

Article

A Feasibility Study of PSE-Based Auditory–Motor Mapping for Post-TKA Home Rehabilitation Design

Wenhuan Gao, Dongzhu Jiang and Wenting Cheng *

School of Industrial Design, Hubei University of Technology, Wuhan 430068, China;
19861837267@163.com (W.G.); 20180088@hbut.edu.cn (D.J.)

* Correspondence: wenting_cheng1984@hbut.edu.cn; Tel.: +86-156-2398-8627

Abstract

Home-based rehabilitation after total knee arthroplasty (TKA) provides patients with the possibility of self-directed training under limited professional supervision, but its actual effect depends on whether patients can perceive, regulate, and complete lower-limb rehabilitation movements by themselves. This study explored a PSE-based auditory–motor mapping approach that translates lower-limb movement information into perceivable auditory cues to support patients’ perception and regulation of movement states. A design-oriented feasibility research process was adopted, including semi-structured interviews, non-participatory observation, thematic analysis, and a within-subject counterbalanced experiment. Joint-angle changes, movement phases, and effort-related movement information were mapped to pitch, rhythm, and loudness cues. In the experimental phase, a web-based functional prototype was used. Fifteen participants with knee pain performed three typical lower-limb training exercises in a simulated rehabilitation scenario, and auditory-cued and non-cued conditions were compared. The results indicated more favourable immediate movement-execution indicators and short-term subjective interaction outcomes under the auditory-cued condition. The Function-Behaviour-Structure framework was further applied to translate the preliminary interaction findings into a conceptual home-based rehabilitation interaction device. These findings provide preliminary support for exploring PSE-based auditory cueing in home rehabilitation interaction design, while further evaluation with actual post-TKA patients and real home-use contexts is still needed.

Keywords: patterned sensory enhancement (PSE); post-TKA; auditory–motor mapping; home rehabilitation design; feasibility study; human–computer interaction (HCI)



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1. Introduction

Total knee arthroplasty (TKA) has become one of the most frequently performed orthopaedic procedures worldwide due to the growing prevalence of knee osteoarthritis in ageing populations [1]. Current projections indicate that the demand for primary TKA will continue to increase substantially over the coming decades, placing sustained pressure on postoperative rehabilitation systems [2,3]. Although surgical techniques and perioperative management have improved considerably, postoperative recovery after TKA remains closely dependent on structured rehabilitation, including home-based exercise programmes in which patients are required to perform repetitive movements with limited professional supervision [4,5].

However, maintaining effective home rehabilitation after TKA remains challenging. Previous studies have reported low long-term exercise adherence and inconsistent move-

ment execution among patients recovering from joint replacement surgery [6,7]. Beyond behavioural barriers such as pain, reduced motivation, or lack of supervision, a key but less explicitly addressed issue concerns patients' ability to perceive and regulate movement during self-directed exercise. Studies on knee proprioception after TKA suggest that proprioceptive function may improve compared with the preoperative condition, but residual impairment or uncertainty in joint position sense may still remain [8–10].

In unsupervised home rehabilitation settings, this sensory uncertainty can appear in different aspects of movement execution. For example, knee flexion-extension requires patients to judge whether the required range of motion has been reached, while ROM recovery after TKA has also motivated sensor-based monitoring approaches [11]. For strengthening exercises such as straight leg raises, recent home-exercise systems have emphasised the value of real-time feedback for improving exercise accuracy after hip and knee arthroplasty, suggesting the need for feedback on elevation angle and hold duration [12]. These examples illustrate a broader perception-execution mismatch in post-TKA home rehabilitation: patients are expected to complete prescribed movements but may lack both continuous therapist feedback and reliable intrinsic perceptual references for judging how the movement is being performed. This mismatch may affect not only the quality and continuity of rehabilitation training, but also patients' confidence and willingness to sustain training over time. From this perspective, the core design challenge lies not merely in detecting whether a movement has been completed but in providing real-time perceptual support that enables more self-regulated movement execution in the absence of continuous therapist feedback.

Recent studies have expanded the technological basis of home-based rehabilitation after TKA in three main directions. First, telerehabilitation studies have shown that remote rehabilitation can improve access to supervision and support follow-up outside hospital settings. For example, Tsang et al. reported that telerehabilitation after total knee replacement can provide a feasible alternative to conventional face-to-face rehabilitation in selected contexts [13]. However, this line of work mainly addresses service delivery and remote supervision, while giving less attention to how patients regulate movement quality during each exercise cycle.

Second, smartphone applications and wearable devices have been increasingly used to record exercise performance, range of motion, and rehabilitation progress. Gordon et al. reviewed randomised controlled studies on smartphone- and wearable-assisted rehabilitation after TKA, showing that digital tools can support postoperative monitoring and patient engagement [14]. Similarly, recent reviews of sensor technologies in TKA rehabilitation have shown that wearable and sensor-based systems can provide objective movement data during home rehabilitation [11]. Nevertheless, these systems primarily focus on measuring, recording, or alerting movement status; they do not fully explain how sensory feedback can be structured to guide movement execution continuously.

Beyond monitoring-oriented technologies, recent interaction-oriented rehabilitation systems have also begun to explore embodied and immersive feedback during self-directed exercise. Su et al. systematically reviewed XR-based rehabilitation after TKA and found that virtual, augmented, and mixed reality interventions could improve postoperative pain, function, and anxiety, indicating the potential of immersive visual feedback in supporting rehabilitation outcomes [15]. Pournajaf et al. further demonstrated that non-immersive VR-based serious-game balance training could improve clinical, gait, and postural outcomes in individuals after total knee replacement, suggesting that interactive virtual environments may support lower-limb movement awareness and balance regulation [16]. These studies move beyond passive monitoring by embedding feedback into the exercise experience itself.

However, their feedback mechanisms remain largely visual, screen-based, or game-oriented. From a human-factors perspective, visually dominated interfaces may place

additional demands on the attentional resources needed to observe and regulate movement [17]. For older adults, VR-based interaction also requires careful consideration of visual, cognitive, and physical modalities, which may influence usability and interaction burden during rehabilitation-oriented tasks [18]. During repetitive self-directed home exercise, such demands may increase interaction burden and may not always provide continuous guidance throughout the movement cycle.

This suggests the need to further examine feedback modalities that can provide continuous perceptual support during rehabilitation movement with reduced reliance on visual feedback, particularly by considering how different sensory channels can be organised in multimodal interaction [19]. To address this problem, the present study first draws on the concept of external sensory feedback. External sensory feedback and biofeedback can transform body states into perceivable signals, potentially allowing users to monitor and adjust movement during execution [20]. Among different feedback modalities, auditory feedback is particularly relevant to rehabilitation movement because sound unfolds over time and can provide continuous temporal information without requiring constant visual attention. Previous studies have suggested that auditory feedback, movement sonification, and auditory-motor coupling may support movement coordination, timing regulation, and sensorimotor learning [21–24]. Therefore, auditory cues may be suitable for guiding repetitive home rehabilitation exercises in which patients need to regulate movement rhythm, amplitude, and phase continuity.

Within this context, Patterned Sensory Enhancement (PSE), a technique originating from Neurologic Music Therapy (NMT), provides a structured basis for organising auditory cues in movement guidance. PSE uses musical elements such as rhythm, melody, harmony, and dynamics to provide temporal, spatial, and force-related cues for functional movement training [25], and recent studies have suggested its potential in neurological and neuromotor rehabilitation contexts [26–28]. For post-TKA home rehabilitation, this technology is relevant because repetitive exercises require support for movement timing, joint-angle change, phase continuity, and sustained exertion.

Despite this theoretical relevance, the use of PSE in post-TKA home rehabilitation remains insufficiently explored, particularly in terms of how its cueing principles can be operationalised as a task-oriented auditory–motor interaction mechanism for assisted lower-limb rehabilitation training. Therefore, this study proposes a PSE-based auditory–motor mapping framework and evaluates its feasibility under simulated rehabilitation conditions and further explores how the resulting interaction requirements can inform the design of a home-based rehabilitation interaction device. In doing so, the study shifts the focus from merely measuring movement to exploring how structured auditory cues may support movement guidance in home rehabilitation contexts.

2. Research Framework

To address the perception–execution mismatch identified in post-TKA home rehabilitation, this study adopts a three-stage design-oriented feasibility research framework: (1) user requirement analysis, which identifies rehabilitation needs, pain points, and interaction requirements through semi-structured interviews, non-participatory observation, and thematic analysis; (2) TKA–PSE mapping development and feasibility evaluation, which establishes a PSE-based auditory–motor mapping model and evaluates its interaction feasibility through a web-based functional prototype and a within-subject experiment; (3) FBS-based design translation, which translates the preliminary interaction requirements into functional requirements, FBS mappings, conceptual design alternatives, and design evaluation. Together, these stages establish a continuous methodological pathway from user problem identification and interaction feasibility evaluation to product design translation, as shown in Figure 1.

