Smart Music Therapist 1.0: Rhythmic Auditory Stimulation Integrated Robotic Walker as a Therapeutic Companion for Gait Rehabilitation

Vithanage T. V. R. H.[1], Senaratne N. A. A. N. R.[1], Welangalle P. D.[1], Amarasinghe Y. W. R.[1], Jayathilaka W. A. D. M.[1], and Jayawardane M. A. M. M.[2]

***Abstract*— This study investigates the development of a robotic walker for gait rehabilitation that integrates social assistive robotics and principles of Rhythmic Auditory Stimulation (RAS), a form of music therapy. The robotic system is intended to supplement, rather than replace, the work of professional music therapists by enabling therapeutic interventions to continue outside of therapy sessions. Robot-facilitated Music Therapy is an evolutionary step of telerehabilitation, providing patients with greater autonomy while still benefiting from the expertise and guidance of therapists. Contributions of the research include 1) Robot-facilitated Music Therapy through a robotic walker as a platform for gait rehabilitation. 2) Remote Music Therapy through a robotic walker as a telerehabilitation platform for music therapists to remotely monitor and consult with patients. 3) Intelligent companionship integrated with a robotic walker for comprehensive user assistance. The proposed system, tested for its functionalities including personified RAS, social interaction, user monitoring, mobility control, and emergency response yielded promising results for real-world application.**

I. INTRODUCTION

Neurological Music Therapy (NMT) has been instrumental in offering therapeutic benefits through techniques like Rhythmic Auditory Stimulation (RAS) for gait rehabilitation of individuals with neurological impairments [1]. RAS leverages the rhythmic entrainment effect, where external auditory cues synchronize with motor patterns, to improve gait parameters such as walking speed, cadence, and stride length [2].

The integration of robotics with music therapy is an emerging area in the field of assistive technology. Research demonstrates the potential for human-robot interaction to accelerate rehabilitation in populations such as individuals with cognitive impairments [3] and autism spectrum disorder [4]. While studies explore RAS combined with smartphone-based systems [5] and exoskeletons [6] for gait rehabilitation, its integration with robotic walkers remains largely unexplored.

Telerehabilitation has been found to be as effective as, if not more than, in-person rehabilitation or standard care [7]. For instance, a social robotic platform has been successfully employed for gait therapy during the pandemic [8]. The COVID-19 pandemic has further accelerated the adoption of remote healthcare models, including telehealth for remote music therapy [9]. This shift highlights the potential for intelligent systems capable of performing music therapy for gait rehabilitation, even in underprivileged communities that lack access to or knowledge of music therapy.

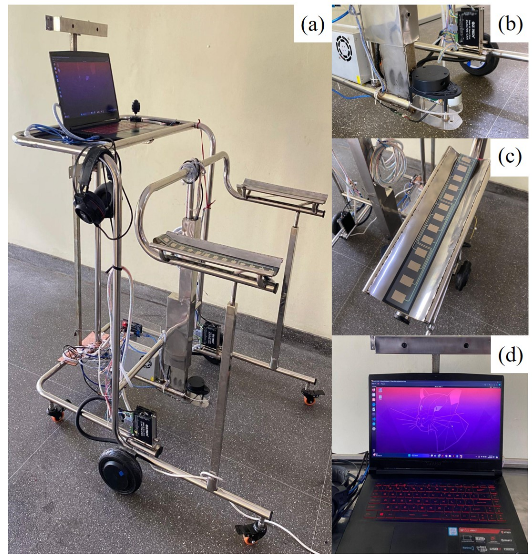

Fig. 1. (a) Robotic Walker platform (b) LiDAR sensor (c) Armrest with force-sensitive resistors (d) Graphical user interface and camera

Our research, therefore, aims to explore the development of a robotic walker (developed prototype in Fig. 1) for gait rehabilitation that integrates socially assistive robotics and principles of music therapy, specifically RAS. We envision robot-facilitated music therapy as an evolutionary step beyond telerehabilitation, offering increased autonomy while ensuring the guidance of expert therapists. This research has potential to make robot-facilitated gait rehabilitation more accessible and effective across diverse communities.

II. METHODOLOGY

A. System Overview

In developing a robotic walker for intelligent companionship, a focus on both therapeutic assistance and social support is necessary for optimal patient outcomes. This directed us to take a multi-functional approach as depicted in Fig. 2 to achieve intelligent human-robot interaction. Each function plays a vital role in providing patients with comprehensive assistance.

