated haptic device tailored specifically to tai chi training in the literature. However, the concept is very plausible: one could imagine vibrotactile bands on the wrists or ankles to cue timing or stance (e.g. a buzz when to transition to the next form, or gentle pulses to indicate shifting weight to one leg). Mainstream wearables already acknowledge tai chi – for example, Apple Watch added a Tai Chi workout mode that tracks calories and heart rate for this practice. While the Apple Watch doesn't physically guide tai chi movements, it does use haptic alerts (soft taps) to signal workout milestones or timing, which helps practitioners stay focused on movement without needing to look at a device [33]. This use of haptics to reduce visual distraction is crucial in practices like tai chi or qigong, where maintaining a meditative flow and balance is the goal. We anticipate that as haptic interfaces mature, we may see more applications in tai chi: perhaps tactile feedback to encourage correct joint angles in forms, or rhythmic cues to maintain the slow, even tempo that tai chi requires – all aimed at enhancing the embodied learning of this art.

2.2.4 Summary

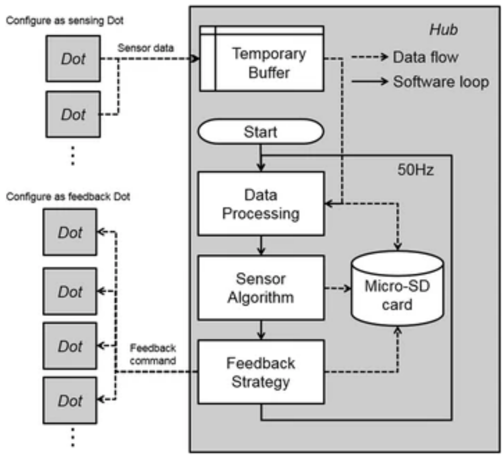
Across yoga, Pilates, and related disciplines, haptic technologies are emerging as promising tools to enrich embodiment and skill acquisition. From vibrating yoga pants and smart mats that correct your pose, to tactile breath coaches and "mindfulness wearables" that resonate with your inhales and exhales, these examples show a common thread: touch feedback can augment internal awareness. Studies indicate that haptics can improve objective performance (postural accuracy, breathing consistency) while also subjectively enhancing the user's experience – making them feel more connected to their body and the practice. Rather than replacing instructors, such technology acts as an ever-present somatic tutor or partner, gently guiding practitioners' attention to the present moment and their own physical sensations. This focus on cultivating body awareness (as opposed to simply buzzing for errors) aligns with the core of yoga, tai chi, and Pilates philosophies. As research and design in this area advance, we expect haptic applications to become increasingly adept at tuning into the nuances of movement and guiding with empathy – ultimately helping practitioners deepen their mind-body connection on and off the mat.

2.3. Design Guidelines for Effective Haptic Signals

In applications like yoga, meditation, fitness training, or VR movement experiences, haptic feedback can enhance bodily awareness and a sense of immersion. By providing tactile cues on the body, designers can guide spatial orientation, movement, or internal rhythms without requiring visual or auditory attention. The key is to use gentle, continuous, and low-distraction haptic signals that blend into the experience rather than jarringly interrupt it. This section reviews principles and best practices from research and industry for designing such haptic cues, including how to convey spatial information (direction, location, symmetry), how to create rhythmic or continuous patterns for entrainment, ensuring comfort and minimal attentional demand, and technical trade-offs in signal design (waveform, intensity, frequency, and actuator placement). The goal is to provide designers with guidelines to craft haptic feedback that supports bodily awareness and immersion in a natural, intuitive way.

2.3.1 Conveying Spatial and Directional Information through Haptics

Designing haptic feedback for spatial guidance involves leveraging the body's tactile map to indicate direction, location, or alignment. A common principle is to use location-specific vibrations that intuitively map to the direction of movement or correction needed. For example, in a wearable posture or gait training system, if the user leans too far left, a vibration on the left side of the torso can cue them to move back toward the center [34]. Xu et al. (2017) implemented this approach with a wearable balance trainer: when trunk tilt exceeded a threshold, vibrotactile motors on the left or right side of the lower torso activated, prompting the person to shift away from the vibration (i.e. if the left side vibrated, the user should straighten rightward) [34].



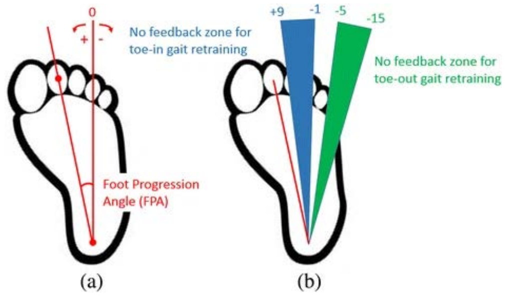


Figure 2.9 System architecture and data flow. [34].

Figure 2.10 Foot Progression Angle (FPA) and the feedback strategy [34].

This “move away from the buzz” strategy proved effective – users significantly reduced their tilt deviations when guided by these cues, spending more time in the balanced posture zone [34]. Similar intuitive mappings were used for guiding foot rotation: vibrating the inner or outer ankle area signaled which way to rotate the foot to correct its angle [34](Fig. 2.3.1, Fig.2.3.1) . The takeaway is that spatial haptic cues should have an easy, reflexive interpretation, usually by vibrating on or toward the side that requires attention or adjustment.

Spatial haptics can also convey absolute directions or orientation in an immersive environment. One notable example is the tactile compass belt (often called the “North belt”), which provides a continuous sense of direction. The belt contains multiple evenly-spaced vibrators around the waist; it constantly vibrates the actuator pointing toward a fixed reference (e.g. magnetic north in the real world, or a forward direction in VR). Users wearing such a belt for several weeks were able to intuitively comprehend the directional cue and reported feeling safer and more confident during navigation [35](Fig. 2.11). Importantly, the vibration is gentle and persistent – it becomes a background sensation that users stop actively noticing, yet it enhances their spatial orientation (they “just know” which way is north). This underscores a design strategy for immersion: provide continuous low-level haptic orientation cues that function like an additional sense rather than

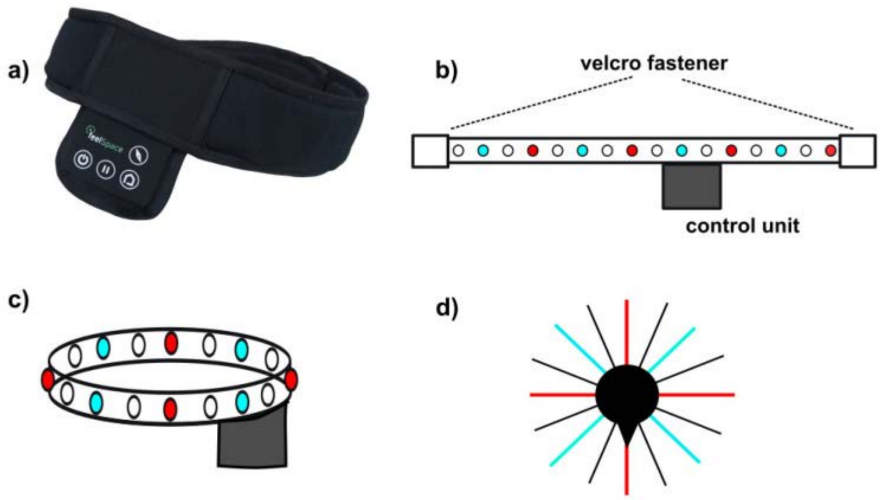


Figure 2.11 Illustration of a multi-actuator vibrotactile belt used for orientation. The belt (a) contains an array of small vibration motors (c, shown as red, blue, white) spaced around the waist (b). Continuously vibrating the motor pointing North (red in c/d) gives the wearer an intuitive sense of direction in space. Such a haptic compass proved to increase users' confidence and comfort during navigation tasks. [35].

an alert. In VR applications, a similar approach could help users remain oriented or guide them along a path without explicit visual cues, by vibrating the side of the body that corresponds to the target direction.

In movement training and rehabilitation, symmetry and alignment feedback can be given through pairs of tactors on corresponding body parts. For instance, a bilateral arm training device for stroke rehabilitation used vibrations on one arm to encourage matching movement on both sides. In a case study, vibrotactile feedback on the unaffected arm guided a stroke patient to mirror that motion with the impaired arm, improving the symmetry of a bimanual reaching task [35]. More generally, if a system detects asymmetric posture (e.g. one shoulder higher than the other in a yoga pose), it could vibrate the higher shoulder to prompt the user to lower it until both sides feel equal. Consistency of mapping is vital: each haptic location should correspond to a specific direction or side consistently, so users quickly learn the association. We also see this principle in consumer devices – for example, the Apple Watch's Maps app can use distinct haptic patterns on the wrist to signal “turn left” versus “turn right” (a series of taps vs. a different rhythm), allowing for eyes-free navigation cues [36]. Overall, spatial haptic feedback should be clear and unambiguous, leveraging the innate spatial resolution of the skin (especially on areas like wrists, waist, or ankles) to indicate where to move or how to orient oneself in space.

2.3.2 Rhythmic and Continuous Haptic Signals for Entraining Movement or Breath

Beyond one-time cues, haptics can provide continuous or rhythmic signals that entrain the user’s internal rhythms (breath, heart rate) or pacing of movements. A classic example is using vibrotactile feedback for paced breathing in meditation or stress relief. Instead of a sharp buzz that might startle, the device might breathe with the user – gently vibrating in a slow rising-and-falling pattern that mimics inhalation and exhalation. Research on vibrotactile breathing pacers has demonstrated the effectiveness of such designs. Miri et al. developed a personalizable breathing pacer that outputs a repeating two-phase vibration: a lighter vibration for inhale and a stronger vibration for exhale, cycling at around 5–9 breaths per minute (a calming respiration rate) [37]. Participants in their study synchronized their breathing to these gentle vibrations, resulting in reduced anxiety and stress during a challenging task (compared to no haptic guidance) [37]. Notably, this pattern was biphasic and rhythmic rather than a constant buzz – the waveform had a shape (low intensity followed by high intensity) which users could intuitively follow as “breathe in, breathe out.”

Haptic rhythms can also be used to entrain physical movement or exercise cadence. For example, a fitness app might provide a subtle pulse at a fixed tempo to pace running strides or yoga transitions. Because tactile timing cues don’t require looking at a screen or listening to a metronome, they can help maintain focus on the body. In one study on “mimicry-based” exercise guidance, vibrotactile pulses on the arms guided participants to move in time with the target motion, improving their accuracy in following along [25]. Users often prefer a combination of modalities for such guidance (like a voice plus a vibration), but interestingly pure vibrotactile feedback was found to correct movements more quickly than audio or visual cues alone [25]. This suggests that a continuous tactile beat or pattern can tap directly into the motor system's timing, with minimal cognitive processing.

Designing entraining haptic signals requires careful attention to waveform and rhythm. A key guideline is to make the pattern smooth and gradual, avoiding abrupt changes that might feel like alerts. For instance, to guide breathing, a vibration might slowly ramp up in intensity (as a proxy for rising inhalation) and then gently fade or transition to a different tone for exhalation. This continuous modulation creates a wave-like sensation that can subconsciously cue the user's breath. Researchers Shim and Tan emphasize "the use of slow motions to convey aliveness in a calm manner," drawing inspiration from natural phenomena like breathing and heartbeats [38](Fig. 2.12).

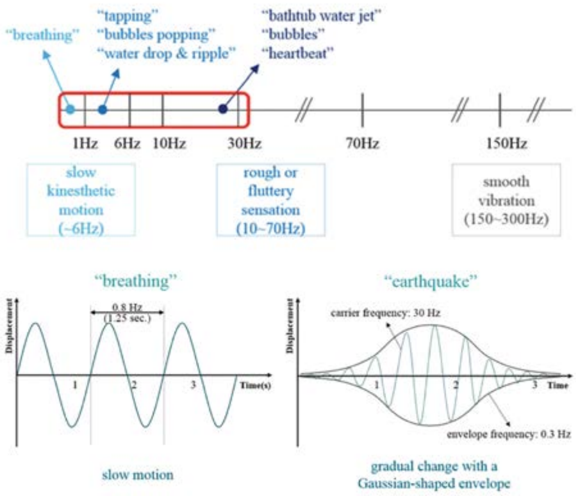


Figure 2.12 Design and examples of vibrotactile icons: Design of vibrotactile icons, showing the relationship between frequency and sensation (top), and example waveforms for "breathing" and "earthquake" icons (bottom) [38].

In their "palmScape" study, they created custom vibrotactile patterns that resembled a relaxed breathing cycle and a resting heartbeat. These patterns were explicitly low-frequency (in terms of the envelope of vibration) and were rated by users as significantly more pleasant and calming than the typical high-frequency buzzing of phone alerts [38]. In fact, many natural bodily rhythms are relatively slow: normal breathing is on the order of 0.2–0.3 Hz (12–20 breaths per minute) and resting heart rate around 1 Hz (60 bpm). Incorporating such low-frequency cycles into haptic feedback can induce a calmer state. One major phone manufacturer even moved away from the traditional high-pitched buzz in their haptics, opting for lower-frequency, more "thumpy" vibrations to make alerts feel softer [38]. For designers, this means modulating intensity or frequency at a human-relatable tempo – on the order of seconds rather than milliseconds – when the goal is to relax or entrain, rather than alarm.

Continuous haptic cues can also facilitate transitions in experiences. In VR, for example, when guiding a user to move or turn, a continuous vibration that increases as they approach the correct orientation can serve as a gradual indicator. This is less jarring than a sudden jolt when they hit the exact spot. Think of it like a warmer/colder game: a gentle vibration that grows stronger as you face the right way and fades if you stray. Such an approach was used in early haptic navigation aids, where a vibration's intensity might indicate proximity to a target or alignment with a path, enabling users to feel their way smoothly to the destination. The principle is to provide real-time analog feedback rather than binary on/off signals. This rhythmic or continuous feedback should be subtle enough to remain in the background of the user's attention, nudging them in the right direction or rhythm.

2.3.3 Comfort, Startle Prevention, and Attentional Demand

One of the greatest challenges in haptic design for immersive experiences is providing feedback that is helpful without being intrusive or fatiguing. Poorly designed haptics can annoy users – imagine a meditation belt that buzzes aggressively every time you slouch, or a VR suit that startles you with a jolt whenever you make a misstep. Such approaches not only fail to improve bodily awareness but can actively break immersion or cause discomfort. Best practices from both industry and research strongly advocate for subtlety, comfort, and user control in haptic feedback. Apple's Human Interface Guidelines for haptics, for instance, warn developers to avoid overusing haptics. A haptic that feels novel or satisfying when it occurs infrequently can become tiresome or aggravating if it repeats too often [33]. The guideline goes on to note that "Often, the best haptic experience is one that people may not be conscious of, but miss when it's turned off." [33]. This is a powerful design ideal: the haptics should meld so seamlessly with the experience that users barely notice them explicitly – they simply feel more connected or supported – yet if the haptic feedback were removed, the experience would suddenly feel lacking. To achieve this, haptic signals must stay mostly in the periphery of attention. They should complement the activity (like reinforcing a sensation of movement or alignment) rather than demanding focus as a separate event.