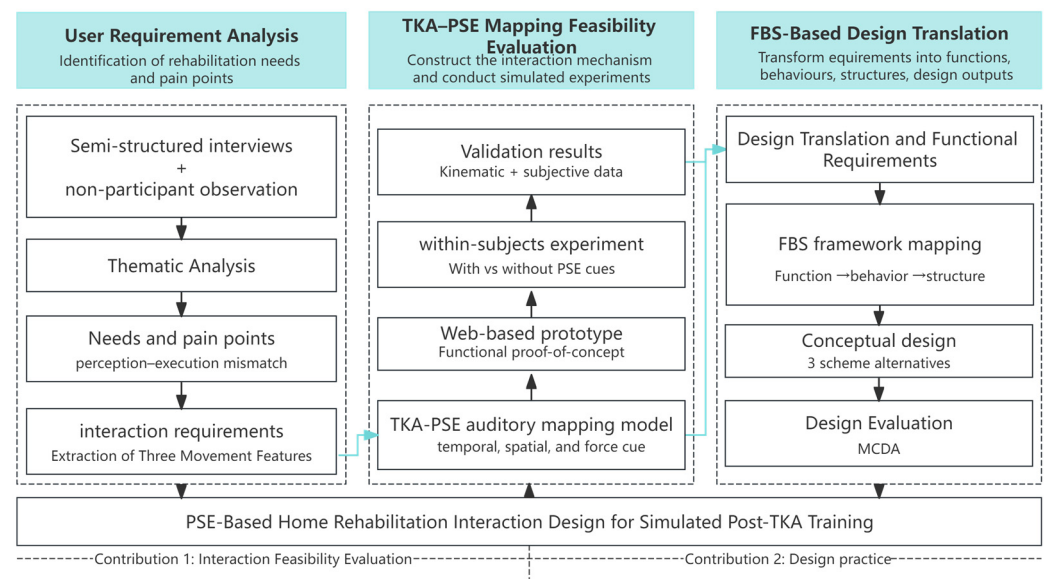


Figure 1. Overall research framework.

This framework connects qualitative requirement identification, PSE-based auditory–motor interaction feasibility evaluation, and FBS-based design development within a coherent research process. Accordingly, the study has two main outputs: first, preliminary feasibility evidence for the PSE-based auditory–motor mapping mechanism in simulated post-TKA rehabilitation movements; and second, a design practice pathway for translating preliminary interaction findings into a home rehabilitation interaction device.

2.1. User Research and Requirement Identification

To ground the system design in authentic rehabilitation needs, a field study was conducted prior to prototype development, aiming to identify practical challenges and behavioural patterns related to post-TKA home rehabilitation.

2.1.1. Field Study Design

A field study was conducted in September 2025 at Pinglu District People’s Hospital, Shuozhou City, Shanxi Province. Representative scenes from the field observation and user interviews are shown in Figure 2. The study employed a qualitative approach, combining non-participatory observation and semi-structured interviews to obtain an initial understanding of the perception–execution mismatch in home rehabilitation contexts.

- **Participants:** A total of 8 participants were recruited, including 3 orthopaedic surgeons (to provide professional clinical perspectives) and 5 TKA patients covering various recovery stages. The patient cohort consisted of 3 females and 2 males.
- **Observation Protocol:** Researchers conducted non-participatory observations of patients’ daily rehabilitation exercise routines, focusing on the core types and movement characteristics of rehabilitation exercises, as well as patients’ execution of clinical instructions, joint stability, and consistency of movement amplitude.
- **Interview Protocol:** Following the observations, semi-structured interviews were conducted to further explore patients’ difficulties during self-directed rehabilitation training, including movement perception uncertainty, rhythm maintenance, confidence during exercise, subjective pain experiences, and the need for external guidance in home-based rehabilitation contexts.

The interview and observation data were summarized to provide an empirical basis for the subsequent thematic analysis and research development, as shown in Table 1.

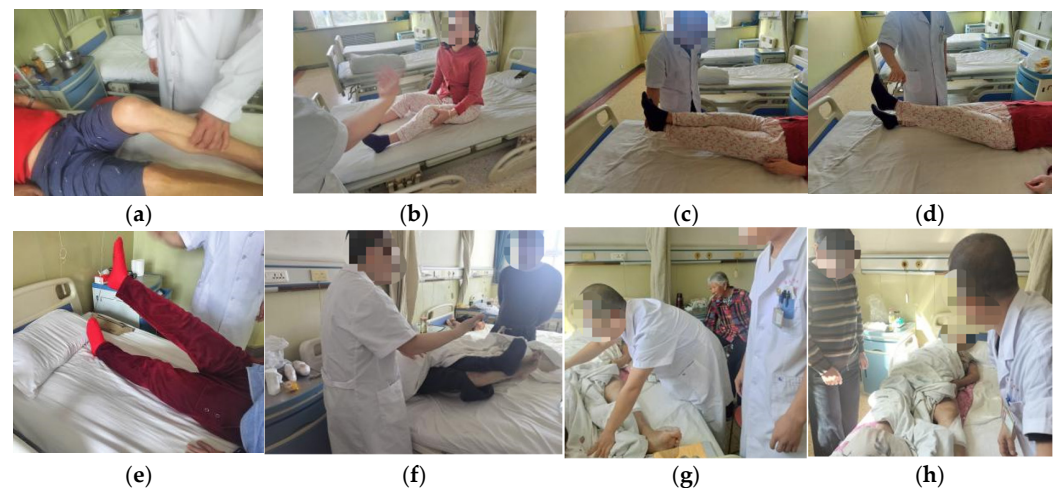


Figure 2. Representative scenes from clinical behavioural observation and user interviews. (a) Knee Flexion and Extension Exercise. (b) Knee Flexion and Extension Exercise. (c) Weight-Bearing Leg Raise Exercise. (d) Straight Leg Raise (SLR) Exercise. (e) Straight Leg Raise (SLR) Exercise. (f) Weight-Bearing Leg Raise Exercise. (g) Knee Flexion and Extension Exercise. (h) Ankle Pump Exercise.

Table 1. User Observation and Interview Records.

Participant	Relevant Information	Observation Findings	Original Interview Statement
P1	Female, 67, 3 weeks post-TKA	Frequently paused during knee flexion training and repeatedly looked down at the knee before movement execution.	"When exercising at home, I cannot tell whether my knee is bending to the correct angle."
P2	Male, 71, 1 month post-TKA	Relied heavily on handrails during standing exercises and hesitated during weight shifting.	"I am afraid of pain during movement, so I usually avoid bending too much."
P3	Female, 65, 2 weeks post-TKA	Demonstrated reduced movement amplitude due to fear of pain.	"Without a therapist beside me, I do not know whether my movements are standard."
P4	Female, 69, 6 weeks post-TKA	Frequently requested therapist confirmation regarding knee angle accuracy.	"Sometimes I stop training midway because I feel uncertain about whether the movement is accurate."
P5	Male, 73, 1 month post-TKA	Movement rhythm was unstable, and exercise continuity was frequently interrupted.	"The rehabilitation exercises are repetitive and difficult to persist with every day."
D1	Rehabilitation physician, 8 years of experience	Frequently provided verbal corrections regarding knee angle and movement trajectory.	"Patients commonly experience reduced proprioception after surgery, especially during early rehabilitation."
D2	Orthopaedic physician, 12 years of experience	Observed poor long-term adherence in home rehabilitation patients.	"Fear of movement and lack of confidence are major reasons for poor home rehabilitation adherence."
D3	Orthopaedic surgeon, 15 years of experience	Emphasised the importance of structured guidance for home rehabilitation and noted common patient errors in movement timing.	"Patients often rush through exercises at home. Without a clear rhythm to follow, they compress the phases and miss the therapeutic window."

2.1.2. Thematic Analysis

The data collected through observation and interviews were subsequently subjected to thematic analysis to identify recurring patterns across participants' and clinicians' accounts. Interview transcripts and observation notes were analysed following the six-phase framework proposed by Braun and Clarke [29], including familiarisation with the data, initial code generation, theme development, theme review, theme definition and nam-

ing, and reporting. Two researchers independently coded the transcripts and observation notes, and discrepancies were discussed until agreement was reached. The findings were treated as preliminary design inputs rather than generalisable clinical conclusions, given the small-scale and context-specific nature of the inquiry.

To make the transition from evidence to themes explicit, the observation records, participant quotations, and clinician feedback listed in Table 1 were treated as evidence sources and further segmented into relevant evidence units. These evidence units were then assigned initial codes. Similar initial codes were compared and grouped into code categories, which were further refined into candidate themes and finally defined as final themes.

Based on the thematic coding process, three final themes for this study were identified: Proprioceptive Uncertainty, Kinesiophobia and Avoidance, and Rhythmic Execution Deficit, as shown in Table 2.

- Codes related to angle judgement, repeated visual checking, therapist confirmation, and reduced proprioceptive awareness were interpreted as evidence that patients had difficulty forming a reliable perception of their own movement during self-directed exercise. This led to the theme Proprioceptive Uncertainty, which highlights a perceptual barrier rather than a simple lack of exercise information.
- Codes related to fear of pain, avoidance of bending, reduced movement amplitude, hesitation, and poor adherence were interpreted as a pattern of protective under-execution. In this case, the problem was not simply a lack of exercise willingness; rather, pain anticipation and low confidence could lead patients to restrict movement before completing the intended exercise range or task. This led to the theme Kinesiophobia and Avoidance.
- Codes related to unstable rhythm, interrupted continuity, rushing through exercises, phase compression, and poor timing control were interpreted as a lack of temporal structure during repetitive home exercise. This theme, Rhythmic Execution Deficit, indicates that patients may not only need to know what movement to perform but also require guidance on how to maintain movement timing, phase continuity, and exercise rhythm across repetitions.

Table 2. Thematic coding process from evidence sources to final themes.