B. Remote and Robot-facilitated Music Therapy

Our platform offers both remote music therapy and robot-facilitated music therapy. Remote Music Therapy is where a

*This work was not supported by any organization
[1]Department of Mechanical Engineering, University of Moratuwa, Sri Lanka. (vithanagetvrh.19, senaratnenaanr.19, welangallepd.19, ranama, dumithj)@uom.lk
[2]Department of Obstetrics and Gynaecology, University of Sri Jayawardenapura, Sri Lanka. madurammj@yahoo.com

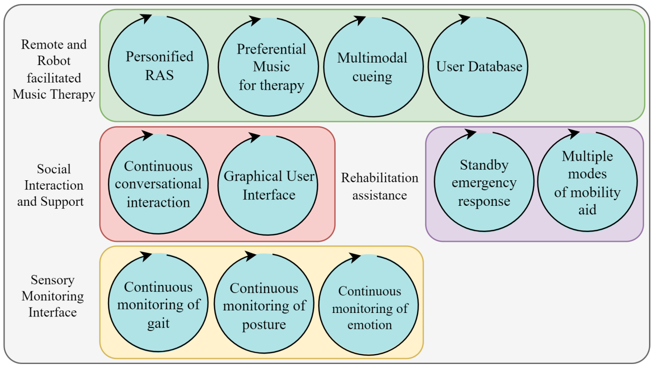

Fig. 2. Functionalities of the smart music therapist

qualified music therapist conducts therapy sessions virtually, providing real-time guidance tailored to the user's condition. Robot-facilitated music therapy utilizes the intelligence of the robotic system to deliver therapy sessions. The platform can also be used by therapists to design customized therapy plans for patients to follow independently, providing greater autonomy to the user. All functionalities of the walker that follow this section are integrated into both remote and robot-facilitated allowing music therapists to surpass the limitations of conventional telerehabilitation.

In the implementation of this system, however, it is important to note that the presence of a caretaker is mandatory during all therapy sessions. This aligns with telerehabilitation best practices for physical therapy goals which emphasize caregiver support for safety and effectiveness [10]. The same applies to robot-facilitated music therapy since walkers carry an inherent fall risk. The proposed solution prioritizes the specialized expertise of music therapists while acknowledging the importance of caregiver presence for standby support.

1) Personified RAS: The system generates personalized cues for RAS to provide tailored physical assistance. The algorithm given by Fig. 3 is used for this purpose. An initial gait assessment is carried out for new users and those returning after a significant period. The gait assessment determines a comfortable walking cadence quantified by steps per minute (spm), interchangeable with beats per minute (bpm) in this context. A therapy session comprises cycles. The length of a cycle, defined in terms of time or distance walked, is determined by the user at the start of a therapy session.

The assessed cadence will be the control input to tailor personalized RAS. At the beginning of each cycle, users are prompted to increment the bpm of the cue if their cadence is improving, thereby encouraging faster strides. If cadence is not improving they have the option to decrement bpm. The rhythmic shift, bpm_{shift}, is a system-recommended value personalized to the user. Before gait training a qualified music therapist verifies this value to ensure safety. For first-time users, the value will be approximated considering factors such as age, condition, and range of spm variation in the initial assessment. For returning users with more data available, a better recommendation can be made using the variation of gait data with applied bpm_{shift} in previous sessions. As shown in Fig. 3 we introduce another variable k in the range of (0, 0.1), to define the threshold for allowable deviation between the bpm of rhythmic cue and measured cadence. Although we are using ±5 to 10% increment for this purpose, as commonly suggested by literature [2], a larger dataset is required to accurately infer both bpm_{shift} and k with the help of machine learning.

2) Preferential Music for therapy: Music that is both high in groove and familiarity has been found to enhance the effectiveness of RAS for gait rehabilitation. [11] Groove in music refers to the ability of music to induce movement or the degree to which the music compels a person to move. To supplement personified RAS, a music filtering algorithm was developed as a part of our intelligent setup, shown in Fig. 3. The groove (danceability) value of a selected set of music was analyzed using [12] and then were categorized as low-groove music and high-groove music using a suitable threshold.