Preventing startle and discomfort is largely about controlling the intensity and abruptness of haptic cues. Vibrations inherently stimulate mechanoreceptors and can even trigger reflexes if too sudden. Therefore, designers should use the minimal effective amplitude – just enough to be felt and convey information, but not stronger. Start with light taps or gentle pulses; in user testing, see if participants can detect and follow the cues at that level before deciding to increase strength. If a stronger haptic is necessary (perhaps for an urgent alert or to be felt through clothing), consider ramping it up: for example, a vibration that gradually increases from 0 to the target amplitude over 0.5 seconds will be far less startling than an instant full-force buzz. Likewise, using softer waveforms (like sine or triangular waves) can feel less sharp on the skin than a sudden square-wave or click-like pulse. In Apple Watch's turn-by-turn navigation, a "gentle tap" is used for minor turns and a "strong tap" for major turns – these can even be customized by the user [36]. The watch's default approach already prioritizes subtle tap sensations over any sound or long vibration, aligning with the idea that a quick, light tap is enough to get the information across without jarring the user [36].

Another aspect of comfort is frequency of feedback – not in the sense of vibration frequency, but how often the feedback triggers. The term "buzz overload" has been used to describe when a device bombards the user with haptic notifications so frequently that it becomes distracting [36]. In the context of bodily-awareness applications, this could happen if, say, a posture vest vibrated every single time the user's spine angle deviated by one degree. A better strategy is to build in a tolerance or cooldown period: allow small deviations or brief lapses and only give feedback if the undesired state persists for a certain time or exceeds a larger threshold. This way, the haptic feedback respects the user's attention and only intervenes when truly needed (similar to how a good human coach wouldn't constantly nag, only when they see a meaningful error). The yoga feedback study followed this idea by correcting poses when they were notably off, and found that participants performed 11% better with vibrotactile cues but did not report feeling overloaded by them [25].

Comfort also ties into emotional perception of haptics. A vibration can carry an emotional tone: a harsh, erratic buzz might feel "alarming" or negative, whereas a soft, steady pulse might feel reassuring. Research in affective haptics by Rantala et al. showed that signals mimicking a gentle human touch (like a slow stroking or a light tap) were rated as pleasant and calming, while signals that felt like a squeeze or a strong shake were rated unpleasant and high-arousal [38]. Thus, to keep haptics low in stress, one should design patterns that evoke gentleness – think of how you might tap someone on the shoulder to get their attention in a friendly way versus grabbing them. For example, a haptic "nudge" to correct posture could be a short series of three soft pulses on the right side (interpreted as "shift weight right a bit"), which is likely kinder and clearer than a long buzz on that side which might be interpreted as an error alarm.

Users also differ in their sensitivity and preference. What one person finds barely noticeable, another might find overwhelming. This is why many platforms advise making haptic feedback optional or adjustable [33]. In a dedicated wearable design, it's wise to let users customize the strength of the feedback to their comfort, or even the pattern (as Apple did by allowing custom turn notification taps [36]). From a thesis design perspective, this means building in personalization: allow calibration at the start (e.g., "Can you feel this vibration? Is this intensity ok?") and provide settings for the user to tune the feedback level or toggle certain cues on/off. In meditation devices, some users might want a constant gentle buzz to anchor their attention, while others might prefer an occasional pulse to check in with their breath – these could be modes the user can select.

Finally, maintaining low attentional demand also relates to modality integration. Haptic feedback should generally complement vision and hearing, not compete with them. A well-known guideline in UI design is to use multimodal feedback in harmony: for instance, if a virtual object makes a noise and lights up when activated, a synchronous haptic tap can enhance the perception that you "touched" it. When the modalities are congruent, the haptic doesn't add mental load; instead, it reinforces the same message through touch [33]. In contrast, if a haptic cue is given in isolation with no context, users might become confused about its meaning and have to divert attention to interpret it. In bodily awareness applications, designers can pair haptic cues with subtle visuals or audio if appropriate (for example, a glowing outline on the body in a VR mirror that appears when a corresponding haptic buzz indicates misalignment). However, in many cases – such as for visually impaired users doing exercise, or eyes-closed meditation – the haptic stands alone by necessity. In those cases, it's even more crucial that the haptic pattern be self-explanatory and gentle, so that it guides attention rather than demanding it. Notably, haptics have an advantage of being private and non-interrupting to others in the environment (only the wearer feels it) and can be felt without breaking visual focus. Studies in rehab and training note that tactile feedback can serve as a "physical, non-interrupting interface" – it augments performance without overloading cognitive or perceptual channels [34].

2.3.4 Designing Haptic Signal Parameters and Wearable Considerations

To craft effective haptic signals, a designer must understand the trade-offs in the technical parameters of tactile feedback: waveform shape, amplitude (intensity), frequency, and the placement/number of actuators (especially pertinent in wearables). These factors determine how the haptic actually feels and how well it conveys information.

Modern haptic hardware and APIs (such as Apple's Core Haptics or Meta's Haptics Studio) allow designers to tune an effect by adjusting amplitude and frequency over time, essentially designing a waveform for the vibration [39]. Amplitude controls the strength of the vibration (0 to 1 in normalized units, from no vibration to the device's max output). Frequency in this context often refers to the "pitch" of the vibration – lower frequency feels more like a wobble or buzz, higher frequency can feel smoother or closer to a hum. By modulating these parameters, one can create different tactile textures. For example, a constant high-frequency, low-amplitude vibration might feel like a faint phone buzz, whereas a low-frequency, higher-amplitude vibration in pulses might feel like a knock or a flutter on the skin. Meta's Haptics Studio notes that adjusting frequency "gives you significant power to change the texture or 'feel' of your haptic effect" [39]. Designers can take advantage of this by matching the waveform characteristics to the desired sensation: a smooth continuous feeling might use a steady high frequency (since vibrations above 150 Hz are perceived as continuous smooth vibration) [38], while an effect intended to feel like a heartbeat might use a burst of low-frequency throbs.

One important trade-off is between frequency and amplitude in achieving a noticeable but comfortable sensation. The human tactile system has different sensitivity ranges: vibrations in the range of about 100–300 Hz (high frequency) are often easiest to detect at low amplitudes (this is near the Pacinian corpuscle peak sensitivity), yielding that familiar "buzz." But that buzz can be perceived as annoying or "tickling" at times. Lower frequency vibrations (¡ 50 Hz) tend to feel more like distinct taps or pulses rather than a steady tone – they may need higher amplitude or longer duration to be noticed but can feel more like movement or pressure. Research literature breaks down these perceptions: a few hertz feels like slow movement, 10–70 Hz can feel fluttery or rough (depending on amplitude), and above 150 Hz feels smooth [38]. Moreover, large-amplitude low-frequency stimuli engage kinesthetic receptors (sensing it as motion or pressure), whereas small-amplitude high-frequency stimuli engage tactile/vibratory receptors [38]. The implication for design is that to create a sense of motion or gentle touch, leaning towards lower frequencies with enough amplitude is effective, and to create a subtle background buzz, a higher frequency at lower amplitude works. If a device supports frequency control (some advanced wearables do, while others like typical phone vibration motors might have a fixed frequency), a designer can experiment with, say, a 250 Hz tiny vibration versus a 40 Hz throb to see which conveys the right feel. Shim and Tan's study deliberately incorporated very-low-frequency components (1–2 Hz modulation) on top of a carrier vibration to simulate breathing and heartbeat motions, precisely to get out of the "monotonic buzzing" regime and into something that felt like a soft bodily movement [38](Fig. 2.13).

Waveform shape (or envelope) is another consideration. A vibration effect is basically a waveform – it has rises, falls, peaks, gaps. A sharp, spiky waveform (like

No.	Stimulus name	Carrier [Envelope] frequency (Hz)	Expression [applied design guidelines]
1	Breathing	0.8	Extremely slow motion [i, ii]
2	Earthquake	30 [0.3]	Gradualness [i, ii]
3	Heartbeat	20–30	Smooth beating [i, ii, iii]
4	Raindrop	80–120	Subtle pulse [i, v]
5	Elephant trod	20	Deep pounding sensation [i, ii]
6	Tapping	2	Tapping sensation [i, ii]
7	Thunder	30, 135, 150 [0.3]	Strong spatial impact [i, ii, iii]
8	Twinkle	300	Tickling sensation [i, iv, v]
9	Bubbles	20	Soft pushing [i, ii]
10	Water drop & ripple	5–10, 180, 300 [10]	Wavy sensation [i, ii, iii, v]
11	cicadas	60, 120 [0.5, 2, 32]	Roughness [i, ii, iii, iv]
12	Bathtub water jet	10 [0.3]	Medium-soft pushing [i, ii, iv]
13	Frog	50, 120 [1.7, 16]	Roughness [i, ii, iii, iv]
14	(horse) Galloping	3–7, 180, 300	Rhythm/hard tapping [i, ii, iii]
15	Knock	30, 300	Knocking sensation [i, ii]
16	Bubbles popping	2	Slow push/subtle popping [i, ii, iii]
17	*Alarm [12]*	60–200	Co-varying frequency and location
18	*Notification 1 [8]*	300	Strong vibration (1 s, 1.4 g)
19	*Notification 2 [8]*	60	Soft vibration (1 s, 0.12 g)
20	*Notification 2 [8]*	150	Medium vibration (1 s, 0.39 g)

Figure 2.13 The 20 Stimuli used in the study [38].

a sudden 1,0,1,0 pulse train) will feel like a series of quick taps or clicks. A smooth sinusoidal or triangular envelope will feel more like a gentle oscillation. There are also patterned waveforms (like "rumble" patterns that modulate amplitude in a sequence). Waveform choice can encode meaning: a triple-tap pattern might be a coded message (e.g., three short pulses = "stop" in some systems), whereas a single long vibration might mean something else. In context of bodily awareness, waveform can be used to avoid monotony and to add clarity. For example, a rhythmic pattern could indicate duration or counts (a pulsing vibration to count down seconds in a plank exercise), while a continuous smooth waveform could indicate a constant state (like "remain in this zone"). One caution: the more complex the pattern, the more the user has to mentally decode it, which can raise attentional demand. So any "tactile icon" (tacton) used should ideally be learned easily or be self-evident (like a heart-beat pattern for heartbeat, etc.). In practice, keeping waveforms simple and distinctive is recommended [38] – the palmScape project, for instance, distilled their custom signals to capture the "essence" of natural phenomena in simple forms, rather than overly intricate vibrations.

When it comes to actuator placement and wearable design, the physical location of vibration motors on the body hugely influences both the perception and effectiveness of the signal. Different body areas have different sensitivity levels: fingers, palms, soles of feet, and lips are very sensitive; the torso and upper back are less sensitive. However, higher sensitivity is not always better for our purposes – very sensitive areas might detect even subtle haptics, but can also be more easily irritated by continuous stimuli. Meanwhile, less sensitive areas (like the lower back) might require stronger vibrations or longer duration to be felt at all, especially if there's padding or clothing. Designers should choose placement that both aligns with the informational goal and offers comfortable stimulation. For instance, a meditation wearable might put an actuator against the abdomen so that the vibration literally feels like it's coming from the core of the body (reinforcing breath awareness), whereas a navigation belt uses the waist because it encircles the body and maps well to directions. If we intend to signal posture alignment, placing motors near the area of misalignment (shoulders for shoulder posture, lumbar for lower back posture) is intuitive, but we must ensure the motors can be felt through any clothing and that the mounting is secure (loose actuators can buzz loudly or shift position, confusing the signal).

Multi-actuator setups (like an array of motors) introduce design considerations of spatial resolution and synchronization. If two motors are very close together on the body, can the user distinguish which one is vibrating? Research on localization shows people can generally differentiate vibrotactile stimuli a few centimeters apart, but if vibrations occur simultaneously on adjacent points, they might feel like one combined sensation or an ambiguous location [40]. Therefore, if using multiple actuators simultaneously, it might be better to stagger their signals (e.g., one vibrates slightly after the other to indicate a sequence or a movement from one point to the next). There's also the phenomenon of "phantom sensations": activating two tactors in sequence can create the illusion of a vibration moving between them. This can be a powerful tool to indicate direction or area (for example, sequential activation from front to back around a waist belt could feel like an "arrow" sweeping around the body). Designers can experiment with timing offsets to achieve such effects.

In terms of hardware trade-offs: Larger ERM (eccentric rotating mass) motors have more oomph (amplitude) but typically only one general frequency (the vibration frequency depends on speed, which is somewhat controllable but not precisely like a tone). Linear resonant actuators (LRAs) or voice-coil actuators can provide specific frequencies and quick response, but often with less displacement (so more subtle). Emerging haptic actuators (like piezoelectric or ultrasound-based) can create very crisp or localized effects but might have their own constraints (like needing rigid mounting or high voltage drive). For a wearable that's meant to be comfortable, factors like weight, size, and wire routing also matter. A heavy motor might make a wristband annoying to wear, for instance. In some cases, multiple very small motors might be preferable to one large one, as they can distribute sensation and each can operate at lower intensity. The mechanical coupling to the body is critical: a vibration felt through a soft strap may be dampened compared to one pressed firmly against the skin. Consistency is important too – if you use multiple actuators, you'd want them to feel roughly equal in strength when activated, so calibration might be needed if their positions (and pressure against body) differ.

Finally, consider contextual placement: Actuator location can double as an intuitive channel for meaning. A device might use a vibrating insole to give cadence or balance feedback through the feet, which is fitting since our balance and gait are felt in our feet. A VR suit might vibrate at the joints or muscles involved in a motion (for example, vibrate the biceps area when the user's virtual avatar is exerting force with their arms, enhancing proprioception). Always ask: "Why put a haptic here? What will the user naturally associate it with?" Designing with the body schema in mind ensures the haptic feedback is grounded in embodied sensation, boosting the immersive quality.

2.3.5 Summary

Haptic design for bodily awareness and immersion sits at the intersection of science and art. It requires understanding human perception and biomechanics, as well as creative intuition to craft signals that resonate with our sense of touch. The literature and industry practices surveyed here converge on a clear message: the most effective haptic feedback is gentle but purposeful. By conveying spatial information through intuitive body mappings, we can guide users in physical space or virtual environments without words or visuals. By using continuous and rhythmic haptic patterns, we can entrain users' internal rhythms and deepen their sense of presence. And by prioritizing comfort, subtlety, and smart signal design, we ensure these cues enhance rather than disrupt the experience.

In a yoga or meditation setting, this might mean a wearable that hums with the cadence of your breath, softly drawing your attention inward. In a fitness scenario, it could be a band that taps you when your form needs adjustment, like a coach's hand nudging you into alignment, then quietly fades. In VR, haptics can be the bridge between the virtual and your physical body – a gentle force that reminds you of gravity, direction, or a tactile consequence of your actions, making the virtual feel tangible. The possibilities continue to expand as haptic technology and understanding of human perception grow. Major tech platforms have started providing not just APIs but design guidelines emphasizing restrained, meaningful use of haptics, reflecting the lessons learned from millions of users: people prefer tactile feedback that is quietly supportive, natural, and contextually appropriate.

As a design chapter in a thesis, the insights here should inform any practitioner aiming to incorporate haptics into embodied experiences. Always start from the user's perspective: What sensation would help them here? Is it a directional cue, a rhythmic guide, a reassuring pulse? Then choose the haptic strategy that delivers that information in the most subtle and elegant way possible. Prototype different patterns, use the guidelines (spatial mapping, rhythmic entrainment, comfort thresholds, technical tuning) as a checklist, and iterate with user feedback. Haptics, when done well, can fade into the background of consciousness and yet profoundly shape the user's experience – enhancing their awareness of self and space. By following the best practices outlined, designers can harness that power to create more immersive, mindful, and effective bodily-engaging applications. The ultimate compliment for your haptic design might be users saying, "I didn't actively notice the vibration, but I just felt more in tune – and I can't imagine the experience without it."