Evidence Sources from Table 1	Initial Codes	Code Categories	Candidate Themes	Final Themes
P1-Obs, P1-Quote; P3-Quote; P4-Obs, P4-Quote; D1-Obs, D1-Quote	Difficulty judging knee angle; repeated visual checking; uncertainty about movement accuracy; dependence on therapist confirmation; reduced proprioceptive awareness; need for external correction	Impaired joint-position self-monitoring; dependence on external confirmation; reduced proprioceptive awareness;	Lack of reliable internal movement reference	Proprioceptive Uncertainty
P2-Obs, P2-Quote; P3-Obs; D2-Obs, D2-Quote	Fear of pain; avoidance of bending; reduced movement amplitude; hesitation during movement; lack of confidence; poor adherence	Pain-related movement avoidance; protective under-execution; confidence-related movement restriction	Fear-driven restriction of movement execution	Kinesiophobia and Avoidance
P5-Obs, P5-Quote; D3-Obs, D3-Quote	Repetitive exercise burden; unstable movement rhythm; interrupted exercise continuity; rushing through exercises; phase compression; shortened or incomplete movement phases; poor timing control	Insufficient temporal guidance; unstable exercise rhythm; loss of movement-phase integrity	Lack of temporal structure during self-directed exercise	Rhythmic Execution Deficit

Note: Obs = observation finding; Quote = original interview statement.

These three themes provided the user-derived basis for constructing the subsequent PSE-based auditory–motor mapping framework. Specifically, proprioceptive uncertainty indicated the need to externalise movement status and joint-angle changes through perceptible feedback; kinesiophobia and avoidance suggested the need for clear and low-burden cues that could support perceived controllability during movement execution; and rhythmic execution deficit highlighted the need for temporal scaffolding to organise movement pace, repetition consistency, and phase continuity. Accordingly, the following section translates these interaction-level requirements into a task-oriented auditory mapping framework, in which rehabilitation movement information is represented through structured PSE cue dimensions.

2.2. PSE-Based Auditory–Motor Mapping Framework

2.2.1. Patterned Sensory Enhancement (PSE)

Patterned Sensory Enhancement (PSE) is a technique within Neurologic Music Therapy that uses structured musical elements to support functional movement patterns. In PSE, musical parameters such as melody, harmony, rhythm, tempo, beat, dynamics, texture, timbre, and pitch can be organised to indicate temporal, spatial, and force cues of movement or fundamental motor patterns [24].

In this study, PSE was employed as an auditory interaction mechanism that translates movement-related information into perceptible auditory cues during self-directed rehabilitation training after TKA. Its purpose was to support patients' perception and regulation of movement timing, movement amplitude, and sustained motor control in home-based rehabilitation.

2.2.2. TKA Mapping Framework Construction

The selected exercises, ankle pumps, knee flexion–extension, and straight leg raises, represent common early-stage rehabilitation exercises after TKA. They correspond to circulation promotion, knee range-of-motion recovery, and lower-limb strength control.

The American Academy of Orthopaedic Surgeons (AAOS) describes ankle pumps as rhythmic up-and-down movements of the foot at the ankle [30]. This description indicates that ankle pumps are not a single isolated movement but are composed of repeated and alternating dorsiflexion–plantarflexion movements of the ankle. Based on this movement structure, the key movement information of ankle pumps is mainly reflected in repetition frequency, movement interval, transition timing between dorsiflexion and plantarflexion, and cycle-to-cycle continuity. These variables collectively point to the temporal organisation of movement execution, meaning that patients need to maintain relatively stable rhythm, interval, and transition timing during repeated movement. Schaefer suggested that auditory rhythmic cueing can support movement rehabilitation by enabling movement to synchronise with the temporal structure of external auditory stimuli, such as metronome beats or music [31]. This provides a theoretical basis for using rhythm-based auditory cues to guide movements that depend on repetition, timing, and pacing. In addition, PSE literature indicates that rhythm, tempo, meter, and beat patterns can provide temporal cues for movement [26]. Therefore, ankle pumps were conceptualised in this study as a movement task dominated by temporal organisation and were further aligned with temporal cues in PSE. In this mapping, rhythm, beat interval, and tempo modulation were used to guide the regularity and pacing of repeated ankle movement.

Knee flexion–extension involves progressive bending and straightening of the operated knee within the available range of motion [30]. Its execution depends on joint-angle change, movement amplitude, movement direction, and brief holding near the flexed position. These features define knee flexion–extension as a spatial joint-angle task. PSE literature indicates that musical elements can provide spatial cues for movement, and previous PSE

work has used ascending and descending melodic lines to represent directional changes in limb movement [26]. Sonification and auditory display research also suggest that pitch can represent continuous data changes, while mapping direction affects how users interpret data-to-sound relationships [32,33]. Increasing knee-joint angle was therefore mapped to rising pitch, and movement direction was represented through pitch contour.

Straight leg raises require knee extension, limb elevation, short-duration holding, and controlled lowering [30]. Their execution depends on sustained limb elevation, holding stability, holding duration, and controlled task completion. These features define straight leg raises as an effort-related task. PSE literature identifies dynamics and related musical elements as force-related movement cues, and long note durations have been used to indicate continuous holding [26]. Moderate dynamic variation and sound continuity were therefore used to support sustained effort awareness, holding stability, and task completion. Loudness and dynamics were used as perceptual cues, not as direct measurements of muscle force.

The resulting PSE-based auditory–motor mapping framework for the three rehabilitation exercises is shown in Figure 3. These mappings were not intended to represent universally optimal auditory strategies, but rather theoretically grounded and perceptually interpretable design choices for feasibility evaluation in post-TKA home rehabilitation.

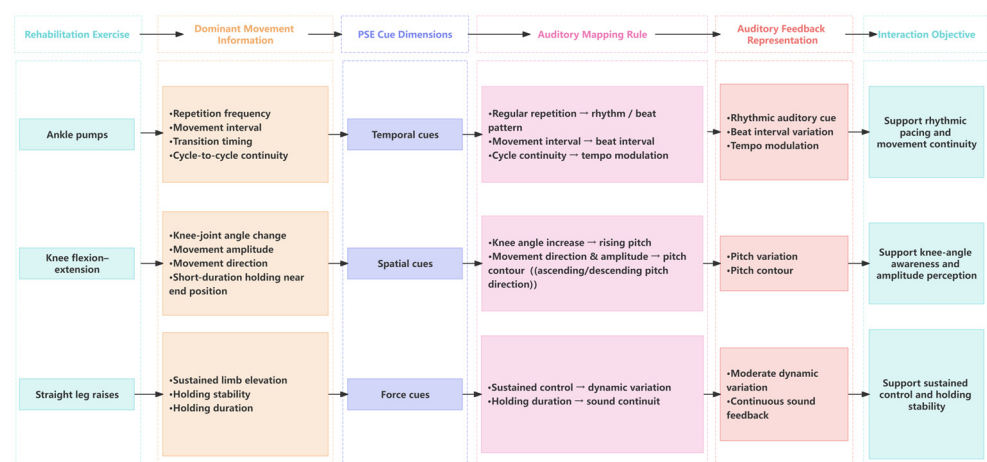


Figure 3. PSE-Based Auditory-Motor Mapping Framework for Post-TKA Rehabilitation.

2.3. Functional Prototype Development

To evaluate the feasibility of the PSE mapping framework under controlled experimental conditions, a minimal functional prototype was constructed, consisting of two components: a simple physical support setup and a web-based interactive interface.

The physical component (Figure 4b) comprised a basic limb-support frame and an RGB camera, providing a low-cost hardware setup for positioning the participant and capturing lower-limb movement in real time. This setup was kept minimal, primarily to focus the evaluation on the interaction mechanism rather than the physical form of a finalised device. The web-based component (Figure 4c) was developed using MediaPipe Pose (@mediapipe/pose version 0.5.1675469404; Google LLC, Mountain View, CA, USA). to extract lower-limb landmarks, including hip, knee, and ankle landmarks, and to compute joint angles from the spatial relationships among these points. The interaction loop followed a closed-loop process: real-time video acquisition, landmark identification, angle computation, and auditory-cue triggering according to predefined PSE mapping rules (Figure 4a). This prototype served as the experimental instrument in Section 3, allowing comparison between auditory-cued and non-cued conditions within a controlled experimental setting.

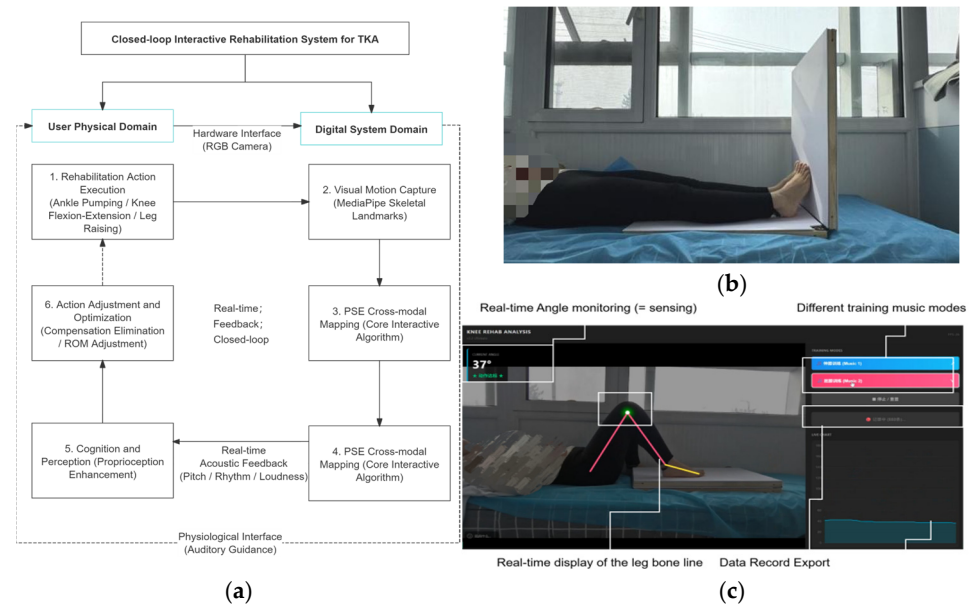


Figure 4. Functional prototype of the PSE-based auditory-motor interaction system. (a) Interactive Rehabilitation System for TKA. (b) Simple physical prototype device. (c) Simulated interactive interface.