Further, this system enabled us to create a continuous bpm range (no missing whole number bpm values within the range) for rhythmic cueing using only a limited number of music tracks, which otherwise would require a large collection of music tracks. This was achieved through two methods. Firstly, embedding metronomic cues to improve the beat salience of low groove music as done in [13] expanded the available amount of music tracks. Secondly, shifting the tempo of music (within a recommended range for a specific track) to match the exact bpm of the user allowed for coverage of a significant bpm range with limited music tracks. The adjustable bpm range for each musical track is known prior by the system. The music used can range from metronomic beats to songs with vocals and instrumental music.

3) Multimodal cueing: Given that the system is applicable for diverse gait-related conditions, we have incorporated multiple modalities for cueing, allowing users to select cueing combinations that suit individual needs. Visual cueing is an inbuilt feature of the Graphical User Interface (discussed later) that displays rhythmic cues on screen in the form of blinking footsteps, with the corresponding foot on the screen blinking at the time of the cue. In auditory cueing, headphones or speakers can be used. In situations where using headphones might interfere with communication with the caretaker or affect the sensory awareness of other senses, speakers are recommended. In haptic cueing, haptic wearables are worn on each leg near the ankle as implemented in [14]. It was verified that the localized vibrations had no effect on the IMU sensors. Through voice interaction, users can adjust the intensity of the cue provided to ensure it is not too uncomfortable or obtrusive.

C. Social Interaction and Support

1) Conversational interaction: Verbal feedback and interaction are increasingly being integrated with gait rehabilitation devices [15]. In our case, we executed a rule-based conversational interface that responds according to

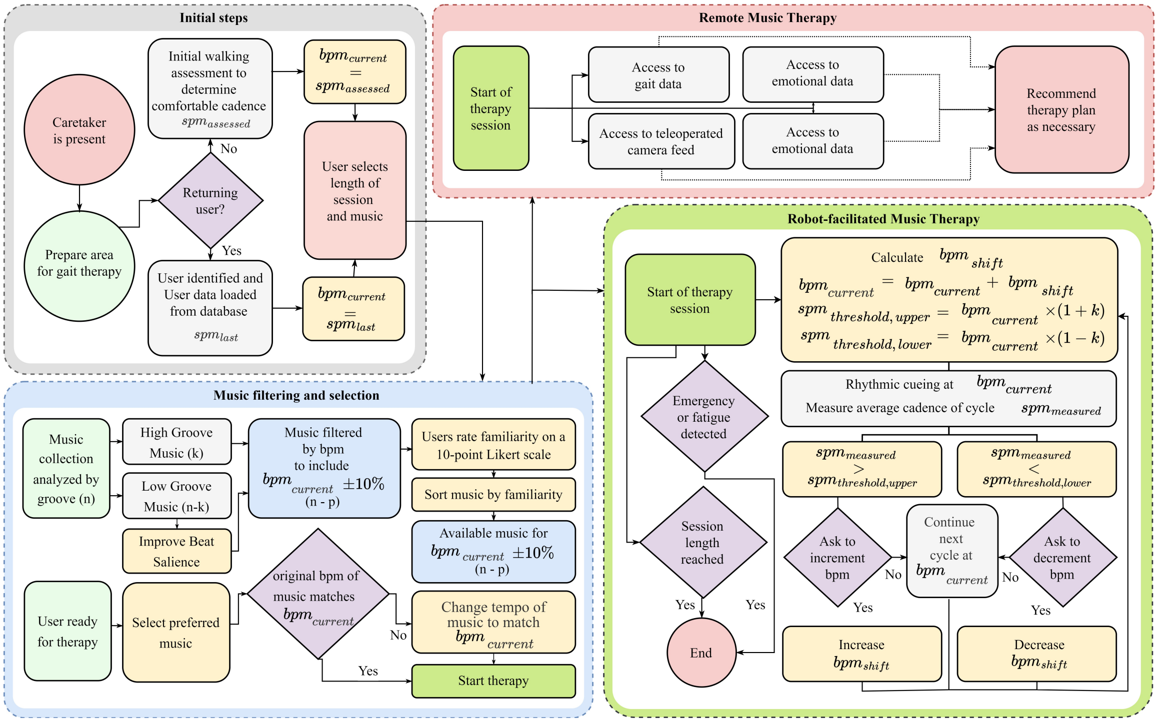

Fig. 3. Personified RAS through Robot-facilitated Music Therapy and Remote Music Therapy with music filtering algorithm

the instances recognized by the user monitoring system. Table 1 provides examples of verbal interaction between the walker and the user in different instances. Our setup uses a ReSpeaker USB Mic Array [16] to perform source separation and echo cancellation first which is crucial in a noisy or crowded environment. Audio inquiries are transformed into text inquiries using the Google Cloud API. These text inquiries are then sent to an agent located on the Dialogflow cloud platform, where Natural Language Understanding (NLU) is performed. The result from the NLU module undergoes a text-to-speech conversion process using the Pyttsx3 Python package.