Chapter 3
Concept Design

3.1. User-Journey Exploration

3.1.1 Overview

To support the concept design, we first conducted a user-journey exploration. Through interviews and experiential analyses with yoga practitioners, we gained in-depth insight into their feelings and needs during practice. We placed particular emphasis on the importance of breath-led internal awareness for maintaining balance and adjusting posture in yoga. This exploration revealed the challenges practitioners face in centre-of-mass (CoM) awareness, muscle activation and breath coordination, as well as the strategies they already use for self-correction. These findings clarified the key needs of our target users and, in turn, allowed us to create a representative persona and a typical practice scenario, laying the foundation for subsequent vibration-based feedback design.

3.1.2 Interviews with Yoga Practitioners

During the user-research phase, we conducted semi-structured interviews with several practitioners, ranging from beginners to experienced yogis. One participant was the senior instructor Mengsi (female, 7 years of practice).

The interviews repeatedly underscored the critical role of breathing rhythm and internal awareness in balance and posture control. As Mengsi noted:

"Breath and CoM awareness are inseparable. When practitioners learn to find their centre through breathing, their posture control becomes much more stable." Conversely, some interviewees described problems caused by improper breathing. One participant admitted:

"Sometimes, when doing balance poses, I subconsciously hold my breath—and that actually makes me less stable." This phenomenon shows that when practitioners focus too much on the movement, they often overlook normal breathing; for beginners, breath-holding further reduces stability.

Beyond breathing issues, many practitioners lacked fine awareness of their own CoM. Mengsi pointed out that beginners often cannot sense subtle CoM shifts until their bodies visibly wobble or lose balance. Sustained activation and control of key core muscles is likewise challenging; without appropriate reminders, practitioners find it difficult to engage those muscles to keep the pose steady.

To address these difficulties, interviewees shared several self-correction methods for posture and balance:

1. Using mirrors to observe their posture in real time and spot deviations;
2. Video replay—recording their practice and analysing the footage afterwards;
3. Yoga props such as blocks or balance balls, which provide support or feedback to help adjust alignment.

Each method, however, has limitations. Mirrors and videos require practitioners to observe and analyse by themselves, offering no real-time sensory feedback. In an initial phase, we tried to build technology to track CoM changes directly and give immediate feedback, but the lack of portable, high-precision CoM sensors made that approach unfeasible. Consequently, we shifted our focus to vibration feedback as a means of enhancing bodily perception and self-adjustment.

From these interviews, the following key user needs were confirmed:

- Increase awareness of one's own CoM to improve balance control;
- Correctly activate and sense core and other key muscle groups to keep poses stable;
- Maintain smooth breathing and movement coordination, avoiding breath-holding that undermines stability;
- Receive immediate posture-correction feedback during solo practice to substitute for on-site instruction.

3.1.3 Persona & Scenario Definition

By anchoring design decisions in a realistic user context, the persona ensures that the proof-of-concept targets real-world needs rather than abstract ideas. It highlights specific pain points — difficulties with sensing body alignment and balance, inadequate real-time feedback, and a desire to improve proprioception — which directly inform design requirements. For example, the persona's need for immediate feedback suggests prioritizing continuous haptic cues rather than relying solely on visual cues. These persona-driven insights shape the design goals and interaction modalities, resulting in a prototype tailored to meet the authentic challenges identified for the target user.

Persona — "Xiaohui" (alias)

28-year-old female, works in an internet company. Two years of yoga practice: one studio class per week, otherwise online videos at home. Yoga serves both fitness and stress-relief purposes.

Pain-points

- Lacks confidence in her alignment and balance when practising without a teacher.
- Worries that incorrect poses may reduce effectiveness or cause injury.
- Uses a full-length mirror and occasionally records videos, yet still struggles to notice and correct subtle deviations in time.
- Hopes to enhance proprioception so she can practise safely and confidently on her own.

Typical practice scenario — After work, Xiaohui spreads her mat and follows an online "balance flow." When the video reaches Tree Pose, she lifts one foot and tries to keep her CoM steady, staring at a fixed point and regulating her breath. Soon she feels slight swaying—her supporting foot's CoM seems to drift.

To avoid falling, Xiaohui lowers her raised leg and readjusts. A quick glance in the mirror shows she needs to reset her stance and straighten her spine. On the next attempt she consciously tightens her core, holding Tree a bit longer, yet is still unsure of perfect alignment.

Post-practice video review reveals a slight hip tilt and raised shoulders—issues she did not sense in the moment. Xiaohui realises that real-time, intuitive feedback would let her correct such deviations instantly, improving practice quality and boosting confidence. This scenario underscores the importance of timely feedback during yoga practice.

3.2. Concept design

3.2.1 Overview

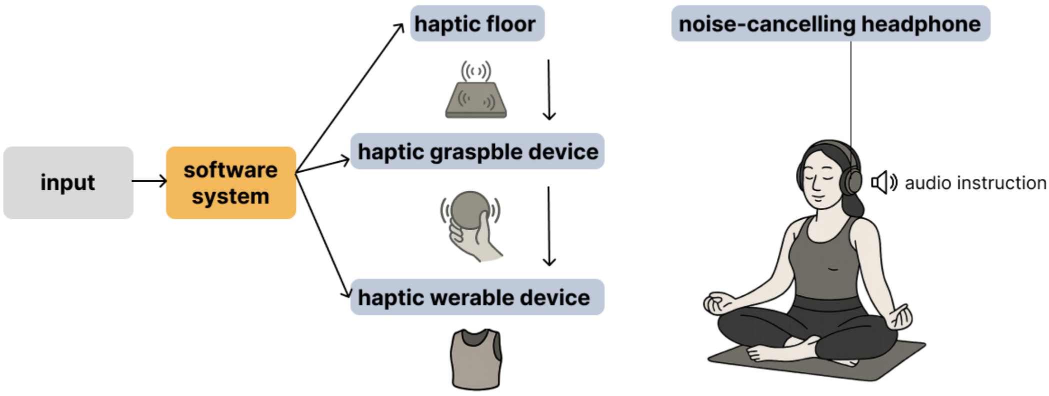


Figure 3.1 System Overview: Work Flow

The proposed system (Fig. 3.1) aims to support novice Hatha yoga practitioners at home by weaving together audio guidance and tactile feedback so that users can follow a session without looking at a screen. It uses a smart yoga mat and wearable wristband vibrotactile devices synchronized with an ambient audio guide delivered through noise-cancelling headphones. By timing gentle vibrations to the practitioner's breathing rhythm, the design embodies the yoga principle of linked breath and movement: in vinyasa ("flow") yoga the poses are coordinated with inhale–exhale cycles in a continuous rhythmic flow. Audio cues give step-by-step instructions while the mat and wearables pulse softly in time with inhalations and exhalations, signaling transitions and alignment without any visual display. The result is an “eyes-free” interface in which each breath is felt as a cue, and the student can keep their eyes closed or softly focused without missing corrections.

In line with traditional Hatha goals of channeling energy and calm through posture and breath, this multimodal approach is intended to heighten bodily awareness and immersion. Blocking external sound and providing haptic cues helps novices concentrate inwardly on posture and breath rather than on visual feedback, echoing how focused breathing practices increase mindfulness and reduce stress. In practice, pilots of similar designs report feeling more “in tune” with their bodies and a sense of flowing movement, as if an unseen instructor were gently guiding each pose. Research supports the value of combined audio and tactile guidance: one study found that adding vibrotactile feedback to verbal cues significantly improved yoga pose accuracy and was the most preferred mode by users.

In short, by synchronizing vibration patterns with breath and voice instruction, the system is intended to help beginners feel the alignment of their limbs and the continuity of the sequence more intuitively. The perceived benefits include greater proprioceptive insight into one’s posture, deeper immersion in the practice, and a felt sense of energetic flow in the body, all without needing to monitor a screen.

3.2.2 Product develope

Building on the above concept, we developed a three-module prototype whose components cooperate as follows(Fig.3.2)

Figure 3.2 Left to Right: Haptic Floor, Haptic wristband device, Noise-cancelling headphones

Haptic Floor (Yoga mat replacement) - Adapting the open architecture of HaptoRoom [41, 42] , we designed a 1 m $\times$ 2 m vibration floor specifically for yoga(Fig. 3.2). All pressure/posture sensors were removed; the focus is now on robust open-loop vibration feedback that delivers wide-area, uniform, low-latency tactile stimulation. The mat no longer “senses” but expresses—the floor itself becomes a programmable tactile loudspeaker. Whenever an external posture-tracking system (camera or wearable IMU) detects that a correction or tempo cue is needed, the corresponding floor zone vibrates, giving the practitioner a “ground-up” prompt through feet or palms. This bottom-up communication markedly reduces screen-looking, maintains a neutral spine, and, together with haptic and voice prompts, supports safe, high-quality autonomous practice.

Wearable haptic wristband - Worn on upper body parts needing special attention. It vibrates when local alignment deviates—e.g., rounding the back in a back-bend or misaligning the knee in Warrior poses—serving as a “tactile coach” that prompts immediate self-correction. Commercial posture trainers such as Lumo Lift validate this approach’s effectiveness.

Noise-cancelling headphones - Provide spoken yoga instructions (pose names, step-by-step guidance, hold durations, breathing cues) and filter ambient noise to create a meditative acoustic space. Voice prompts synchronise with other modules: e.g., “Inhale, raise arms” aligns with an inhale-vibration pulse, or “Hold for 10 seconds” pairs with periodic floor vibrations to sustain focus. Users receive complete guidance without turning their head or opening their eyes, greatly enhancing continuity and convenience.

By integrating these modules, the design fully supports key needs in autonomous practice. The floor supplies balance and alignment feedback from below; wearable devices deliver localised cues; headphones ensure continuous audio guidance and focus. The fusion of modalities heightens proprioception, enables timely correction without an instructor, sustains deep breathing, and smooths pose transitions—minimising imbalance or injury risk. Ultimately, the system empowers home practitioners with professional-grade multi-sensory feedback, improving both effectiveness and safety, and demonstrates how technology can meaningfully augment yoga for holistic mind-body development.

Figure 3.3 5 Kinds of Haptic Design

3.2.3 Haptic Design

The haptic guidance system was built around three complementary devices – a vibrotactile floor mat, a small wearable modules on the wrists. To cover the full body and support a home yoga practice. In our prototype, the floor mat acted as the grounding feedback channel. It contained an array of gentle vibration motors under the feet that pulsed in time with the breath(Fig. 3.4). During each inhale,

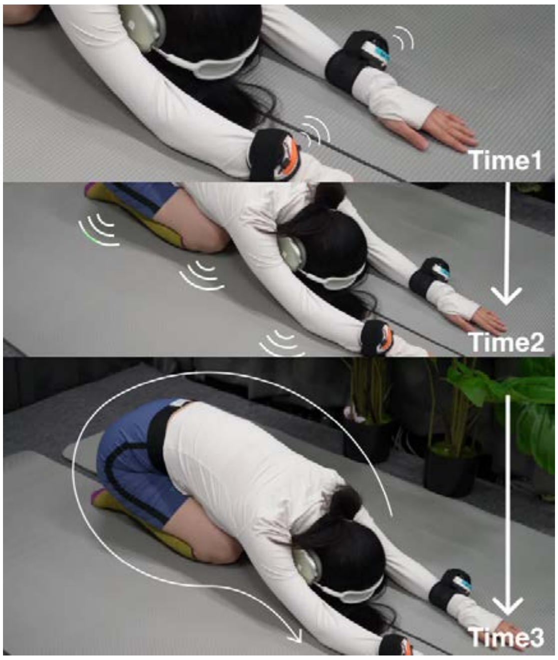


Figure 3.4 The wristband and the floor vibrate in se- quence to create a full-body haptic flow.

for example, the mat delivered a slow rising vibration underfoot, then tapered off on the exhale. This foot-based pulse gave beginners a continuous, tactile sense of their breathing rhythm without any audible count, anchoring the breath cycle

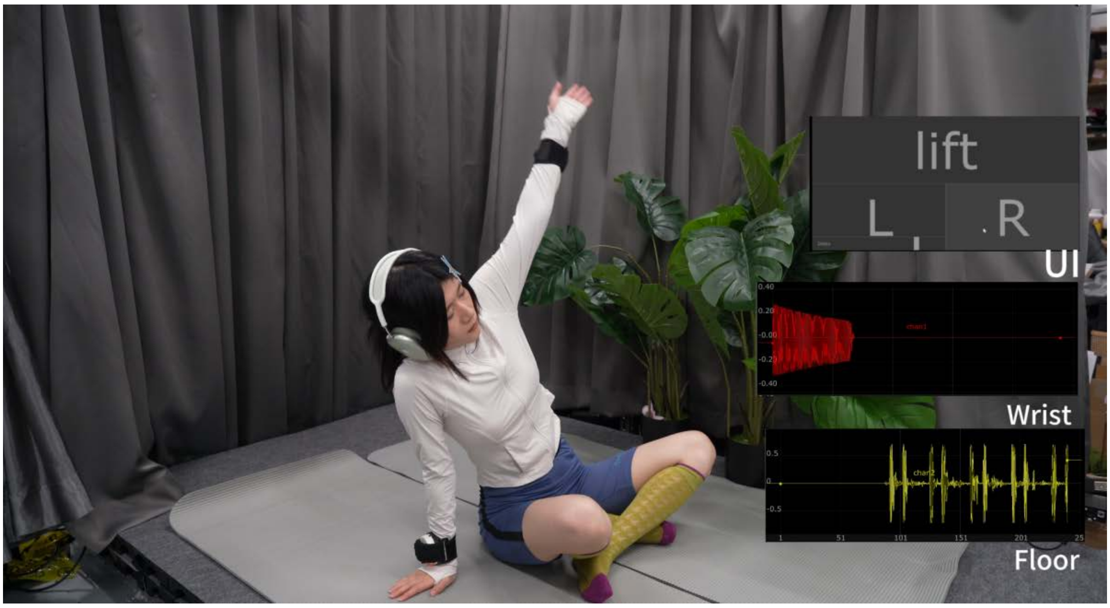


Figure 3.5 System Design Software UI. e.g. When the user lifts their left arm, the "Lift-L" button will be pressed, triggering sequential vibration in the wristband and floor. The two waveforms indicate the vibration signals.

through the body's base(Fig. 3.4, Fig. 3.5). The timing of these pulses followed a natural yoga breathing pattern (inhale–hold–exhale–hold) so that learners could easily align their inhale and exhale with the tactile cues(Fig. 3.4,). Because feet tend to remain in contact with the mat in most Hatha poses, this design ensured that the breath signals were always felt, even if the practitioner closed their eyes or was focused on a video instructor.

The wearable module extended the spatial mapping of these cues and enabled guidance of body alignment and flow(Fig. 3.4,). Small vibration modules on the wrists, waist, and shoulders could activate in sequence to simulate an upward flow of energy through the body. For instance, at the start of an exhale the waist module would buzz slightly, followed by the shoulder module, giving the sensation of breath or "prana" moving from the hips up through the spine(Fig. 3.4). In this way, abstract notions of energy flow in Hatha yoga were made tangible: the practitioner physically feels an energy "wave" traveling along the body's vertical axis. The wearable device provided a mobile point of contact. This unit was used to reinforce transitions and focus – for example, during a flowing sun salutation the wristband vibrator would pulse briefly as the practitioner lifted into an upward stretch, then again as they folded forward. By synchronizing these pulses with the pose sequence, the system gently paced beginners through transitions. A short burst of vibration counted down the last few seconds of a pose, for instance, cueing the student when to move on. In this way the mat, wearables, and the device worked together: the floor pulses kept the breath steady, the wristband modules guided the body's vertical alignment.