3. Experimental Feasibility Evaluation and Results

Building on the research framework established in Section 2, an experimental feasibility evaluation was conducted to examine the proposed auditory interaction mechanism in a simulated rehabilitation movement scenario.

3.1. Study Design

A within-subject counterbalanced experiment was conducted to compare task-level movement performance and subjective experience between auditory-cued and non-cued conditions. This design allows for direct within-individual comparison, thereby controlling for inter-subject variability such as baseline motor ability and movement experience. Each participant completed the prescribed tasks under two conditions: “With Auditory Cues” (supported by the PSE web prototype) and “No Auditory Cues” (relying on traditional verbal instructions). To minimise order effects such as learning effects or physical fatigue, the sequence of conditions was counterbalanced. Participants were randomly assigned to two groups: one group completed the auditory-cued session first, followed by the non-cued session; the other group followed the reverse order. A washout period of at least 30 min was implemented between sessions to allow for physiological recovery and to reduce residual sensory influence.

3.2. Participants

The experimental evaluation was conducted as a preliminary feasibility study under simulated home rehabilitation conditions. Participants were individuals with knee pain conditions rather than actual post-TKA patients. This sampling choice was made because the current study aimed to examine whether the proposed auditory cues could be perceived, followed, and used during knee-related rehabilitation movements under controlled experimental conditions, while avoiding the additional clinical variability and safety constraints associated with early postoperative TKA populations. Before the experiment, all participants received instructions and practised the three rehabilitation-inspired movements, including ankle pumps, knee flexion-extension, and straight leg raises. This helped ensure that they understood the basic movement tasks before evaluating the auditory-motor feedback. This sample allowed us to test the interaction feasibility and perceptual usability

of the PSE-based auditory–motor mapping framework, but not its clinical effectiveness for post-TKA rehabilitation, proprioceptive recovery, long-term adherence, or functional outcomes. Fifteen participants with knee pain conditions ($N = 15$) were recruited from Pinglu District People’s Hospital, Shuozhou City, Shanxi Province. Inclusion criteria included: (1) presence of knee pain affecting daily movement; (2) ability to understand instructions and perform basic lower-limb exercises; and (3) no severe visual or auditory impairments.

3.3. Experimental Tasks

The experimental tasks consisted of three rehabilitation-inspired lower-limb movements derived from common post-TKA rehabilitation exercises defined in the PSE-based auditory–motor mapping framework: ankle pumps, knee flexion–extension, and straight leg raises. Ankle pumps were selected to examine rhythmic stability and repeated dorsiflexion–plantarflexion control, as this task requires participants to maintain a stable movement tempo across multiple cycles. Knee flexion–extension was used to evaluate spatial movement control, including the ability to regulate joint angle changes, complete the flexion–extension cycle, and maintain phase continuity. Straight leg raises were included to assess sustained force-related control, particularly the ability to elevate the limb, maintain the target posture, and avoid premature angle decline. Together, these three tasks cover temporal, spatial, and force-related movement characteristics, corresponding to the rhythm, pitch, and loudness dimensions of the proposed PSE auditory–motor mapping framework.

Figure 5 presents a representative comparison of knee flexion–extension movements under the non-cued and auditory-cued conditions.

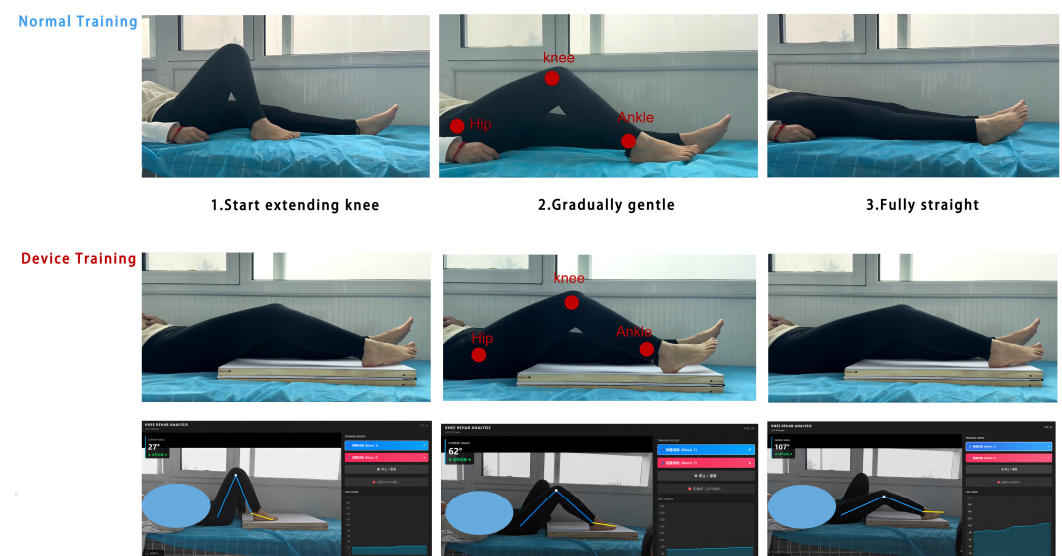


Figure 5. Representative knee flexion–extension exercise under two feedback conditions.

3.4. Measures

3.4.1. Kinematic Measures

The web-based prototype automatically recorded real-time joint angles and time-series coordinate data during each rehabilitation exercise. The raw data were exported as comma-separated values (CSV) files for subsequent analysis. For quantitative analysis of task-level movement characteristics, the following kinematic indicators were derived:

Knee flexion peak ROM ($^{\circ}$)

$$\text{PeakROM} = \theta_{\max} - \theta_{\min} \quad (1)$$

where θ_{max} denotes the maximum knee joint angle and θ_{min} denotes the minimum knee joint angle recorded during the session.

Ankle total ROM ($^{\circ}$)

$$\text{Total ROM} = \theta_{max} - \theta_{min} \quad (2)$$

where θ_{max} and θ_{min} denote the maximum and minimum ankle joint angles recorded across all pump cycles.

Ankle Stability SD (ms)

$$SD = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (T_i - \bar{T})^2} \quad (3)$$

Ankle Stability SD (ms) was calculated as the standard deviation of the duration of repeated ankle pump cycles.

Maximum Hip Elevation Angle ($^{\circ}$)

$$\theta_{hip} = \max(\theta_{SLR}) \quad (4)$$

where θ_{SLR} denotes the hip joint angle during the straight leg raise task, computed from the vectors formed by the shoulder, hip, and knee landmarks.

Hold Duration (s)

$$T_{hold} = t_{release} - t_{target} \quad (5)$$

where t_{target} notes the time at which the limb reached the target elevation angle and $t_{release}$ denotes the time at which the angle fell below the threshold.

Kinematic Data: All kinematic data were analysed using IBM SPSS Statistics. Given the within-subject counterbalanced design, paired-samples *t*-tests were employed to compare each kinematic variable between the WithMusic and NoMusic conditions. Statistical significance was set at $\alpha = 0.05$ (two-tailed). Effect sizes were calculated using Cohen's *d* for paired designs, with thresholds of 0.2, 0.5, and 0.8 indicating small, medium, and large effects, respectively. Data normality was confirmed using the Shapiro–Wilk test prior to parametric analysis; all variables satisfied the normality assumption (all $W > 0.90$, $p > 0.05$).

3.4.2. Subjective Measures

After each experimental session, participants completed a questionnaire designed to assess their subjective experience. The questionnaire included items measuring:

- **Perception Clarity:** Participants' perceived understanding of their joint position and movement trajectory.
- **Movement Following:** The ease and accuracy with which participants felt they could follow the prescribed movement patterns.
- **Kinesiophobia (Fear of Movement):** Participants' fear or anxiety associated with movement during exercise. Unlike the positive-experience items, lower scores on this item indicate lower fear of movement.
- **Intention to Use:** Participants' likelihood and willingness to use the system for future home rehabilitation.

All subjective items were rated on a 5-point Likert scale. For Perception Clarity, Movement Following, and Intention to Use, higher scores indicated more positive perceived experience. For Kinesiophobia, higher scores indicated greater fear of movement.

Subjective experience data were analysed using Wilcoxon Signed-Rank Tests, a non-parametric approach suitable for ordinal scale data. The analysis was conducted using IBM SPSS Statistics (version 26.0; IBM Corp., Armonk, NY, USA). For each subjective dimension, comparisons were made between the WithMusic and NoMusic conditions. The effect size for each Wilcoxon signed-rank test was calculated using the formula $r = |Z| / \sqrt{N}$, where *Z* is the Z-statistic from the Wilcoxon test and *N* is the number of participants. Effect size

thresholds for r were interpreted according to Cohen (1992): $r < 0.3$ indicated a small effect, $0.3 \leq r < 0.5$ indicated a medium effect, and $r \geq 0.5$ indicated a large effect.

3.5. Statistical Analysis

3.5.1. Kinematic Performance Analysis

Kinematic data were extracted from the web-based prototype across three tasks under both conditions. Paired-samples t -tests were applied following confirmation of normality via Shapiro–Wilk test (all $p > 0.05$). The following results should be interpreted as preliminary evidence of interaction feasibility and perceived movement support under simulated rehabilitation conditions. Results are summarised in Table 3, and representative kinematic trajectories are illustrated in Figure 6.

Table 3. Kinematic performance across three tasks under two feedback conditions ($N = 15$, paired-samples t -test).

Task	Metric	NoMusic (Mean $\pm$ SD)	WithMusic (Mean $\pm$ SD)	Mean Diff	$t(14)$	p	95% CI	Cohen's d
Knee Flexion	Peak ROM ($^{\circ}$)	100.60 $\pm$ 9.87	106.40 $\pm$ 9.61	+5.80	8.651	<0.001	[4.362, 7.238]	2.233
Ankle Pumps	Total ROM ($^{\circ}$)	35.93 $\pm$ 4.93	39.40 $\pm$ 5.34	+3.47	5.082	<0.001	[2.003, 4.930]	1.312
	Stability SD (ms)	687.16 $\pm$ 199.28	380.26 $\pm$ 75.80	−306.91	6.974	<0.001	[212.521, 401.290]	1.801
Straight Leg Raise	Max Hip Angle ($^{\circ}$)	28.21 $\pm$ 3.88	33.41 $\pm$ 6.15	+5.20	5.318	<0.001	[3.102, 7.297]	1.374
	Hold Duration (s)	3.82 $\pm$ 1.17	6.20 $\pm$ 2.27	+2.38	6.424	<0.001	[1.585, 3.175]	1.659

ROM = range of motion; SD = standard deviation; CI = confidence interval. † Normality confirmed via Shapiro–Wilk test for all variables (all $W > 0.90$, $p > 0.05$).

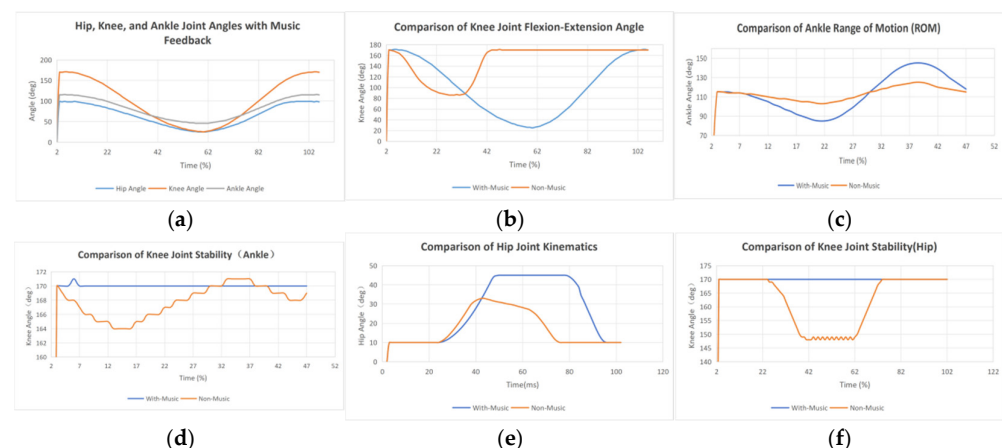


Figure 6. Comparison of kinematic trajectories under WithMusic and NoMusic conditions across three rehabilitation tasks for one typical participant: (a) representative multi-joint coordination; (b) knee flexion–extension trajectory; (c) ankle pump angle trajectory; (d) knee stability during ankle pump; (e) hip trajectory during straight leg raise; (f) knee stability during straight leg raise.

Compared with the NoMusic condition, the auditory-cued condition showed more favourable task-level kinematic outcomes across the five indicators. For the knee flexion task, peak ROM (Equation (1)) improved from $100.60 \pm 9.87^{\circ}$ to $106.40 \pm 9.61^{\circ}$ (Mean Diff = $+5.80^{\circ}$, $t(14) = 8.651$, Cohen's $d = 2.233$). For the ankle pump task, total ROM (Equation (2)) increased from $35.93 \pm 4.93^{\circ}$ to $39.40 \pm 5.34^{\circ}$ (Mean Diff = $+3.47^{\circ}$, $t(14) = 5.082$, Cohen's $d = 1.312$), while rhythm stability (Equation (3)) improved substantially, with Stability SD reducing from 687.16 ± 199.28 ms to 380.26 ± 75.80 ms (Mean Diff = -306.91 ms, $t(14) = 6.974$, Cohen's $d = 1.801$), indicating more consistent inter-cycle timing under auditory cueing. For the straight leg raise task, maximum hip elevation angle (Equation (4)) increased from $28.21 \pm 3.88^{\circ}$ to $33.41 \pm 6.15^{\circ}$ (Mean Diff = $+5.20^{\circ}$, $t(14) = 5.318$, Cohen's $d = 1.374$), and hold duration (Equation (5)) improved from

3.82 ± 1.17 s to 6.20 ± 2.27 s (Mean Diff = +2.38 s, $t(14) = 6.424$, Cohen's $d = 1.659$), suggesting that auditory cueing may have supported holding-phase task performance during the simulated straight leg raise task.

Effect sizes across all kinematic indicators were large (Cohen's $d = 1.312$ – 2.233). These unusually large and consistent effects should be interpreted with caution. Several factors may have contributed to the magnitude of these estimates, including the small sample size, the within-subject design, the relatively homogeneous baseline characteristics of the participants, and the immediate and targeted nature of the auditory cues. Because the evaluation was conducted during a short simulated session, novelty effects, increased attention to the feedback, and short-term task familiarity may also have amplified the observed differences between the auditory-cued and non-cued conditions. Therefore, these effect sizes should not be interpreted as stable estimates of clinical or long-term rehabilitation effects. Instead, they provide preliminary evidence of interaction feasibility and should be verified in larger samples, with longer intervention periods, and more ecologically valid rehabilitation settings.

To further illustrate the movement process underlying the group-level results, Figure 6 presents representative time-series trajectory comparisons from one typical participant across the three rehabilitation tasks.

The multi-joint trajectory recorded during knee flexion–extension showed that the web-based prototype could capture dynamic changes in hip, knee, and ankle angles, thereby providing a data basis for subsequent movement process analysis (Figure 6a). Meanwhile, the coordinated variations among the three joints suggest that knee flexion–extension under auditory cueing involved observable multi-joint coordination rather than an isolated single-joint movement. For knee flexion–extension, the WithMusic trajectory presented a clearer flexion–extension cycle, whereas the NoMusic trajectory showed earlier return to extension and insufficient maintenance of the flexion phase (Figure 6b). During ankle pump training, the WithMusic condition showed larger ankle angle oscillations and more stable knee positioning, suggesting improved rhythmic execution and reduced knee-angle fluctuation (Figure 6c,d). For straight leg raise, the WithMusic condition showed a higher and more sustained hip elevation trajectory, together with a more stable knee–extension angle, while the NoMusic condition exhibited earlier angle decline and greater knee fluctuation (Figure 6e,f).

3.5.2. Subjective Experience Analysis

Subjective evaluation data were analysed using Wilcoxon signed-rank tests. The results, summarised in Table 4, should be interpreted as preliminary evidence of short-term perceived interaction experience under simulated rehabilitation conditions.

Table 4. Subjective experience ratings between conditions ($N = 15$).

Evaluation Dimension	NoMusic Mdn ($M \pm SD$)	WithMusic Mdn ($M \pm SD$)	Z	p	r
Perception Clarity	3.0 (2.60 ± 0.63)	3.0 (3.40 ± 0.63)	−3.207	0.001	0.828
Movement Following	3.0 (2.93 ± 0.70)	4.0 (3.73 ± 0.46)	−2.972	0.003	0.767
Kinesiophobia (Fear) [†]	4.0 (3.60 ± 0.99)	2.0 (2.33 ± 0.90)	−2.939	0.003	0.759
Intention to Use	4.0 (3.67 ± 0.62)	4.0 (4.20 ± 0.78)	−2.138	0.033	0.552

Mdn = median; M = mean; SD = standard deviation. Scores were rated on a 5-point Likert scale (1–5). Effect size was calculated as $r = |Z| / \sqrt{N}$, with 0.1, 0.3, and 0.5 indicating small, medium, and large effects, respectively.

[†] Lower scores for kinesiophobia indicate lower fear of movement.

Compared with the NoMusic condition, the auditory-cued condition showed more favourable subjective ratings across the four evaluated dimensions, with differences ob-

served between conditions (all $p < 0.05$, $r = 0.552$ – 0.828). The largest difference was observed in Kinesiophobia scores, where median scores decreased from 4.0 to 2.0 ($Z = -2.939$, $p = 0.003$, $r = 0.759$). Eleven of the 15 participants reported lower fear-of-movement scores, while only one participant showed an opposite trend. This indicates that participants reported lower perceived fear during the simulated session under the auditory-cued condition. Perception Clarity ($Z = -3.207$, $p = 0.001$, $r = 0.828$) and Movement Following ($Z = -2.972$, $p = 0.003$, $r = 0.767$) also showed higher ratings under the auditory-cued condition, with 11 and 10 participants respectively reporting positive changes and no opposite trends. Intention to Use showed a relatively smaller difference between conditions ($Z = -2.138$, $p = 0.033$, $r = 0.552$), with 9 participants reporting increased intention and 2 participants showing an opposite trend, suggesting greater individual variability in short-term perceived acceptability.