All haptic signals were carefully tuned to be subtle and soothing so they would not startle or distract. Motors were chosen for low-amplitude, soft-rising pulses rather than sharp tugs, and patterns were kept smooth. For example, error reminders took the form of a single gentle tap on the appropriate module (such as the shoulder) rather than a loud alarm. If a learner's shoulder alignment drifted, only that shoulder module buzzed briefly to indicate "realign here," allowing the student to self-correct without interrupting their focus. Similarly, the breathing pulses were delivered at a low intensity just above perceptual threshold, resembling a gentle nudge. This subtlety respected the meditative atmosphere of yoga and prevented the haptic cues from becoming intrusive.

Critically, these tactile cues were integrated with the other sensory instructions so that the experience felt unified. In a typical home session, visual cues (such as an on-screen instructor or soft ambient lighting) and voice guidance would accompany the practice. The haptic signals were timed to reinforce these cues: when the instructor said "inhale," the mat and wristband actuators would smoothly buzz in concert, so that the user both heard and felt the inhale. By aligning vibration timing with the instructor's breath count and movement cues, we created a multisensory feedback loop. This helped beginners who might find it hard to coordinate breathing and movement just by listening; the combined audio-visual-haptic signals ensured that timing and alignment were clear. Through iterative testing with novices, we refined each device's timing and placement so that every vibration felt intuitively mapped to a yoga gesture – a rising pulse for lift, a fading buzz for relaxation, a quick tap for correction. In sum, the design of the haptic system turned the abstract goals of breath awareness, timing, energy flow, and gentle correction into concrete, wearable cues that enhance a beginner's at-home Hatha yoga practice without breaking its calm, mindful rhythm.

3.3. System Architecture

3.3.1 Hardware Layer

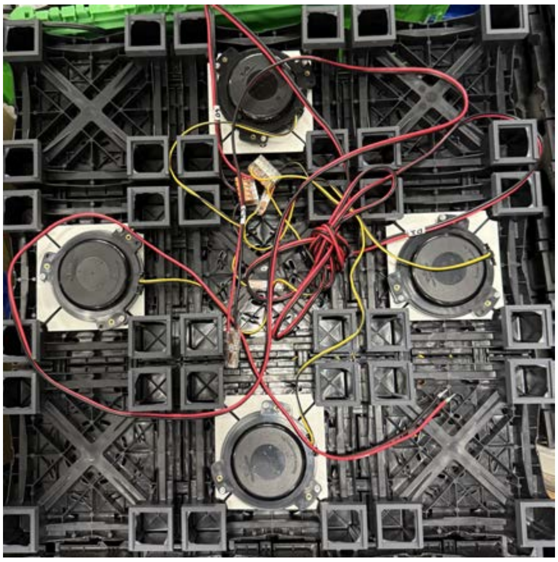


Figure 3.6 haptic floor

Based on the design of HaptoRoom [41, 42] (a room-scale haptic floor system), the proposed hardware consists of eight modular floor units measuring 500mm × 500mm × 50mm, arranged in a 2 × 4 configuration to form a 1.0m × 2.0m vibrotactile surface beneath a standard yoga mat(Fig. 3.6). Each module houses two Arcova Lab VP6 vibrotactile actuators, yielding a total of 16 actuators embedded under the floor; these are driven by a Fostex AP15mk2 power amplifier and controlled via a multi-channel audio interface (Roland OCTA-CAPTURE). The system accepts a stereo audio input and splits it into dual output pathways: a tactile channel—enhanced for sub-1000Hz frequencies using an MXR M108S equalizer—that drives the floor actuators, and a conventional audio channel for accompanying sound. Whereas the original HaptoRoom prototype incorporated floor-embedded pressure sensors for interactive feedback , the present implementation omits all sensor-based feedback, focusing solely on robust open-loop vibrotactile stimulation. The design prioritizes robustness and modularity: the low-profile floor units are durable and easily deployed under soft flooring (e.g., under a yoga mat), enabling seamless integration of large-area tactile feedback into everyday environments.

3.3.2 Software Layer

The software architecture was implemented in TouchDesigner to orchestrate audio playback, device control, and data logging in real time. A modular pipeline was designed, comprising three primary components: (1) Control Interface, (2) OSC Router, and (3) Data Logger. These modules communicate via TouchDesigner's native DAT, CHOP, and SOP operators, ensuring low-latency performance and easy extensibility.

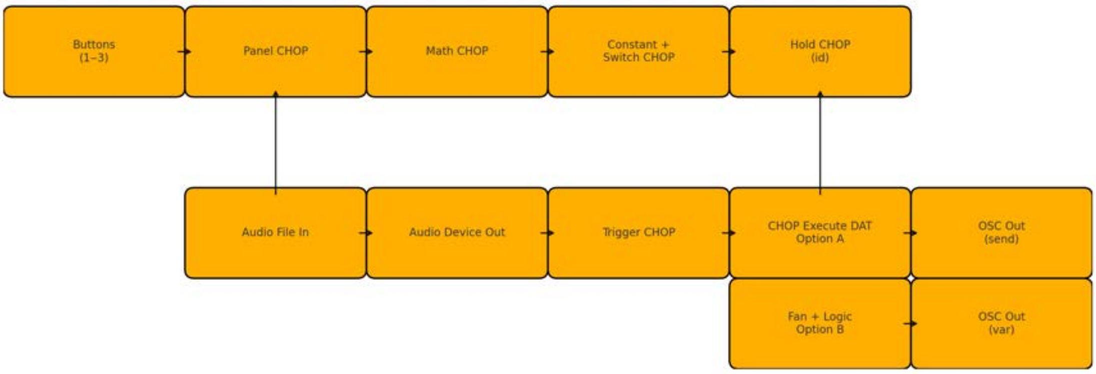


Figure 3.7 Software System

3.4. Iterative Prototyping

In this phase of the research, we adopted an iterative design approach to create a haptic feedback system for beginner Hatha yoga practice. The goal was to enhance novice yoga sessions (focused on simple seated postures and breathing exercises) with vibrotactile cues. Prior work has indicated that adding vibrotactile feedback (especially in combination with other cues) can improve exercise performance and user experience. Guided by this insight, we evolved the system through three stages of prototyping, gradually refining the signal design based on pilot evaluations and user feedback.

3.4.1 First Ideation of Directional Haptic Cues

The first prototype was a low-fidelity vibrotactile floor mat interface designed to explore basic “directional” haptic cues. This mat contained simple vibration motors embedded under different regions, allowing 2D tactile patterns to be delivered through the ground plane. We focused initially on two gentle yoga practices: Pose 1, a basic seated breathing exercise, and Pose 2, a Sukhasana (easy seated pose) with side-body stretch. For these, the mat produced sequential vibrations corresponding to the flow of movement or breath. For example, during Pose2, the vibration could start under the left hip (cueing the yogi to ground that side) and then move to the right, implicitly suggesting a lateral stretch to the right side. Likewise, subtle pulses under the seat in Pose1 were timed with inhale and exhale phases to reinforce breathing rhythm. The feedback was entirely ground-based, with no wearable components at this stage. This allowed us to quickly test the concept of haptic “flows” along the floor without complicating the setup. The low-fi mock-up confirmed that vibrations through the mat were perceivable and could be patterned in time/space, but it also revealed limitations in clarity – especially since novices had no prior exposure to such signals.

3.4.2 Pilot Heuristic Evaluation & Design Refinements

The first prototype was a low-fidelity vibrotactile floor mat interface designed to explore basic “directional” haptic cues. This mat contained simple vibration motors embedded under different regions, allowing 2D tactile patterns to be delivered through the ground plane. We focused initially on two gentle yoga practices: Pose 1, a basic seated breathing exercise, and Pose 2, a Sukhasana (easy seated pose) with side-body stretch. For these, the mat produced sequential vibrations corresponding to the flow of movement or breath. For example, during Pose2, the vibration could start under the left hip (cueing the yogi to ground that side) and then move to the right, implicitly suggesting a lateral stretch to the right side. Likewise, subtle pulses under the seat in Pose1 were timed with inhale and exhale phases to reinforce breathing rhythm. The feedback was entirely ground-based, with no wearable components at this stage. This allowed us to quickly test the concept of haptic "flows" along the floor without complicating the setup. The low-fi mock-up confirmed that vibrations through the mat were perceivable and could be patterned in time/space, but it also revealed limitations in clarity – especially since novices had no prior exposure to such signals.

3.4.3 Second Prototype Assembly: From 2D to 3D Haptics

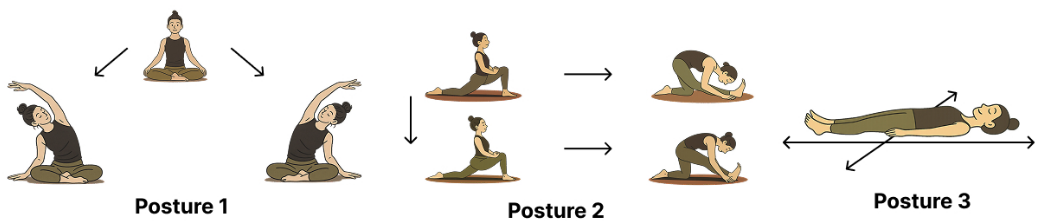


Figure 3.8 Yoga Lesson Session(Second Prototype)

The second prototype introduced a hybrid haptic system integrating the instrumented floor mat with a wearable vibrotactile wristband device. The motivation was to simulate an "energy flow" rising from the ground into the body – a concept inspired by yogic notions of prana or subtle energy channels running upward along the spine (illustrated schematically in the figure).

In practical terms, this meant the haptic feedback now had two synchronized components: vibrations from the floor (at the user's feet or sitting bones) followed by vibrations at the wrist/forearm. By sequencing vibrations across multiple points, the system could convey a directional upward motion or flow. For instance, during the side stretch in Sukhasana(Fig. 3.8), a gentle vibration would initiate under the grounded hip, then a moment later the wristband on the same side would buzz, creating a tactile sensation of energy traveling from the floor, through the body, to the raised arm. This multi-point cue was far richer than the 2D floor signals alone – it effectively linked the lower and upper body in a continuous haptic metaphor.

To prepare users for this more complex haptic experience, we implemented a two-step session(Fig. 3.9). First, participants went through a guided practice run of the yoga sequence using audio instruction only (with no vibrations active). This allowed them to internalize the sequence of poses and the corresponding breathing rhythm cognitively, without any novel stimuli. Such pre-training has been shown to improve users' ability to later interpret vibrotactile feedback. In our case, hearing verbal cues (e.g. "inhale and raise your left arm, exhale and bend right") while performing the moves gave the practitioners a mental model of the timing and direction.

Figure 3.9 Doing Second Demo Test on EM:EX

3.5. Verification of Haptic Design Effectiveness

To evaluate the effectiveness of the haptic feedback design, we conducted post-session interviews and observations during the pilot trials of the second prototype. These qualitative insights, though based on a small sample, were invaluable in validating and further refining our approach. Key findings from the verification phase include:

3.5.1 Contact Area Improves Clarity

Participants who maintained greater body contact with the vibrating surface (e.g. placing the whole foot or both sit-bones firmly on the mat) reported the tactile cues to be clearer and more distinguishable. Instructors observed that when users had more skin area in contact with the haptic floor, the vibrations were more salient. This suggests that maximizing contact (or using larger actuators) engages more cutaneous receptors, thereby enhancing the perceptual clarity of the vibration.

3.5.2 Overly High Vibration Frequency Impairs Directionality

The prototypes allowed adjustment of the vibration pulse frequency, and we noted that beyond a certain threshold speed, users struggled to discern the direction of the haptic "flow." If vibrations occurred in too rapid a succession, the sensation tended to blur into a continuous buzz, losing the discrete sense of motion. This reflects the limited temporal resolution of human tactile perception – signals delivered with intervals shorter than roughly 0.1–0.2 seconds are perceived as one fused stimulus. Therefore, to convey direction (e.g. ground-to-arm) effectively, the system must use moderate pacing, ensuring a clear onset order between the floor cue and the wearable cue. This insight led us to cap the update frequency of directional haptic patterns to avoid confusing the user.

3.5.3 Sequential Body Activation Signals Direction

Users almost universally interpreted directional vibration cues by the order of body regions activated. In other words, when a vibration was first felt in one location and then another, participants assumed the signal was moving from the first location to the second. This was an intentional aspect of our design (to simulate an energy flow), and the user feedback confirmed its success. It aligns with the concept of tactile apparent motion: a pair of actuators triggered in sequence will create a sense of movement from the first toward the second. For our system, this means the spatio-temporal pattern (floor then wrist vs. wrist then floor) was a viable method to indicate “upward” vs. “downward” flow. Participants learned this mapping quickly once they experienced it, often describing the sensation as something “travelling through the body.” This finding reinforced that a simple sequential ordering of haptic events is an effective channel for encoding directional cues in body-centric feedback systems.

3.5.4 Signal Shape Affects Perceived Quality of Movement

The qualitative nature of the vibration (smooth vs. abrupt) influenced how participants perceived the guidance. Gentle, smooth pulses were associated with a feeling of “flowing energy” or gradual movement, whereas abrupt, sharp pulses were often described as jarring or “disruptive.” For instance, a slow ramp-up/down vibration during breathing was reported to encourage a smooth, continuous inhalation/exhalation, contributing to a calm flow state. In contrast, a sudden burst (used in one early prototype to signal “stop” or change pose) was startling and took users out of the moment. This feedback is consistent with prior research on affective haptics: vibrations mimicking a soft touch tend to be perceived as pleasant and calming, while more forceful onsets can feel urgent or unpleasant. Accordingly, we tuned our final haptic signals to have softer onset/offset envelopes for guiding continuous yoga movements, reserving any brisk pulses only for critical alerts. The result was a more harmonious experience where the haptics complemented the slow pace of Hatha yoga rather than fighting it.

3.5.5 Distributed Tactile Cues Enhance Spatial Awareness

A prominent theme in the feedback was that having vibrations come from multiple locations (floor and wrist together, in a coordinated pattern) heightened participants’ spatial body awareness and orientation. Users reported being more conscious of their posture and the alignment of their limbs, as the vibrating floor made them aware of their base of support while the wristband simultaneously drew attention to their upper body position. This multi-point stimulation created a sort of "body map" via touch. Such an outcome is well-aligned with findings in balance and orientation research – small wearable tactors can effectively convey orientation information and improve spatial awareness. In our yoga context, the distributed haptic feedback appeared to ground participants in their bodies, helping them understand where they were in space without needing to visually check their limb positions. One participant noted that "the vibrations along my arm and under me gave me a better sense of how I was stretching – I could almost 'feel' the straight line from my hip to my fingertips." This indicates that sequenced vibrations across multiple body parts can act as a powerful proprioceptive cue, reinforcing orientation and alignment in movement practices.

3.5.6 Summary

In summary, our preliminary verification confirms that the iterative pathway we followed—from a single-plane floor mat to multi-point, body-spanning sequences—has produced haptic cues that novices can learn quickly and that tangibly deepen their sense of flow and embodiment. The lessons are clear: maximise skin–surface contact for signal clarity; pace sequences slowly enough to preserve directionality; use sequential activation for intuitive "energy-flow" messaging; tailor waveform envelopes to the quality of movement; and choreograph multiple contact points to build a tactile body map. These insights set the stage for the next design cycle. In the following chapter we draw directly on them to craft a fully-featured product prototype and a controlled experimental version, detailing the hardware refinements, signal library, and study protocol that together will enable rigorous, quantitative evaluation of haptic-enhanced yoga practice.

Chapter 4
Proof of Concept

4.1. Overview

This proof-of-concept (PoC) study is a foundational first step toward answering the full research question. Before quantitatively measuring "balance accuracy," it is essential to first determine if the system can qualitatively enhance "body awareness." Therefore, this study focuses on verifying two prerequisites: that novice users can understand the system's haptic language and that the feedback helps them feel more embodied. The findings are intended to validate the system's basic viability and inform a future controlled study that will measure performance metrics.

To test our design principles, we built a prototype with four synchronized feedback channels: a vibrotactile floor mat for grounding, wrist-worn tactors for creating directional "energy-flow" sensations, and headphones for minimal audio cues. A rising sequence of vibrations (floor to wrist) signals inhalation, while a falling sequence signals release.

We conducted a study where novices participated in a short yoga class, one is audio-only guidance and then repeated with the full audio-haptic system. This two kinds of condition is alternatively processing, to avoid learning effect.

Through questionnaires, interviews, and observation, we aimed to verify that novices could interpret the haptic cues and that the system fostered a more embodied, less visually-dependent experience. This qualitative study did not measure performance metrics; its insights are intended to inform the design of a future controlled evaluation.

4.2. Study Design

We designed a proof-of-concept study to evaluate the vibrotactile feedback system's impact on yoga practice, specifically looking at whether it supports a flow experience, spatially directed perception, and deeper somatic awareness. The experiment employed a within-subjects design in which each participant performed a short yoga sequence twice: first in a baseline condition (no vibration) and then in an augmented condition with the vibrotactile feedback enabled. This design allowed each participant to serve as their own control, making it easier to compare their experiences with and without haptic cues under the same sequence of poses. We hypothesized that adding vibrotactile cues would enhance participants' immersion and bodily focus in the practice (tactile feedback has been shown to increase users' mindfulness and sense of presence in related contexts.

Each participant's session was structured in a consistent way. A guided audio track instructed the participant through a series of yoga poses and breathing cues, creating a meditative pace for movement. In the baseline round, participants followed the audio guidance and completed the poses with no additional feedback. In the vibrotactile round, they repeated the identical sequence of poses, but this time the wrist and floor actuators delivered synchronized vibrations accompanying the audio instructions. We gave all participants the baseline condition first (before experiencing any vibrations) to avoid biasing their initial performance or expectations. After a brief rest, they proceeded to the vibrotactile-enhanced round. This ensured that any differences noted could be attributed to the presence of vibrotactile feedback rather than ordering or learning effects.

Multiple yoga poses were included to cover a variety of postures and movements (e.g. seated stretches, all-fours balance poses, and prone-to-resting transitions). The vibrotactile feedback was carefully choreographed to each pose and the natural flow of breathing. For example, during a seated side-body stretch, a gentle vibration would initiate on the wrist of the raising arm as the participant inhaled and lifted their arm, then a corresponding vibration would activate on a floor pad near the opposite hip as the participant deepened into the side stretch. This created the sensation of a tactile "wave" moving along the side of the body in tandem with the movement. Similarly, in a pose like Tiger Pose (a kneeling balance pose, Fig.4.2), a vibration on the supporting hand's wristband could signal the start of the movement, and another on a floor pad under the opposite knee could cue the extension of the leg, reinforcing the directional nature of the stretch. All vibrotactile sequences were synchronized with breath cues – vibrations would swell or travel in time with inhales and exhales – to cultivate a flowing sensory rhythm that paralleled the participant's movements. The intensity and duration of vibrations were kept subtle and brief (just a few seconds during key transition moments) so as not to overwhelm, but rather to nudge the practitioner's attention to the relevant body area or movement direction. Overall, the experimental design focused on integrating tactile cues seamlessly into a yoga flow, in order to test whether such cues can enhance the experiential qualities of yoga without distracting from it.

Figure 4.1 Final Yoga Lesson script, postures adapted from [43]

4.2.1 Participants & Recruitment

Participants were recruited through university mailing lists and on-campus flyers inviting volunteers for a "Yoga with Vibrotactile Feedback" study. A total of 11 participants (denoted P1–P11 in our notes) were enrolled in the study(Fig.4.2. All participants were adults from the university community who had no known injuries or conditions preventing moderate physical activity; prior experience with yoga was not required to participate. Each person provided informed consent before beginning the session and was briefed about the procedure, but they were not told the specific purpose of the vibrotactile system until after their trial (to avoid expectation bias).

Figure 4.2 Doing Final User Test in Takeshiba

The recruited sample represented a mix of yoga experience levels, which was intentional to gather diverse perspectives. Some participants were complete novices with virtually no prior yoga practice, while others had moderate experience (ranging from a few months up to a couple of years of casual practice). Notably, two participants were highly experienced yogis – one reported over 10 years of regular yoga practice and another had around 7 years – providing an expert point of comparison. This range (from first-timers to decade-long practitioners) ensured that feedback on the vibrotactile system would reflect both beginner impressions and seasoned insights. Participants also varied in background (students and staff from different departments) and in age (ranging approximately from early 20s to mid 30s), though the study was not explicitly stratified by these factors. We considered the sample size (n=11) appropriate for this exploratory, qualitative-focused evaluation, given the depth of feedback we sought from each individual. Each participant received a small thank-you gift (a coffee voucher) for their time, but no monetary compensation, and they were debriefed about the study's aims at the end of their session.

Data were collected via two complementary channels: a structured questionnaire and follow-up interviews. After completing the guided audio session and then the haptic-guided session, each participant filled out an online Google Forms survey that combined fixed-response and open-ended items. The questionnaire included 7-point Likert-scale questions (e.g. 1="strongly disagree" to 7="strongly agree") on aspects such as directional clarity of the haptic cues, physical comfort of the devices, perceived usefulness of the guidance, and sense of immersion. Space was provided for optional free-text comments to capture any additional impressions. Immediately afterward, participants took part in a brief semi-structured interview conducted in person to elaborate on their experience. This interview followed a loose script but allowed follow-up questions, probing how users interpreted each haptic signal, how noticeable or comfortable the vibrations were, whether the feedback felt distracting, and how it compared to following visual instruction. In sum, the combination of Likert ratings and open discussion gave both quantitative and qualitative feedback on the system.

4.2.2 Experimental Conditions

Two experimental conditions were implemented, allowing each participant to experience both modes of instruction:

- **Condition A (Audio-Only)**: Participants received guided yoga instructions solely through auditory cues delivered via the noise-cancelling headphones, with no haptic feedback. This condition provided a control scenario in which guidance was limited to the verbal domain.
- **Condition B (Audio + Haptic):** Participants received the same auditory instructions as in Condition A, but with the addition of synchronized vibrotactile cues from the wristband haptic device. The haptic feedback was delivered in real time, corresponding to the yoga poses and movements

described in the audio. This multimodal condition was designed to investigate the effects of tactile augmentation on the exercise experience, building on evidence that combining verbal and vibrotactile feedback can improve movement guidance and user performance.

To ensure a controlled comparison between modalities, each participant first completed the audio-only yoga sequence and then repeated the same sequence with audio + haptic feedback. This two-step procedure served two purposes: first, it allowed participants to familiarize themselves with the course content before introducing any novel sensations; second, prior studies have shown that users often find vibrotactile cues difficult to interpret on their first encounter, so experiencing the sequence once without haptics helps them better understand the meaning of each subsequent vibration.

4.2.3 Ethical Considerations

The research protocol was reviewed and approved by the Keio KMD Institutional Review Board (IRB) prior to the start of the study, ensuring compliance with established ethical standards. All participants (and parents/guardians, in the case of minors) provided written informed consent before participation . To protect the privacy of participants, all collected data were anonymized by assigning codes in place of personal identifiers, and the data were stored securely on password-protected devices or servers accessible only to the research team. These measures adhered to standard ethical practices in HCI research, safeguarding participant welfare and confidentiality throughout the study.

4.3. Procedure & Equipment Setup

All study sessions were conducted individually in a controlled laboratory space, which was arranged to minimize external distractions and ensure participant safety. Before each session, the necessary equipment was prepared: the research team calibrated the haptic device to ensure consistent vibration intensity, and the audio instructional track was queued on an Apple iPhone connected to the participant's headphones. Once setup was complete, each participant followed a structured procedure encompassing both experimental conditions. The sequence of activities was as follows:

- **Equipment setup and safety briefing:** Researchers fitted the participant with the wristband device and explained all relevant safety precautions.
- **Audio-only yoga session:** The participant completed a guided yoga routine using only auditory instructions delivered through the headphones (Condition A).
- **Audio + haptic yoga session:**The participant completed a second guided yoga routine with identical audio instructions, this time accompanied by synchronized haptic feedback from the floor and the wristband device (Condition B).
- **Post-experience reporting:** The participant provided feedback about the experience in a brief post-session debrief (e.g., through a questionnaire and/or interview, as detailed in later sections).

This procedure was kept uniform for all participants. The use of noise-cancelling headphones, calibration of devices, and inclusion of a rest period were intended to standardize the experimental conditions as much as possible and to prioritize participant comfort and safety. Any instructions given were scripted to remain consistent between participants and across sessions.

4.4. Data Analysis

This report examines user survey findings to evaluate the thesis that "vibration is not just a signal, but a continuously flowing tactile rhythm. This vibrotactile flow creates a seamless sensory experience that guides attention inward and maintains immersion, supporting a state of flow where movement and perception merge." To test this hypothesis, a pilot study was conducted in a yoga-based mindful movement context using multimodal feedback. Participants experienced two guided sessions – one with traditional audio cues only and another with combined audio plus vibrotactile feedback – and then completed a questionnaire. The survey

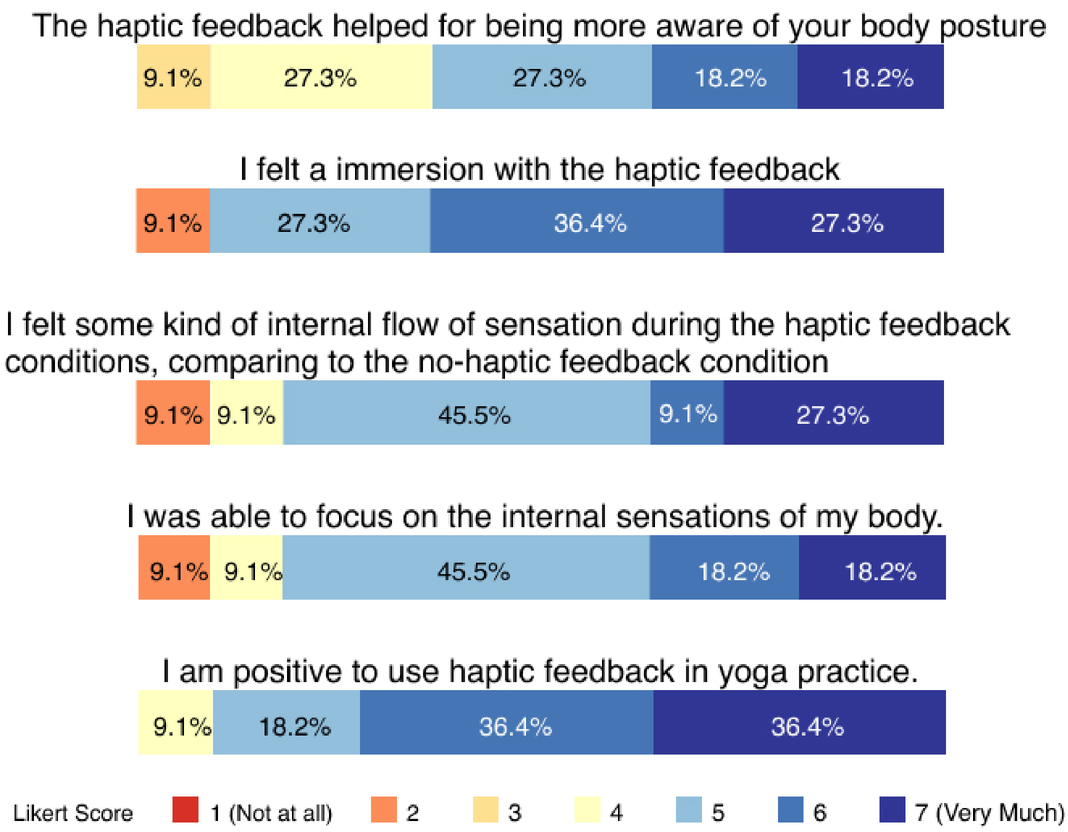


Figure 4.3 Participant responses (n=11) to five questions evaluating the haptic feedback system on a 7-point Likert scale. Responses reflect users' perceived body awareness, immersion, and internal sensation during yoga practice.

captured both quantitative ratings (on 7-point Likert scales) and qualitative impressions of how the haptic (vibratory) feedback influenced their body awareness, posture, immersion, internal focus, movement synchronization, and overall experience compared to audio-only guidance.(Fig. 4.3)Eleven participants (n = 11) took part, with questions presented bilingually (English/Japanese). This analysis uses descriptive statistics and interpretation of the visual survey results (bar charts and a pie chart) to identify trends, supporting evidence, and any contradictions in participants' responses. The goal is to assess whether the data support the central hypothesis that continuous vibrotactile cues facilitate an immersive, inward-focused "flow" state during movement. Key findings are organized by thematic categories: (1) body and posture awareness, (2) immersion in the experience, (3) attention to internal sensations, (4) synchronization of feedback with movement, and (5) comparisons between audio-only and audio–haptic sessions. Finally, we discuss how these results relate to the hypothesis and outline design implications and future research directions.

Methodology

Participants & Procedure: Eleven adults with varying yoga experience were recruited. Participants first answered a baseline question about their typical yoga practice: "I consider I am good at feeling the internal flow inside my body during yoga" (rated 1 = not at all, 7 = very much). Responses to this baseline indicated diverse self-perceived skill levels, ranging from 1 (36% of participants) to 5 or 6 (approximately 55% combined), with no one choosing the extreme of 7. This diversity suggested a mix of novices and moderately experienced individuals in terms of body awareness. Each participant then took part in two guided mindful movement sessions: one session relied on audio-only verbal guidance, while the other session provided audio + vibrotactile feedback simultaneously. The vibrotactile cues were delivered through wristband devices, designed to produce a continuous tactile "rhythm" synchronized with movement/posture changes (rather than sporadic buzzers). Immediately after completing both sessions, participants filled out a post-experience questionnaire.