Because intention to use was measured immediately after a short simulated session, this result should be interpreted as short-term perceived acceptability rather than evidence of sustained user acceptance, rehabilitation adherence, or long-term clinical applicability.

4. Design Practice

Although the PSE-based auditory–motor mapping framework showed preliminary interaction feasibility at the task-execution level, its design value also depends on whether this interaction mechanism can be further translated into a human–computer interaction product suitable for home-based rehabilitation contexts. Therefore, this study developed a conceptual design for a home-based rehabilitation interaction device. The design process included product-level requirement translation, FBS-based function–behaviour–structure mapping, conceptual scheme generation, and design evaluation.

4.1. Design Requirements Analysis

As shown in Figure 7, the design requirements were derived through a cross-analysis of three analytical inputs: thematic analysis findings, rehabilitation exercise task characteristics, and the home-use context. Based on the translation process presented in the figure, six product-level functional requirements were extracted: movement perception and recognition, low-burden interaction cueing, PSE-based auditory feedback and execution guidance, minimalist design, multi-posture training adaptability, and safe support and protective contact. These requirements provide the functional basis for the subsequent FBS mapping.

4.2. Function–Behaviour–Structure Mapping

After the functional requirements were clarified, the next step was to translate these requirements into behavioural mechanisms and corresponding structural solutions. For this purpose, the Function–Behaviour–Structure (FBS) model was introduced to progressively map functional requirements into behavioural representations and structural components, thereby providing a systematic reference for subsequent design development, as shown in Figure 8.

The Function–Behaviour–Structure (FBS) model is a systematic design theory framework that decomposes complex design problems into three hierarchical levels: function, behaviour, and structure and emphasises the dynamic mapping relationships among them [34,35]. By analysing the functional requirements of a design object, the model supports the derivation of system behaviours from functional intentions and further identifies the structural configurations required to realise these behaviours [35]. Cascini et al. extended the FBS framework by incorporating user needs and contextual factors, enabling design decisions to be more directly grounded in user experience and usage context [36]. This perspective aligns with the present study, in which FBS mapping was grounded in user-derived requirements and home rehabilitation contexts identified through the preceding research process.

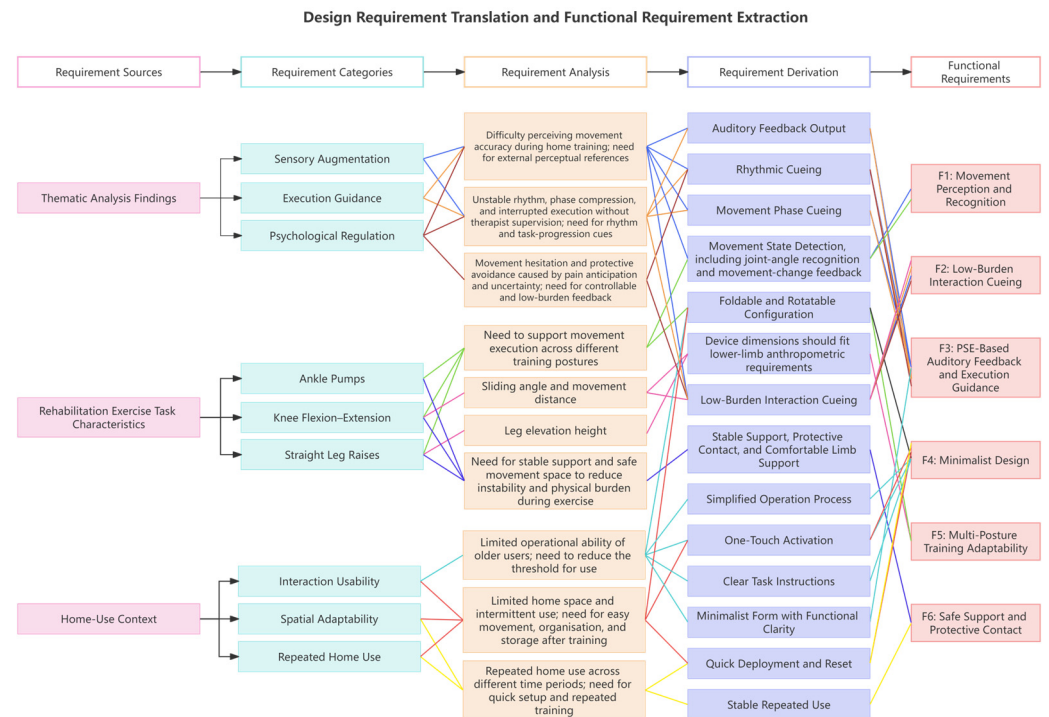


Figure 7. Design Requirement Translation and Functional Requirement Extraction. The colored lines are used to visually distinguish different requirement translation paths.

FBS Mapping for TKA Home Rehabilitation System

Function	Behaviour	Structure
F1: Movement Perception Recognition		
F1.1: External Perceptual Guidance	Map joint-angle changes to continuous pitch variation	S1 Camera + S2 Pose Module + S3 Processing Unit + S7 Speaker
F1.2: Movement State Awareness	Detect hip/knee/ankle landmarks	S1 Camera + S2 Pose Module + S3 Processing Unit
F1.3: Movement Change Feedback	Monitor motion/trajectory deviations	S3 Processing Unit + S4 Display Screen + S8 Guidance Light
F2: Low-Burden interaction Cueing		
F2.1 Simplified Operation	Enable one-touch start	S5 Start Button
F2.2 Clear Task Instructions	Display task-specific instructions	S4 Display Screen + S7 Speaker
F2.3 User Identification and Task Logging	Record user and task data	S6 QR Code Scanner + S3 Processing Unit
F3: PSE-Based Auditory Feedback and Execution Guidance		
F3.1 Rhythm-Based Temporal Cueing	Provide temporal pacing for movement cycles	S3 Processing Unit + S7 Speaker
F3.2 Pitch-Based Spatial Cueing	Represent joint-angle changes through pitch variation	S3 Processing Unit + S7 Speaker
F3.3 Movement Phase Cueing	Indicate movement phase transitions through auditory feedback	S3 Processing Unit + S7 Speaker + S8 Guidance Light
F3.4 Movement Confidence Support	Provide adaptive feedback to support movement confidence	S7 Speaker
F4: Minimalist Design		
F4.1 Functional Clarity	Simplify interface elements	S4 Display Screen + S5 Start Button
F4.2 Tactile-Visual Integration	Provide visual and tactile guidance cues	S8 Guidance Light + S12 Soft Fabric Aperture Interface
F4.3 Quick Deployment and Reset	Support quick setup and reset	S11 Base Platform + S13 Folding and Rotating Support
F5: Multi-Posture Training Adaptability		
F5.1 Foldable and Rotatable Configuration	Adjust training angle	S13 Folding and Rotating Support
F5.2 Lower-Limb Anthropometric Fit	Accommodate different lower-limb movement ranges	S9 Main Support Frame + S10 Protective Padding + S12 Soft Fabric Aperture Interface
F5.3 Multi-Task Movement Support	Support multiple exercises	S9 Main Support Frame + S11 Base Platform + S13 Folding and Rotating Support
F6: Safe Support and Protective Contact		
F6.1 Stable Limb Support	Maintain stable limb positioning during exercise	S9 Main Support Frame + S11 Base Platform
F6.2 Protective Contact	Absorb contact pressure	S10 Protective Padding + S12 Soft Fabric Aperture Interface
F6.3 Safe Movement Constraint	Guide movement within a safe exercise range	S9 Main Support Frame + S10 Protective Padding + S11 Base Platform

Figure 8. FBS mapping from rehabilitation function to physical system structure.

The function–behaviour mapping followed the logic of “functional intention → behavioural manifestation.” As shown in Figure 8, the identified functional requirements were translated into corresponding system behaviours, including mapping joint angles to

pitch, detecting lower-limb landmarks, monitoring movement changes, enabling one-touch start, providing task guidance, recording user and task data, providing rhythmic cues, representing angle changes, cueing phase transitions, providing controllable feedback, simplifying interface elements, displaying circular light cues, supporting quick setup and reset, adjusting training angles, supporting multiple exercises, providing stable support, absorbing contact pressure, and guiding a safe movement plane. These behaviours describe how the system responds to the design requirements at the interaction and operation levels.

The behaviour–structure mapping further translated these behaviours into implementable structural modules. Movement perception and recognition were mainly supported by the Camera Module (S1), Pose Module (S2), Processing Unit (S3), Speaker Module (S7), Display Screen (S4), and Guidance Light (S8). Low-burden interaction cueing was supported by the Start Button (S5), Display Screen (S4), Speaker Module (S7), QR Code Scanner (S6), and Processing Unit (S3). PSE-based auditory feedback and execution guidance were primarily realised through the Processing Unit (S3), Speaker Module (S7), and Guidance Light (S8). Minimalist interaction and quick deployment were supported by the Display Screen (S4), Start Button (S5), Guidance Light (S8), Soft Fabric Aperture Interface (S12), Base Platform (S11), and Folding and Rotating Support Structure (S13). Multi-posture adaptability and safe support were realised through the Main Support Frame (S9), Protective Padding (S10), Base Platform (S11), Soft Fabric Aperture Interface (S12), and Folding and Rotating Support Structure (S13).