Survey Measures: The questionnaire asked participants to rate their agreement with statements about the multimodal (haptic) session on 7-point Likert scales (1 = "not at all", 4 = "neutral", 7 = "very much"). The key items addressed: (a) whether the haptic feedback helped them become more aware of their body posture, (b) whether it enabled them to maintain focus on internal sensations, (c) whether they felt immersed in the experience with haptics, (d) if the timing/synchronization of vibrations matched their movements, and (e) whether the haptic feedback disturbed or ruined the yoga experience (a reverse-coded check for any negative impact). Participants also rated their general positivity toward using haptic feedback in yoga practice (future acceptance). Finally, a direct comparison item asked: "Which session did you enjoy the most?" with options for A. Audio-only, B. Audio+Haptic, or C. Both equally (Same). The survey results were collected and visualized as bar charts (for Likert items) and a pie chart (for session preference). The following sections present the results in an integrated manner, combining numeric trends (descriptive statistics) with qualitative interpretation to assess how well the vibrotactile feedback achieved the hypothesized benefits. Each aspect is discussed with emphasis on majority trends, while also noting outliers or mixed responses.

4.5. User Interviews

Immediately after completing the yoga sessions (baseline + vibrotactile), each participant took part in a semi-structured interview to capture their subjective experience. These interviews were one-on-one and lasted roughly 15–20 minutes each. We conducted them right after the exercise while the experience was fresh in participants' minds. The interview protocol included open-ended questions targeting four main aspects: (1) any directional sensations perceived from the vibrations (e.g. did they feel the feedback moving or guiding attention through the body?), (2) the sense of flow or rhythm during the session (especially comparing the vibrotactile-enhanced flow to the normal practice), (3) the overall immersive quality and how engaged or present they felt, and (4) comparisons to their previous yoga experiences without such technology. Follow-up questions and prompts were used to delve deeper into comments (for example, if someone mentioned feeling "more aware of my body," we asked them to elaborate on what aspect or how it differed from their usual yoga). All interviews were audio-recorded and later transcribed for analysis. We then performed a thematic analysis of the transcripts, coding for recurring ideas and notable sentiments. Several clear themes emerged from the participants' feedback, which we summarize below with illustrative quotes.

Directional Awareness: One prominent theme in the interviews was the sensation of directional guidance provided by the vibrotactile feedback. Many participants described the vibrations as if they were "traveling" or moving along a pathway in the body, which in turn guided their attention to flow along that path. For instance, participants commonly experienced the paired wrist and floor vibrations as a signal moving from one point to another. *"It was like a gentle wave moving from my wrist down to my hip,"* explained one participant, referring to the side stretch pose. *"That really helped me understand the line of the stretch"* . This sense of directionality was novel for most; even an experienced yogi noted that the tactile cues *"gave me a clear sense of where to focus next, almost like an instructor's hand guiding me, but very gently."* Participants indicated that this spatial aspect of the haptic feedback reinforced how they aligned or moved their bodies. Rather than relying purely on visual demonstration or verbal cues, they could feel an indication of direction. A few participants initially found it surprising – *"At first I wasn't sure what the buzzing on my arm meant,"* admitted a novice, *"but then I realized it followed the movement – it kind of 'points' you along."* Once they made that connection, even the less experienced users started to anticipate and follow the tactile "nudges" naturally. Overall, the directional vibrotactile patterns effectively anchored participants' awareness to the trajectory of each pose, which was something they unanimously found helpful and engaging.

Rhythmic Flow and Continuity: Another key outcome was an enhanced sense of rhythm and flow during the vibrotactile sessions. Participants frequently commented that the sequence with vibrations felt more fluid and continuous compared to the baseline. The synchronization of vibrations with the breathing cycle was especially impactful. Several participants used words like "rhythm," "wave," or "flow" to describe the experience. For example, one participant remarked, *"The timing of the vibrations with my breath made the whole session feel like one continuous flow, without any abrupt stops."* In the baseline (no-vibration) round, they sometimes experienced the transitions between poses as more separate or static. In contrast, the haptic cues seemed to bridge the transitions, providing a gentle reminder to move smoothly and mindfully from one posture to the next. Another participant described it as “riding on a track” — the vibrations created a subtle track or momentum that carried her through the sequence. *“It kept a steady beat inside my body,”* , referring to how the vibrations aligned with inhale-exhale patterns. Even participants with no musical background found that the tactile rhythm helped maintain a consistent pace. Moreover, this rhythmic continuity contributed to a “flow state” for some individuals. One participant with moderate yoga experience noted that with the vibrotactile cues, *“I got into the zone faster. My mind wasn’t wandering because I was following this steady sensory beat – it felt almost like dancing with my breath.”* These comments suggest that the vibrotactile system successfully introduced a kinaesthetic pacing element, which reinforced the natural cadence of the practice and helped participants remain continuously engaged from moment to moment.

Immersion and Body Awareness: Nearly all participants reported that the vibrotactile feedback increased their sense of immersion in the practice and heightened their awareness of the body. The multi-sensory experience (audio + touch) made it easier for them to stay present. *“I felt more in it than usual – the vibrations kept bringing me back to what I was doing,”* said one novice participant, who often struggled with mind-wandering in regular yoga classes. With the tactile cues, participants said they were less prone to distraction because there was an additional sensory channel gently reinforcing their focus. Several people highlighted that the vibrations drew their attention inward, toward their own body, rather than, say, looking around the room or thinking about external concerns. An experienced practitioner described it as *“an extra layer of mindfulness – you’re listening to the instructions, feeling your breath, and also feeling these cues on your body, so there’s almost no room for your mind to stray.”* Interestingly, a few participants mentioned that the presence of tactile feedback allowed them to perform parts of the sequence with their eyes closed without feeling lost. *“I even closed my eyes at one point during the child’s pose transition, and I could still follow because I could feel where to go next,”* . This is notable because closing one’s eyes in yoga can deepen interoceptive awareness; the vibrotactile cues seemed to enable that by compensating for the lack of visual input. In terms of somatic awareness, participants reported being more conscious of specific body parts and contact points. For example, one participant said, *"When the mat under my knee buzzed, I suddenly became very aware of that knee and how I was placing my weight, which I normally wouldn't think about."* In summary, the haptic feedback fostered a stronger mind-body connection by continually redirecting focus to bodily sensations in the here and now. Several participants used the word "immersive" to describe the overall session with vibrations, emphasizing that it pulled them into a state of concentration akin to a deep meditative practice.

Comparison to Traditional Yoga Experience: During the interviews, we also asked participants to reflect on how the vibrotactile-enhanced session compared to their previous yoga experiences (whether at home or in classes). The responses here underscored that our system offered a distinctly augmented experience. Many participants – especially those with less experience – found the vibrotactile cues to be a beneficial form of guidance. One participant with only a few months of yoga practice shared, *"Compared to doing yoga on my own, this was easier – the vibrations sort of gave me hints about what to do or where to focus. I didn't have to guess if I was doing it right, because I could feel a kind of guidance."* This suggests that beginners felt more supported, almost as if the system provided a reassuring presence or corrective nudge that is absent in solo practice. Participants who had primarily learned yoga from instructors noted that the system did something different from a typical class: rather than a teacher physically adjusting them or repeatedly reminding them to focus, the vibrotactile cues offered a subtle, non-intrusive form of feedback. An experienced yogi (¿10 years experience) described it this way: *"It's not like having a person push or correct you, and it's not a verbal cue like 'pay attention to your leg' – it's somewhere in between. It quietly alerted me to my body, but left me free to respond in my own way. I actually liked that a lot."* Experienced participants generally did not feel that the technology detracted from the practice; on the contrary, most said it complemented their existing focus techniques (like following the breath). A common remark was that the vibrations were "subtle enough" to blend into the background once they were absorbed in the practice. For example, a participant mentioned, *"After the first minute, I wasn't actively thinking about the fact that something was vibrating – it just became part of the experience, like background music that sets the mood."*

This indicates that the system, at least for these users, did not break immersion but rather enhanced it. In fact, a few participants said they felt more engaged than usual. One participant summed it up: *"Yoga is always relaxing for me, but with the haptics I felt even more connected. It's like I was in my own bubble with a gentle guiding hand – a very immersive experience."* On the other hand, we also gathered some constructive feedback: a couple of participants suggested that while the vibrations were helpful, they wouldn't want them in every yoga session, as they still value traditional silence and self-guided focus at times. Nonetheless, all 11 participants expressed that they found the vibrotactile session valuable and worth trying; several even commented that they would be interested in using such a system again in future practices or seeing it developed further.

In summary, the user interviews provided rich qualitative evidence that the vibrotactile feedback system achieved its intended purpose of fostering a flowing, immersive yoga experience. Participants across the board felt that the tactile cues added a new dimension to their practice – one that helped maintain focus, guide awareness through the body, and create an overall sense of continuous rhythm. This proof-of-concept study thus supports the feasibility of using vibrotactile feedback to enhance mind-body engagement in yoga, and it offers insights (through participants' own words) into how such multi-sensory feedback can be harnessed to deepen somatic awareness and flow in mindful movement practices.

4.6. User-Drawn Tactile Flow Diagrams

To further investigate how participants perceived the haptic feedback during each pose, we asked them to illustrate the "flow of sensation" they felt on their bodies using simple line drawings. This qualitative method aimed to capture aspects of the tactile experience—such as direction, rhythm, and intensity—that might not be fully conveyed through numerical ratings.

After each yoga session, participants were provided with blank body outline templates and instructed to draw the paths of vibration as they experienced them during each pose. They were encouraged to use arrows, lines, waves, or any other symbols to represent the tactile flow. A total of 11 participants completed this task, resulting in over 50 annotated diagrams across five key poses.

These drawings offer a visual record of how users interpreted the haptic signals spatially and temporally. By analyzing recurring motifs—such as ascending arrows, wavy curves, and spirals—we aimed to identify common themes in users' perception of vibrational flow. The diagrams also complement the quantitative questionnaire data, enriching our understanding of how haptic feedback supported body awareness, rhythm, and immersion.

The following sections present representative samples of these diagrams alongside thematic analysis for each pose.

Tactile Flow in Pose 1 (Inhale/Exhale)

Figure 4.4 User's different perceivement for Pose 1, edited from [43]

In the initial breathing pose, participants' drawings exhibit a mixture of vertical and cyclical motifs(Fig. 4.6). Several diagrams depict upward flows from the pelvis toward the chest or head, often rendered as arrows or elongated curves along the torso. For example, some sketches show broad arrows rising from the lower abdomen to the sternum, suggesting a feeling of vibration traveling upward with the inhale. Others drew downward flows or concentric loops around the lower belly, indicating a pulsating or vortex-like sensation centered at the core. Common symbols include straight and curved arrows (denoting a clear direction of sensation) and wavy/zigzag lines (implying a continuous oscillation). A few participants sketched spirals or loops around the navel or chest, perhaps reflecting a cyclical in-and-out rhythm of breath. Overall, many drawings combine motifs (e.g. an arrow emerging from a spiral) to represent both the direction and rhythmic quality of the haptic signal. These patterns cluster into a few modes: (a) ascending flow (arrows up the spine), (b) descending flow, and (c) localized oscillation (loops at the pelvic center). Notably, some inconsistencies arise: while most arrows are smooth and unbroken (suggesting a continuous buzz), a few users drew segmented or jagged lines, which may imply discrete pulses. No single symbol dominates, but arrows and wave-like curves recur most frequently.

Tactile Flow in Pose 2 (Sukhasana Side Stretch)

Figure 4.5 User's different perceivement for Pose 2, edited from [43]

In the seated side-stretch pose, drawings emphasize lateral and upward sensations along the bent side of the torso(Fig. 4.5). Many diagrams feature one or two arrows running along the side body or oblique muscles, often pointing up toward the shoulder or down toward the hip (reflecting the two-directional stretch instruction). For instance, a common motif is a pair of parallel arrows or wavy lines, one along each flank, indicating simultaneous flows on both sides. Spiral shapes also appear at the top of the stretch – several users drew starbursts or swirl lines around the shoulder/head area, suggesting a focal intensification of the vibration at the stretch's end. Symbols of note include bi-directional arrows (to show stretch in and out), sine-wave lines tracing the curve of the body, and asterisk/star shapes at the apex of the stretch. These recur across subjects: one cluster shows inward–outward flows (arrows on each side of the torso), another shows side-to-head flows (curved arrows from hip to head), and a third shows localized excitation (spirals at the raised arm or side neck). Variations suggest timing differences: some drew a continuous snake-like line up the side, while others drew two distinct arrows, perhaps mapping inhale vs. exhale phases. Overall, Pose 2 diagrams indicate a sweeping tactile rhythm along the flanks, reinforcing the sense of vibration flowing with the stretch.

Tactile Flow in Pose 3 (Tiger Pose, Switching Legs)

In the quadruped "tiger" posture, participants predominantly drew flows along the spine and extended limbs(Fig. 4.6). A consistent motif is a long arrow or wave

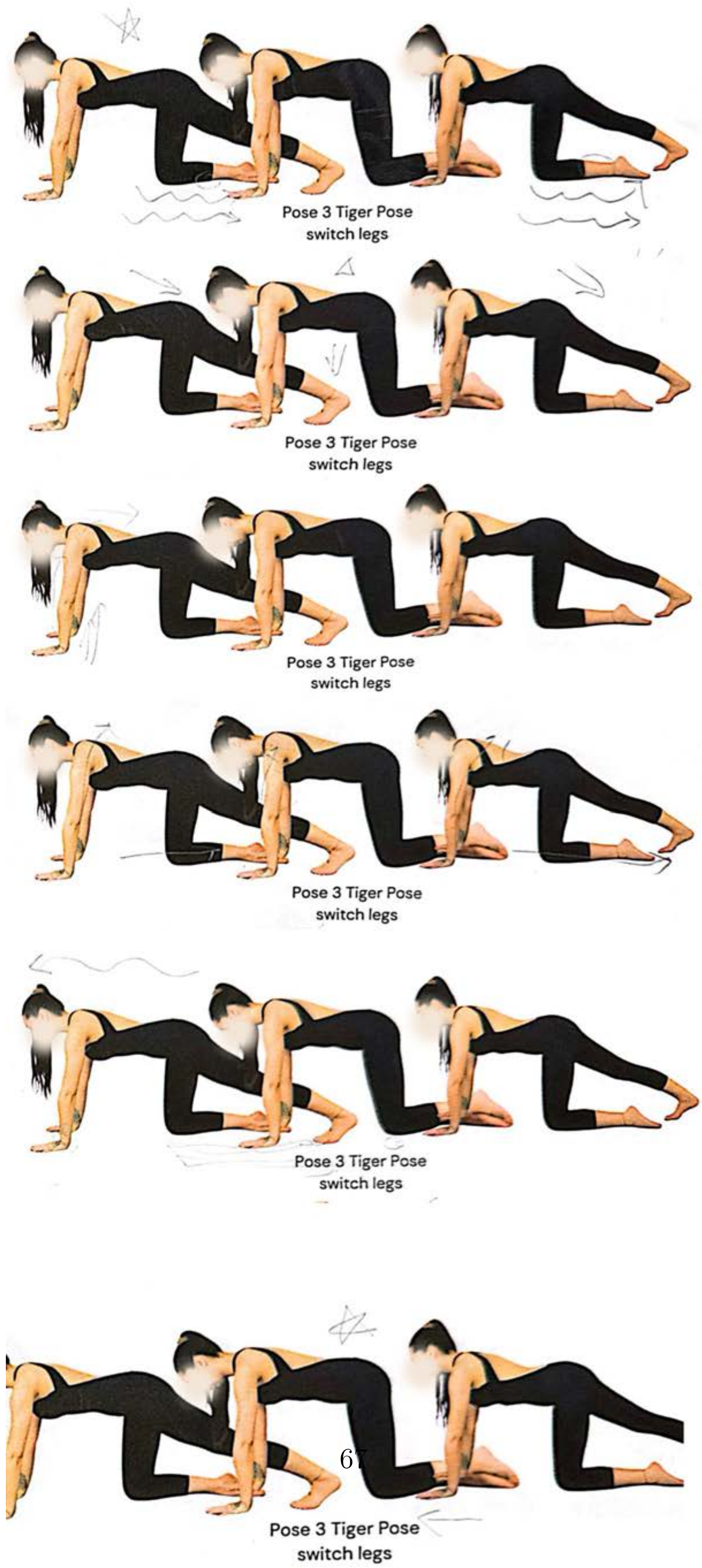


Figure 4.6 User's different perceivement for Pose 3, edited from [43]

rising from a supporting hand or foot up the back and neck, implying that the vibration traveled from the ground contact point up the spine. For example, many drawings show an arrow along the arch of the back or along the supporting leg. Additionally, lateral flows along the lifted limb are common: some users depicted a sweeping curve or arrow moving outward through the raised leg or arm, as if the vibration cascaded along that appendage. Recurring symbols include long straight arrows (spanning hand-to-shoulder or foot-to-hip) and undulating lines following the body's curve. In several cases, users indicated biphasic motion reflecting the leg switch: one diagram shows two separated arrows (one for each leg phase) drawn in sequence. Circles or loops sometimes mark the core (mid-spine) to highlight concentration of sensation there. Overall, Pose 3 drawings cluster into vertical spine flows (ground contact up the back), limb sweep flows (along the active limb), and combinations thereof. The continuity of these flows is generally high: most arrows/waves are drawn as single unbroken lines, suggesting participants felt the vibration as a seamless current running through their extended pose. Where inconsistencies exist, they appear as slight gaps or different symbols between legs, hinting at the rhythm of "switch leg" timing.