After mapping functions to structures using the FBS framework, the corresponding key structural modules of the product are summarised in Table 5.

Table 5. Structural Components.

Serial	Structure	Function	Example
S1	Camera Module	Captures real-time motion data for lower-limb trajectory tracking.	
S2	Pose Module	Extracts skeletal landmarks and joint coordinates via AI algorithms.	
S3	Processing Unit	Computes knee joint angles and executes PSE cross-modal mapping rules.	
S4	Display Screen	Provides visual progress confirmation and rehabilitation performance analytics.	
S5	Start Button	Facilitates rapid system activation and one-touch simplified interaction.	
S6	QR Code Scanner	Enables user identification and automated rehabilitation data logging.	
S7	Speaker Module	Delivers real-time PSE auditory feedback (pitch, rhythm, and loudness).	
S8	Guidance Light	Provides visual scaffolding and cues for movement phase transitions.	

Table 5. Cont.

Serial	Structure	Function	Example
S9	Main Support Frame	Serves as the primary load-bearing structure for stable limb movement.	
S10	Protective Padding	Absorbs contact forces and ensures ergonomic comfort during exercise.	
S11	Base Platform	Provides a stable physical foundation for the home rehabilitation hub.	
S12	Soft Fabric Aperture Interface	Provides intuitive tactile-visual scaffolding via dynamic light ring	
S13	Folding and Rotating Support	Enables multi-posture adaptability for supine, seated, or standing training.	

4.3. Structural Configuration and Integration

Based on the FBS mapping results, the structural system of the TKA rehabilitation hub is categorised into four modules: Sensing and Intelligence (S1–S3), Interaction and Interface (S4–S6, S12), Feedback (S7, S8), and Physical Support and Execution (S9–S11, S13), as illustrated in Figure 9.

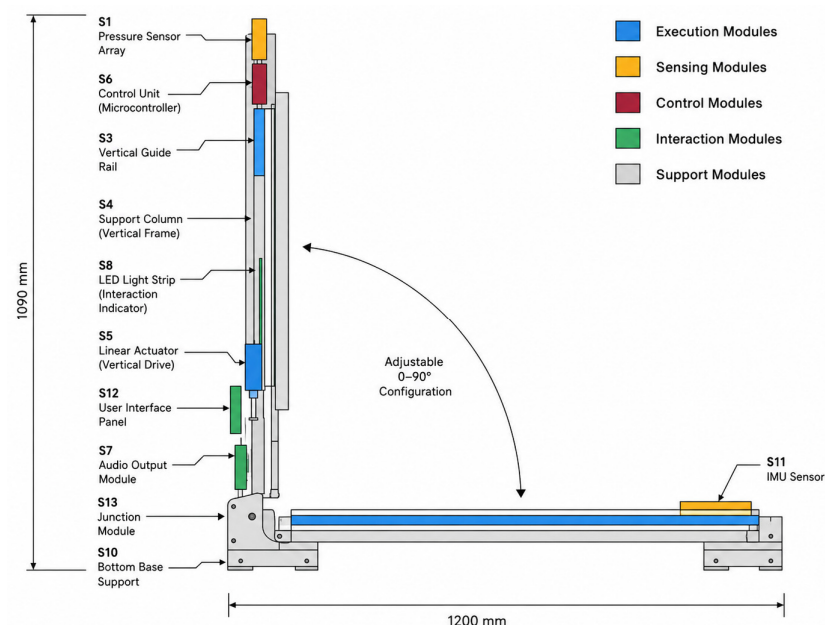


Figure 9. Basic functional structure module layout diagram.

The spatial layout is designed to support the “perception–execution” coordination requirements of home-based rehabilitation. The Sensing Modules (S1, S2) are mounted at the top of the vertical frame to ensure an unobstructed field of view for real-time skeletal landmark extraction. To support intuitive interaction for home users, the Soft Fabric Aperture Interface (S12) and Guidance Lights (S8) are integrated into the central panel, providing visual guidance through dynamic light rings.

Crucially, the system incorporates a Folding and Rotating Support Structure (S13) connected to the Main Support Frame (S9). This structural configuration allows the device

to transition between horizontal, angled, and vertical orientations to accommodate different training postures. The Base Platform (S11) and Protective Padding (S10) were designed to support structural stability and user comfort across these training postures, addressing the requirement for multi-posture adaptability in a home environment.

4.4. Design Alternatives and Design Evaluation

Based on the function, behaviour, and structure translation derived from the FBS framework, three conceptual alternatives for a home-based rehabilitation interaction device were developed, as shown in Figure 10. Alternative A, the Minimalist Flat-Panel Interaction Device, emphasises a simple structural form and basic interaction support. Alternative B, the Movable Home-Based Interaction Device, focuses on mobility and spatial adaptability in home environments. Alternative C, the Portable Flexible-Folding Interaction Device, emphasises multi-posture use, flexible physical interaction, and foldable storage. All three alternatives were developed around the home-based translation of the auditory–motor mapping mechanism, while differing in structural configuration, mode of use, and scenario adaptability.

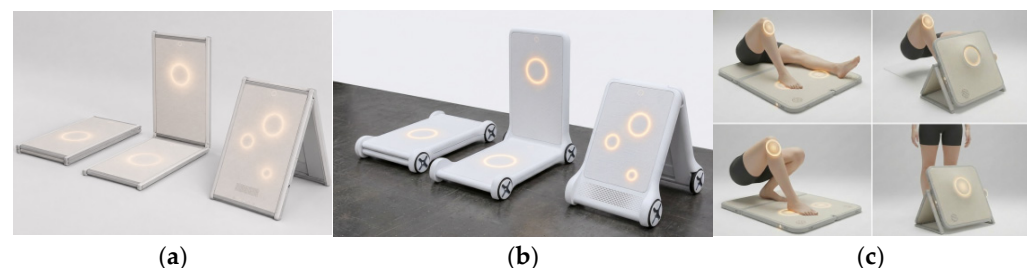


Figure 10. Three conceptual design alternatives. (a) Minimalist Flat-Panel Interaction. (b) Movable Home-Based Interaction Device. (c) Portable Flexible-Folding Interaction Device.

To provide a structured comparison among alternatives, a multi-criteria decision analysis (MCDA) was conducted. A total of 15 evaluators participated in the assessment, including 3 rehabilitation-related professionals, 7 design professionals, and 5 potential target users who had participated in the experimental phase. The evaluators reviewed the renderings, functional descriptions, and interaction workflows of each alternative and rated them using a five-point Likert scale, where 1 indicated very low suitability and 5 indicated very high suitability. The evaluation criteria consisted of five primary indicators and 13 secondary indicators, covering functional performance, interaction usability, ergonomics and safety, form and aesthetics, and storage and portability. For each secondary indicator, the mean score and 95% confidence interval were calculated. The evaluation results are presented in Table 6.

As shown in Table 6, Alternative C achieved the highest overall mean score (3.95), followed by Alternative B (3.68) and Alternative A (3.52). Alternative C showed relatively balanced evaluation results across the indicators, particularly in operation simplicity and control, ease of learning, and multi-posture adaptability. Therefore, Alternative C was selected as the basis for further conceptual refinement. However, this evaluation should be understood as a structured concept-selection process rather than validation of the final home-based rehabilitation device. Further physical prototyping, usability testing, safety assessment, and real-world home-use evaluation are required before the selected concept can be considered a validated rehabilitation product.

Table 6. Multi-criteria evaluation scores and 95% confidence intervals for design alternatives (scale: 1–5, $N = 15$).

Primary Indicator	Secondary Indicator	Alt. A Mean [95% CI]	Alt. B Mean [95% CI]	Alt. C Mean [95% CI]
Functional performance	Movement perception accuracy	4.50 [4.27, 4.73]	3.70 [3.38, 4.02]	4.00 [3.72, 4.28]
	Auditory feedback effectiveness	4.00 [3.72, 4.28]	3.90 [3.54, 4.26]	4.10 [3.83, 4.37]
	Movement guidance clarity	4.30 [4.03, 4.57]	3.60 [3.20, 4.00]	3.90 [3.60, 4.20]
Interaction usability	Operation simplicity and control	3.50 [3.08, 3.92]	3.20 [2.75, 3.65]	4.00 [3.71, 4.29]
	Interface readability	3.60 [3.22, 3.98]	3.50 [3.08, 3.92]	3.90 [3.56, 4.24]
	Ease of learning	3.40 [2.95, 3.85]	3.10 [2.61, 3.59]	4.00 [3.75, 4.25]
Ergonomics and safety	Multi-posture adaptability	2.80 [2.33, 3.27]	3.50 [3.12, 3.88]	4.30 [4.07, 4.53]
	Structural stability	4.30 [4.05, 4.55]	3.70 [3.37, 4.03]	3.90 [3.60, 4.20]
	Material comfort and tactility	3.10 [2.70, 3.50]	3.80 [3.50, 4.10]	4.00 [3.68, 4.32]
Form and aesthetics	Home environment integration	3.00 [2.51, 3.49]	4.40 [4.15, 4.65]	3.70 [3.34, 4.06]
	Visual affinity (non-medical)	2.90 [2.40, 3.40]	4.50 [4.27, 4.73]	3.80 [3.46, 4.14]
Storage and portability	Space efficiency in stored state	3.00 [2.47, 3.53]	3.40 [2.97, 3.83]	3.90 [3.61, 4.19]
	Moving convenience	3.40 [2.98, 3.82]	3.60 [3.22, 3.98]	3.80 [3.47, 4.13]
Overall mean score	-	3.52	3.68	3.95

5. Discussion

5.1. Theoretical Contributions

Building on existing research on home-based rehabilitation after total knee arthroplasty (TKA) and auditory feedback interaction, this study proposes a PSE-based auditory–motor mapping framework. The theoretical contributions of this framework are mainly reflected in two aspects.