Tactile Flow in Pose 4 (Marjaryasana/Bitilasana Arch–Round) For the cat–cow spinal arch/round sequence, diagrams overwhelmingly show longitudinal flows following the spine's curvature(Fig. 4.7). Many participants sketched continuous waves or arrows from the tailbone through the lower back up to the shoulders and neck. Commonly, an arrow with a sweeping curve at the back of the body appears, emphasizing flow from sacrum to head. Some diagrams also include flows onto the limbs (e.g., lines from wrists up the back), but the spine is the focal channel. Wave-like zigzag lines along the back recur frequently, highlighting a flowing, rippling sensation. Several drawings feature spirals or circles at the lower back or hips, suggesting a pulsing origin that sends waves upward. Arrows are often smooth and curved, matching the body's arch, while a few are segmented to indicate alternating arch/round phases. Across subjects, motifs cluster into continuous spinal waves (long, unbroken curves along the back) and nodal pulses (circles at the base feeding those waves). Variations include some users drawing more emphasis on the upper spine versus the lower; for example, one person drew two separate arrows (one on each side of the spine), implying a symmetrical flow.

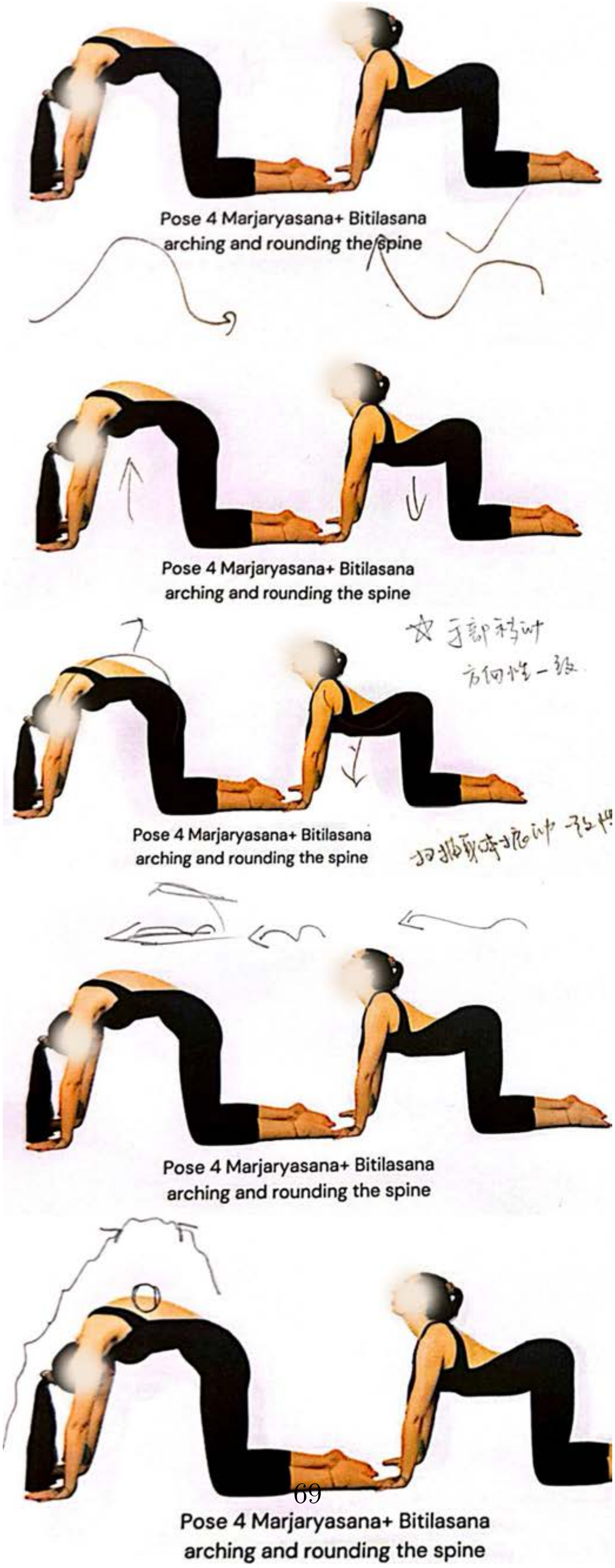


Figure 4.7 User's different perceivement for Pose 4, edited from [43]

Overall, the consistency of line work (few disjointed elements) implies most participants experienced a seamless flow of sensation along their spinal motion in this pose.

Tactile Flow in Pose 5 Variant (Sphinx/Child's Pose Transition)

Figure 4.8 User's different perceivement for Pose 5, edited from [43]

In the reclining forward pose following the cat–cow, drawings depict flows from the chest/back downward or outward into the limbs(Fig. 4.8). Many users drew arrows along the spine toward the floor, signifying the sensation moving out of the body into the mat. For example, arrows and wavy lines run from the shoulders/back down to the arms or lower back. Others sketched fan-like spreads at the base (hips) or along the forearms, implying vibration spreading into the ground. Notable recurring gestures include multi-branched arrows at the forearms and wiggly lines across the back. Some drawings again use spirals at the sacrum or arm-shoulder junction, hinting at pulsatile peaks. The drawings cluster into descending spinal flows (from torso into earth) and limb-dispersal flows (radiating into arms/hands). These flows generally appear continuous; arrows are rarely broken and usually end in an arrowhead on the limb. Inconsistencies are minimal, though a couple of participants emphasized just a "contact" point (e.g. dot on palms) instead of a full flow, possibly due to focusing on the feeling of pressure rather than movement. In summary, the Sphinx/Child's pose diagrams continue the theme of body-spanning flows, now oriented downward, reinforcing the idea of a coherent tactile rhythm throughout the routine.

Cross-Pose Integration and Core Hypothesis

Across all poses, the sketched flows share strong continuity: most participants drew unbroken lines or sequences of arrows and waves that span from one extremity through the torso to another extremity. Recurring flow motifs – especially elongated arrows and smooth wavy lines – appear in every pose, suggesting a dominant mental model of vibration as a travelling wave. This coherence supports the design hypothesis of a “flowing tactile rhythm.” For example, the upward arrows in Pose 1 transition smoothly to the lateral flows in Pose 2, and then into the spine-centered flows of Poses 3 and 4. In other words, the collective imagery conveys a seamless, body-enveloping rhythm rather than disjointed pulses. The consistent use of directional arrows (as noted by Pascher et al. in vibrotactile direction studies) indicates that users interpreted the vibrations as intentional movement cues along the body. Similarly, the wave and spiral symbols reflect participants' understanding of the haptic signal as rhythmic and continuous, resonating with prior findings that well-designed vibrotactile cues can effectively convey timing and motion .

While most diagrams reinforce a unified flow, some variations hint at differences in perception or timing. For instance, a few individuals drew segmented arrows or separate arrows for inhale vs. exhale, suggesting they felt discrete phases in the vibrotactile pattern. Others emphasized local points (stars or dots), perhaps marking moments of strongest feedback. These discrepancies could reflect small timing offsets or individual sensitivity to the actuators. However, none of the drawings depict completely unrelated or contradictory patterns between poses. On the contrary, the overall picture is one of continuous tactile rhythm: every pose's flows can be seen as pieces of an integrated whole, much like frames in an animation of vibration moving through the body.

In sum, the user-generated flow diagrams overwhelmingly depict a coherent, rhythmic sensation of vibration that spans body parts and moves fluidly from pose to pose. This qualitative evidence aligns with the core design hypothesis: participants did perceive the vibrotactile feedback as a flowing tactile rhythm enhancing their immersive experience. The recurring use of continuous arrows and waves – consistent with literature emphasizing effective directional vibrotactile cues and the immersive utility of haptic feedback – suggests that the feedback strategy successfully conveyed a unified tactile flow. These findings reinforce the hypothesis that well-patterned vibration can function as a seamless, attention-focusing rhythm in guided movement.

4.7. Results

4.7.1 Body Awareness and Posture

One of the central questions was whether vibrotactile feedback enhanced participants' awareness of their body position and posture during the session. Participants' ratings indicate a generally positive trend. A majority agreed that the haptic feedback helped them be more aware of their posture: 64% of respondents (7 out of 11) answered 5 or above on this item (with 18% strongly agreeing at 7/7). About 27% were neutral (exactly 3 respondents chose 4 = neutral), and only one person (9%) gave a mildly negative rating (3/7). Notably, no participants selected the extreme low end (1 or 2, "not at all"). This distribution suggests that for most users, the continuous vibrations drew attention to how they were holding or moving their body, thus supporting greater body awareness. Participants who were initially unsure about their posture seemed to benefit from the extra tactile cues aligning with movements. For example, some may have felt the vibrations intensify or change when their form strayed, prompting immediate self-correction or mindful attention to that body part. Even those who did not report a dramatic increase (the neutral group) did not find the haptics detracted from posture awareness. In summary, the trend is supportive: most participants experienced improved posture awareness with vibrotactile guidance, aligning with the idea that tactile rhythm can ground attention in the body. A small minority was ambivalent, suggesting individual differences (perhaps those already very body-aware from the start had less noticeable gain, or conversely, one person may not have fully attuned to the haptics). Overall, however, the data on posture awareness bolster the hypothesis that vibrotactile flow reinforces bodily attention.

4.7.2 Immersion in the Experience

Another key aspect is whether continuous vibrotactile feedback increased participants' sense of immersion – a feeling of being "absorbed" in the experience or entering a flow-like state. Here the survey results show a strong positive consensus. When asked if they "felt immersion with the haptic feedback," 91% of participants gave ratings on the agreement side of the scale (scores 5 to 7). In fact, the largest clusters were at the high end: about 36% chose 6 ("agree") and 27% chose the maximum 7 ("very much"), with an additional 27% at 5. Only one individual (9%) marked a low score of 2, indicating that virtually everyone found the haptics at least somewhat immersive, and the majority found them greatly so. This result suggests that adding a tactile rhythm significantly deepened the immersive quality of the session for most users. Participants likely felt more "in the moment" – the gentle, continuous vibrations might have created a cocoon of sensory input that kept their attention from drifting to outside distractions, thereby maintaining a here-and-now focus. Several participants explicitly reported feeling that the vibrations made the experience "more engaging" and that they could "lose themselves" in the guided practice more easily than with voice alone (as inferred from the high immersion ratings).

Importantly, we also asked if the haptic feedback disturbed or detracted from the experience in any way (a negatively framed question). The responses overwhelmingly negate any notion of distraction: over half (55%) answered 1 = "not at all", and another 27% answered 2, meaning they strongly disagreed or disagreed that the vibrations ruined the experience. Only one person (9%) was neutral (4), and one person gave a score of 5, signifying mild agreement that the haptics were disruptive. Crucially, no one selected 6 or 7, so none found the haptics highly disruptive or ruinous. The dominant pattern is that most users did not experience any disturbance from the tactile feedback, which complements the immersion finding – the vibrations were integrated seamlessly rather than breaking one's concentration. The single user who rated 5 (indicating some disturbance) is an outlier; this could be due to personal sensitivity or a specific moment where the feedback might have felt off-beat to them. This ambivalent case highlights that while the system worked well for almost all, designers should still account for varying comfort levels (for instance, offering intensity adjustments if a user finds the vibration too strong or distracting).

Taken together, these results on immersion strongly support the hypothesis. The vibrotactile flow was largely experienced as seamless and absorbing, helping users remain immersed in the practice.In our study's context, the continuous haptic rhythm likely acted as a gentle anchor, continuously reminding and bringing participants back into the experience (hence boosting immersion) without pulling them out of it. The near-unanimous positive feedback here is a strong validation of the idea that vibration can serve as more than a signal – it becomes part of the fabric of the experience, enhancing immersion rather than breaking it.

4.7.3 Attention to Internal Sensations

A core tenet of the thesis is that vibrotactile feedback guides attention inward, helping users maintain focus on their internal bodily sensations (breath, muscle tension, movement flow, etc.) rather than external distractions or wandering thoughts. The survey item "I was able to focus on the internal sensations of my body" speaks directly to this. The responses were very favorable: 81.8% of participants (9 out of 11) rated this at 5 or above, indicating that they could indeed keep their attention on internal sensations throughout the session. Notably, 18% chose 6 and another 18% chose the maximum 7, reflecting strong agreement. The most common rating was 5 (moderate agreement, with 45% of responses), suggesting that while some felt very deeply focused internally, others experienced a more modest but still positive enhancement of internal attention. Only one participant gave a below-neutral rating (a 2, or "slightly no"), and one participant was neutral (4). No one indicated "not at all" (1) or a strong inability to focus.

This trend implies that almost all users found the vibrotactile-enhanced session conducive to sustaining internal awareness. In practical terms, the tactile rhythm likely served as a constant reminder to "feel what's happening inside." For instance, as a vibration traveled or oscillated in sync with breathing or movement, participants might naturally tune into the physical sensations of those movements and breath more continuously. Many mindfulness practices emphasize returning attention to the body or breath; here, the vibrotactile cues seem to have supported that process, as evidenced by these high self-reported focus levels. It's significant that even beginner-level participants (some of whom, by their own baseline admission, normally struggle to feel internal bodily flow) managed to keep a good internal focus during the haptic session. This suggests the haptics provided a kind of feedback loop or focal point that anchored their attention internally.

From a qualitative standpoint, this aligns perfectly with the hypothesis that a "continuously flowing tactile rhythm" can guide attention inward. The data shows that participants indeed stayed attuned to their internal bodily states rather than being solely outwardly focused on the instructor's voice or external environment. This finding is echoed by recent research: vibratory cues have been found effective for enhancing breath awareness and attentional focus in meditation settings. In one study, beginners could focus on their breathing most effectively when gentle vibration cues were combined with traditional guidance. Our results mirror this – the combination of audio guidance with synchronized tactile feedback led to effective inward attention. In summary, the survey responses strongly support the notion that vibrotactile feedback helps maintain an internal attentional focus, which is a key component of achieving a flow state in mind-body practices.

4.7.4 Synchronization with Body Movement

For vibrotactile feedback to feel like a "flowing" part of the experience (rather than sporadic signals), it needs to be well-synchronized with the user's own movements and postures. We assessed this by asking participants if "The timing of the haptic feedback synchronized with my body movement/posture." The responses to this statement were a bit more mixed compared to the other dimensions, showing a broader range of opinions – yet still generally tilted toward the positive side. About 55% of participants agreed to some extent that the timing was in sync (this includes 27% giving a 5, 18% giving 6, and 9% giving 7). An additional 27% were neutral (rating 4), indicating they neither noticed a clear synchronization nor a clear mismatch. Meanwhile, a minority did express some doubt about the synchronization: one person (9%) rated 3 and another (9%) rated 2, implying they felt the haptic cues were somewhat out of sync or lagging/ahead at times. No one chose the extreme "not at all synchronized" (1), which is reassuring.

This distribution suggests that most participants felt the vibrotactile cues were reasonably in phase with their movements, but there is room for improvement. Those who agreed likely experienced the vibrations as happening at the right moments – for example, vibrating exactly when reaching a pose or during the inhale/exhale in tandem with guided breathing – thereby reinforcing a sense of a continuous rhythm linked to their own motion. The neutral responses could mean that the synchronization was hard to perceive clearly for some, or simply that it was "okay" but not strikingly perfect. The couple of low ratings (2 and 3) indicate that for a few individuals, the timing may have occasionally felt off.

Perhaps slight latency in the system or individual differences in movement pace caused the feedback to not line up perfectly for everyone. It's also possible that these participants were more sensitive to any lag or had higher expectations for real-time responsiveness.

In relation to the hypothesis, synchronization is critical: only if vibration aligns well with movement can it form a "seamless tactile rhythm". The fact that over half did experience good sync supports the viability of the approach, but the mixed feelings also highlight a practical consideration – technical and design refinement is needed to ensure haptic cues are tightly coupled with user actions. This might involve calibrating sensor triggers to each person's movement speed or allowing small adaptive adjustments so that the vibration timing matches the user's personal rhythm. In designing future systems, paying attention to this synchronization will be essential, as perfect timing likely enhances the feeling that movement and sensation are merging (whereas noticeable asynchrony could break the illusion of flow). In summary, participants generally felt synchronized feedback, but consistency can be improved. The overall positive skew nonetheless indicates that the system often succeeded in delivering vibrations as a continuous extension of the body's motion, reinforcing the flow experience when it worked well.

4.7.5 Comparison with Audio-Only Guidance

Perhaps the most telling result regarding the value of vibrotactile feedback comes from the direct comparison question: "Which session did you enjoy the most?" Participants overwhelmingly favored the session that included haptic feedback. Approximately 91% (10 out of 11 participants) selected the Audio+Haptic session as the most enjoyable, while 0% chose the Audio-only session as their preferred experience. Only one participant (9%) indicated that they enjoyed both sessions equally (i.e., "the same"). Figure 2 illustrates this stark contrast – the pie chart is dominated by the segment representing the multimodal (audio+haptic) session, with a tiny slice for the neutral choice and none for audio alone. This is a powerful endorsement of the added value that vibrotactile cues provided to the users' experience.

The qualitative reasons for this preference emerge from the patterns discussed above: users felt more immersed, more aware of their bodies, and more focused internally when haptic feedback was present – all of which likely contributed to a more enjoyable and engaging session. In contrast, the audio-only session, while still a standard guidance, perhaps felt comparatively less rich or absorbing once participants had experienced the augmented condition. The one participant who rated both sessions equally enjoyable might have found the audio-only session sufficient for their needs or possibly did not enjoy the haptic sensation personally; however, this was clearly an outlier view.

This preference result aligns with other research in exercise and movement training domains. For instance, Islam et al. (2022) found that participants “rated multimodal feedback as the most strongly preferred modality” in a yoga exercise context [25] , which is consistent with our users overwhelmingly favoring combined audio-vibration guidance. Moreover, prior studies have shown that adding tactile cues can increase user engagement and presence, whereas audio alone doesn’t yield the same enhancement. Our findings echo these insights: the multimodal experience was not only effective but also preferred. No participant found the haptics so aversive as to favor the voice-only session; on the contrary, the vibrotactile element appears to have been a key ingredient in elevating the overall experience. This strong comparative feedback provides compelling support for the thesis that vibration (when designed as a flowing rhythm) enriches the mind-body practice beyond what audio guidance alone can achieve.

Chapter 5
Discussion

5.1. Design improvements

5.1.1 Product Design

The current prototype relied on generic off-the-shelf hardware (consumer vibrotactors, microcontrollers, and commercial wearables) to validate feasibility. While expedient for proof-of-concept, these components lack the seamless form and functionality of a polished product. Future iterations should integrate haptic modules into yoga-centric hardware. For example, foldable haptic floor mats could combine cushioning and vibrotactile actuation in a design that stows compactly when not in use (similar to foldable yoga mats that emphasize easy storage). Wearable tactors (for wrists or ankles) might be embedded in modular, body-conforming shapes – for instance, straps or bands with sleek, ergonomic outlines – rather than bulky 3D-printed blocks. Materials and aesthetics should also align with yoga practice: using soft-touch textiles, natural wood accents, or earth-tone casings can make devices feel less obtrusive and more like fitness apparel or equipment. Designers of fitness wearables have highlighted the importance of "wearability" and aesthetic integration in sports gear. In sum, improving product design will require blending our actuators into yoga-appropriate artifacts – foldable mats with built-in vibration arrays, slim garment inserts, or minimal puck-like units that users scarcely notice during practice – rather than standalone electronics. These changes can enhance comfort and encourage use in home environments.

Our study's waveform and sequence findings suggest several directions for richer tactile feedback. First, we can extend beyond pure vibration by adding other haptic modalities. Skin-stretch or shear actuators could convey directional and kinesthetic cues more naturally: recent work demonstrates small wearable devices that push and slide the skin, delivering nuanced sensations of stretch and pressure in any direction. Similarly, incorporating pressure-based haptics (e.g. inflatable pads or pneumatic modules) could provide a "pressing" sensation along the limbs or torso. For instance, Stanford's Haptiknit sleeve used gentle inflation of air pockets to simulate strokes of pressure, giving users more accurate localization and comfortable feedback. We might explore pressure gradients along the floor mat (e.g. sections that inflate or tense) to guide weight shifts. We also propose thermal cues (thermohaptics) to evoke the flow of energy (prāṇa). Recent prototypes have integrated thermoelectric elements with vibration to create warming or cooling sensations alongside touch . A controlled warmth spreading slowly could symbolize rising breath energy, for example.

5.1.2 Haptic Design

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5.2. User Perception of Haptic Cues

Our interviews confirmed several perceptual principles. In general, larger contact area yielded a clearer sensation: users felt stronger, more distinct feedback when an actuator pressed on a broader surface. This aligns with haptics research showing that increasing skin-surface contact improves tactile acuity. Conversely, when contact was small or point-like, cues felt weaker. We also observed a clear trade-off with pulse frequency: very rapid pulses (above 10–15 Hz) became indistinguishable as directional cues, and users reported them as a continuous buzz with little spatial feel. This matches prior findings that high-frequency vibrations blur directional perception.

Participants consistently relied on the spatial sequence of activations to infer direction. When actuators fired in a clear left-to-right or radial sequence, users could follow the haptic "wave" of motion and knew which way to turn or shift. This mirrors the concept of apparent haptic motion in prior work, where discrete taps presented sequentially create an illusion of continuous motion along the skin . In contrast, simultaneous or poorly timed pulses were confusing.

Finally, users preferred "soft" or smooth waveforms. Gentle, ramped vibrations (akin to a gradual stroke) felt more comfortable and noticeable than abrupt, square pulses. One study found that a slow inflation could create a "pleasant stroke" sensation, whereas discrete taps felt more like an unpleasant crawling tickle. In our sessions, participants echoed this: sinusoids or sloping envelope pulses were rated calmer and easier to interpret than harsh on–off patterns. These qualitative insights (larger surface = clearer feel; sequential patterns aid direction; smooth pulses are more pleasant) will guide how we tune future signals.

5.3. Design Implications for At-Home Fitness Tech

These findings suggest broader guidelines for designing sensory-rich home exercise systems. First, hardware must fit the home context: devices should be lightweight, portable, and unobtrusive. Heavy or bulky rigs detract from living spaces. For example, the pressure-based haptic sleeve was noted to be "much more lightweight, wearable, and comfortable" than previous designs, a quality important for at-home gear. Foldable or multipurpose components (e.g. a mat that houses actuators but folds away or doubles as a cushion) make setup and storage easier.

Second, embrace multisurface and ambient interactions. Home workouts often use walls, floors, furniture, or exercise objects as touchpoints. Embedding tactile cues into multiple surfaces (e.g. a vibrating mat underfoot combined with wristbands) can reinforce body awareness without forcing a single device onto the user. Third, leverage audio–haptic co-design to reduce screen dependence. In home yoga, instructors typically appear via video on a screen. By pairing voice cues with complementary haptic signals, one can minimize the need for visual monitoring. Wearable X's Nadi system exemplifies this: its app provides spoken guidance while a "pulse" device gently vibrates to confirm correct alignment.

In our study, users appreciated haptics that coincided with audio instructions, noting they could keep eyes closed or focus on their body rather than watching video cues. This suggests that combining sound and touch can enhance immersion and free up attention. Indeed, prior work shows that providing vibrotactile feedback alongside other cues can significantly improve exercise performance and engagement.

In summary, home fitness technology should blend senses – matching vibrations with breathing or voice guidance – so the experience feels natural and less visually demanding.

5.4. Limitations

This work has several limitations. The participant sample was modest, limiting generalizability. We mostly evaluated users in relatively static poses and short interactions, so the findings may not fully capture performance in flowing sequences or longer sessions. Our floor vibrotactile module also introduced noise and resonance, which in a quiet apartment could distract or mask subtle cues. The participant pool lacked diversity in body types and yoga experience, so hardware fit and perceptual results might differ for taller, heavier, or more flexible practitioners. Finally, we did not record physiological data (e.g. heart rate, breathing) that could have quantified relaxation or focus. Together, these constraints suggest caution in extrapolating our results; future studies should use larger, varied samples, dynamic routines, and objective measures to validate these qualitative observations.

5.5. Future Work

Dynamic Asana Sequences. We will expand the system to guide full flowing sequences of poses (vinyasa-style), not just individual static postures. Continuous transitions will test how haptic cues can sustain flow states. Breath-Responsive Feedback. Incorporating respiratory sensors (e.g. chest bands or smart textiles) would allow closed-loop coupling between breathing and haptics. For instance, inhale/exhale cycles could modulate vibration intensity or temperature. Prior prototypes have shown that clear, guided haptic signals greatly aid breathing exercises, while mis-timed or excessive vibration can increase cognitive load. Longitudinal Training Studies. We plan multi-week deployment studies to see how users adapt over time. Does the system improve learning of poses, confidence, or engagement across sessions? Longitudinal data can reveal retention and training effects that short tests cannot. Proprioception and Flow Metrics. Future evaluation should include objective measures of proprioceptive accuracy (e.g. joint angle tracking) and psychological flow state questionnaires. We want to quantify whether haptic cues truly heighten body awareness or induce a “flow” experience in at-home practice. Co-Design with Instructors. Finally, engaging experienced yoga teachers in the design process will ensure that feedback modalities align with pedagogical needs. Co-design workshops can uncover which cues instructors find most intuitive or helpful, leading to a system that supports both novice learners and expert guidance. These future directions aim to build on our findings by making the system more robust, personalized, and pedagogically grounded, ultimately contributing to more immersive and effective home fitness technologies.

Chapter 6
Conclusion

The audio-haptic guidance system was built around four complementary devices – a vibrotactile floor mat, a wristband vibrating unit, to cover the full body and support a home yoga practice. In our prototype, the floor mat acted as the grounding feedback channel. It contained an array of gentle vibration motors under the feet that pulsed in time with the breath. During each inhale, for example, the mat delivered a slow rising vibration underfoot, then tapered off on the exhale. This foot-based pulse gave beginners a continuous, tactile sense of their breathing rhythm without any audible count, anchoring the breath cycle through the body's base. The timing of these pulses followed a natural yoga breathing pattern (inhale–hold–exhale–hold) so that learners could easily align their inhale and exhale with the tactile cues. Because feet tend to remain in contact with the mat in most Hatha poses, this design ensured that the breath signals were always felt, even if the practitioner closed their eyes or was focused on a video instructor.

The wristband unit extended the spatial mapping of these cues and enabled guidance of body alignment and flow. Small vibration modules on the wrists, waist, and chest could activate in sequence to simulate an upward flow of energy through the body. For instance, at the start of an exhale the waist module would buzz slightly, followed by the chest module, giving the sensation of breath or "prana" moving from the hips up through the spine. In this way, abstract notions of energy flow in Hatha yoga were made tangible: the practitioner physically feels an energy "wave" traveling along the body's vertical axis. The wristband device provided a mobile point of contact, which the user could grasp or hold against the chest. This unit was used to reinforce transitions and focus – for example, during a flowing sun salutation the wristband vibrator would pulse briefly as the practitioner lifted into an upward stretch, then again as they folded forward. By synchronizing these pulses with the pose sequence, the system gently paced beginners through transitions. A short burst of vibration counted down the last few seconds of a pose, for instance, cueing the student when to move on. In this way the mat, wristband device worked together: the floor pulses kept the breath steady, the wristband modules guided the body's vertical alignment, and the hand-held cues marked the timing of movement.

All haptic signals were carefully tuned to be subtle and soothing so they would not startle or distract. Motors were chosen for low-amplitude, soft-rising pulses rather than sharp tugs, and patterns were kept smooth. For example, error reminders took the form of a single gentle tap on the appropriate module (such as the hand) rather than a loud alarm. If a learner's shoulder alignment drifted, only that shoulder module buzzed briefly to indicate "realign here," allowing the student to self-correct without interrupting their focus. Similarly, the breathing pulses were delivered at a low intensity just above perceptual threshold, resembling a gentle nudge. This subtlety respected the meditative atmosphere of yoga and prevented the haptic cues from becoming intrusive.

Critically, these tactile cues were integrated with the other sensory instructions so that the experience felt unified. In a typical home session, visual cues (such as an on-screen instructor or soft ambient lighting) and voice guidance would accompany the practice. The haptic signals were timed to reinforce these cues: when the instructor said "inhale," the mat and the wristband would smoothly buzz in concert, so that the user both heard and felt the inhale. By aligning vibration timing with the instructor's breath count and movement cues, we created a multisensory feedback loop. This helped beginners who might find it hard to coordinate breathing and movement just by listening; the combined audio-visual-haptic signals ensured that timing and alignment were clear. Through iterative testing with novices, we refined each device's timing and placement so that every vibration felt intuitively mapped to a yoga gesture – a rising pulse for lift, a fading buzz for relaxation, a quick tap for correction. In sum, the design of the haptic system turned the abstract goals of breath awareness, timing, energy flow, and gentle correction into concrete, full-body haptic that enhance a beginner's at-home Hatha yoga practice without breaking its calm, mindful rhythm.

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