First, this study extends PSE from its general application in music therapy and neurological rehabilitation to the interaction design of typical TKA rehabilitation movements. In previous studies, PSE has mainly been used to improve movement rhythm or enhance overall motor performance. However, its structured mapping mechanism at the level of specific rehabilitation movements remains insufficiently examined. This study further clarifies the relationships between joint-angle changes, movement phases, exertion-related movement features, and auditory parameters, including rhythm, pitch, and dynamics. In doing so, it establishes a cross-modal mapping pathway that can be translated into design practice, thereby addressing the gap between the theoretical effectiveness of PSE and its structured implementation in rehabilitation interaction design.

Second, this study extends the theoretical interpretation of the perception–execution gap in TKA home rehabilitation. Unlike traditional perspectives that primarily attribute this problem to proprioceptive decline or muscle weakness, the qualitative findings of this study suggest that the core issue lies in movement-regulation difficulties caused by the absence of an external perceptual structure. Specifically, the movement uncertainty, rhythmic instability, and kinesiophobia observed during rehabilitation reflect the lack of a stable external reference system for continuously organising and calibrating movement execution. Therefore, this study shifts the understanding of rehabilitation from a purely physiological execution problem to a perceptual-structure design problem.

5.2. Practical and Industrial Implications

The findings of this study provide actionable design implications for TKA home rehabilitation systems and general movement rehabilitation devices. The core implications can be summarised in four aspects.

First, this study extends the results of the experimental feasibility evaluation into design practice and provides a new research pathway for the early-stage design of rehabilitation interaction products. Through the Function–Behaviour–Structure (FBS) framework, the design requirements identified from user research and rehabilitation task analysis were translated into functional, behavioural, and structural elements for subsequent product design. Accordingly, the research process extends beyond interaction-mechanism exploration and forms a continuous design practice pathway from “user problem identification—cross-modal mapping construction—prototype-based feasibility evaluation—design requirement translation—FBS-based design translation—conceptual product generation”. This provides methodological support for the design research of TKA home rehabilitation systems and related movement rehabilitation devices.

Second, performance expectancy should be treated as an important objective in system design. The experimental results suggest that structured auditory feedback can provide an additional perceptual reference during movement execution and support users’ understanding of movement rhythm, joint-angle change, and phase transition. This indicates that users’ perceived improvement in movement controllability may serve as an important basis for system acceptance and continued use. Therefore, future rehabilitation devices should strengthen the perceivable support provided by real-time feedback for movement-execution quality.

Third, effort expectancy requires the system to maintain a low learning cost and a low operational burden. The findings suggest that structured auditory cues can support movement execution without increasing visual attentional demands. This indicates that, in home rehabilitation scenarios, simple, intuitive, and continuous feedback mechanisms may have greater practical value than complex interactive interfaces.

Fourth, task–technology fit is an important consideration for rehabilitation interaction design. The mapping analysis of ankle pumps, knee flexion–extension, and straight leg raises shows that different rehabilitation tasks require different feedback structures. Therefore, rehabilitation systems should construct modular mapping mechanisms based on movement types rather than adopting a uniform feedback rule.

5.3. Limitations and Future Research Directions

This study has several limitations that should be further verified and addressed in future research.

First, the proposed framework was not evaluated with actual post-TKA patients. Instead, participants with knee pain conditions were recruited to simulate TKA rehabilitation movement tasks. Therefore, the current findings primarily indicate the interaction feasibility of the auditory–motor mapping framework in simulated TKA rehabilitation movement scenarios. They should not be directly interpreted as evidence of clinical effectiveness in relation to postoperative functional recovery, pain reduction, or long-term rehabilitation adherence.

Second, this study focused only on short-term interaction responses and did not examine key variables in the long-term rehabilitation process, such as motor learning retention, functional recovery trajectories, changes in training adherence, or the long-term evolution of pain. Accordingly, the findings should be understood as task-level interaction feasibility evaluation rather than evidence of clinical rehabilitation effectiveness.

Third, the camera-based motion capture and feedback system still has technical limitations in real home environments. Factors such as lighting variation, body-joint occlusion, unstable movement speed, and individual anatomical differences may affect the stability of joint-angle estimation and the consistency of auditory feedback. Therefore, future work should incorporate adaptive calibration mechanisms and latency compensation strategies to improve system stability.

Fourth, the subjective questionnaire was developed for this preliminary feasibility study and should be interpreted as a study-specific measure of short-term perceived interaction experience rather than a validated clinical rehabilitation scale. Reliability testing was not conducted because each dimension was assessed using a single item. Future studies involving actual post-TKA patients should include validated clinical and rehabilitation questionnaires to assess long-term outcomes more rigorously.

Finally, this study did not fully account for individual differences, including auditory perceptual ability, cognitive characteristics, and rehabilitation-stage-specific needs. As a result, the current model remains a unified mapping mechanism rather than a personalised feedback system. Future research should therefore further develop personalised and adaptive auditory feedback strategies.

Future work should focus on three main directions: (1) evaluating the framework with actual post-TKA patients; (2) conducting longitudinal studies to evaluate functional recovery and rehabilitation adherence; and (3) developing personalised and adaptive auditory mapping mechanisms to improve the applicability and stability of the system in real home rehabilitation environments.

6. Conclusions

This study addressed the perception–execution disconnection in home-based rehabilitation after total knee arthroplasty (TKA). Patterned Sensory Enhancement (PSE) was introduced as a structured auditory–motor mapping mechanism, through which joint-angle changes, movement phases, and exertion-related movement features were translated into pitch, rhythm, and loudness cues. The aim was to examine the interaction feasibility of auditory feedback in simulated TKA rehabilitation movement scenarios.

A web-based functional prototype was developed, and a within-subject controlled experiment was conducted with participants with knee pain conditions who simulated typical TKA rehabilitation movement tasks. The results suggest that structured auditory cues can provide an additional perceptual reference during movement execution and may support users' understanding of movement rhythm, joint-angle changes, and phase transitions.

At the level of design translation, this study further employed the Function–Behaviour–Structure (FBS) framework to transform the design requirements identified from user research, the PSE-based auditory–motor mapping mechanism, and the findings from the prototype feasibility experiment into functional, behavioural, and structural elements for rehabilitation interaction product design. Accordingly, this study forms a continuous design practice pathway from user problem identification, cross-modal mapping construction, and prototype-based feasibility evaluation to design requirement translation, FBS-based design translation, and conceptual product generation. This pathway provides methodological support for early-stage design research on TKA home rehabilitation systems and related movement rehabilitation devices.

It should be noted that the findings of this study represent early-stage interaction feasibility evidence rather than evidence of clinical rehabilitation effectiveness. Future research should involve actual post-TKA patients, real home-based rehabilitation environments, and long-term follow-up evaluation to assess the applicability and stability of the proposed framework in practical rehabilitation processes.

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Institutional Review Board Statement: This study was exempt from ethical review in accordance with Article 32 of the Measures for Ethical Review of Life Science and Medical Research Involving Humans (National Health Commission of China, 2023, https://www.gov.cn/zhengce/zhengceku/2023-02/28/content_5743658.htm (accessed on 12 February 2026)), which permits exemption for studies using anonymized data that pose no harm to participants and involve no sensitive personal information. The study was a non-interventional, minimal-risk feasibility evaluation conducted in a simulated rehabilitation movement scenario. It did not involve clinical procedures, medical treatments, therapeutic interventions, medication, biological sample collection, invasive measurements, or changes to participants' standard medical care. Participants were only involved in non-participatory observation, semi-structured interviews, camera-based movement recording, interaction with a web-based prototype, and subjective questionnaires. All participant data were anonymized prior to analysis, and no personally identifiable information or sensitive medical records were collected or retained. Data were limited to anonymized interview and questionnaire responses and kinematic measurements derived from camera-based pose estimation. The study posed no foreseeable risks to participants and was conducted in accordance with the ethical principles of the Declaration of Helsinki.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data supporting the reported results in this study are available upon request from the corresponding author.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

TKA	Total Knee Arthroplasty
PSE	Patterned Sensory Enhancement
NMT	Neurologic Music Therapy
FBS	Function-Behaviour-Structure
HCI	Human-Computer Interaction
ROM	Range of Motion
SLR	Straight Leg Raise
VR	Virtual Reality
XR	Extended Reality
AR	Augmented Reality
MR	Mixed Reality
MCDA	Multi-Criteria Decision Analysis
SD	Standard Deviation
CI	Confidence Interval
AAOS	American Academy of Orthopaedic Surgeons
CSV	Comma-Separated Values
SPSS	Statistical Package for the Social Sciences

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