2) Graphical User Interface (GUI): Our system features two distinct Graphical User Interfaces (GUIs) - one for the user and another for the therapist. The user-facing GUI offers functionalities that allow users to select their preferred music and observe visual rhythmic cues. Both the user-facing and therapist-facing GUIs serve as dashboards to visualize analyzed gait parameters. In addition to displaying gait data, the therapist-facing GUI includes a built-in remote control feature to manage the teleoperated camera on the walker. The development of these GUIs was accomplished using the Python Tkinter library.

TABLE I

EXAMPLES FOR VERBAL INTERACTION AT DIFFERENT INSTANCES

Instance	Verbal Interaction (as an example)
Greeting	Good morning name, how are you today?
Encouragement	You are doing a wonderful job today. Keep going.
Cue bpm check	The music seems a bit too fast (or slow), shall I slow it down (fasten it up) a bit?
Fatigue Detection	You seem a little tired. Shall we pause for a bit?
Queries on Gait Performance	You have great improvement in your cadence from the last session.
General Talk	Did you know Oasis' song 'All Around the World' is the longest song ever to reach number one on the UK Singles Chart?

D. Sensory Monitoring Interface

1) Monitoring of gait: Our platform can analyze gait data to quantify the progress of gait rehabilitation. This aids the remotely-present music therapist and the user to have an overview of their gait performance. A user-facing LiDAR (Light Detection and Ranging) sensor and user-worn Inertial Measurement Units (IMUs) were utilized for spatial and temporal gait data collection. The LiDAR sensor detects the position of the legs by modeling each leg as a cylinder. The peak points of each shin is obtained.

Recent literature [17] suggests the optimal locations for mounting IMU are the shank and the foot which we have implemented. Post-processing was required to extract meaningful information from the two sensors. We analyze the temporal parameters cadence, gait events, gait phases, step time, stride time, and swing/stance time by the IMU and the spatial parameters step length, stride length, and step width by the LiDAR sensor.

2) Monitoring of emotion: To implement intelligent companionship the ability to detect and act upon user emotions is crucial. Conditions like Parkinson's Disease are intricately linked with mood disorders, including depression, anxiety, and bipolar disorders. [18] Social isolation and anxiety can also affect the life of such individuals. Thus, utilizing the

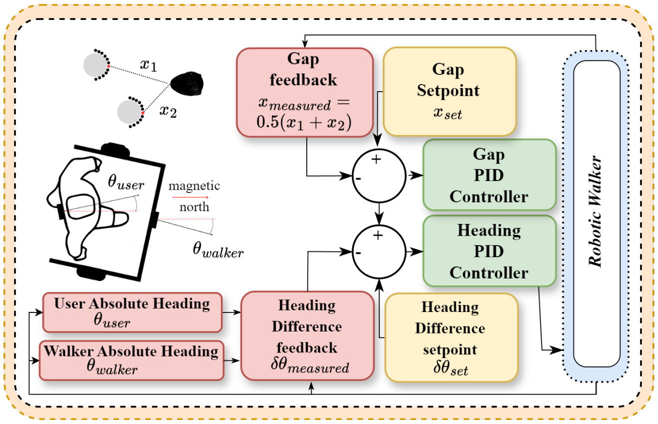

Fig. 4. Cascaded PID Controller

user-facing camera we run a facial emotion recognition algorithm using the Deepface library [19], to track the user's emotional state.

Emotion recognition of senior adults proves to be challenging compared to younger adults [20] The existing classes in the Deepface library include 'angry', 'disgust', 'fear', 'happy', 'sad', 'surprise', and 'neutral'. To mitigate the shortcomings in adult emotion recognition, we have created a superset for emotion classification as 'Positive', 'Neutral', and 'Negative'. 'Positive' encompasses 'happy' and sad' while 'Negative' includes 'angry', 'disgust', 'fear', and 'sad'. The response for fatigue detection, broadly classified as a 'Negative' emotion, is covered under respective sections in mobility state transition and conversational interaction.

3) Monitoring of posture: Since we employ a front-following mode of walker support (later described) where the user has no contact with the walker but tracks the user's movement to follow in proximity, it is essential to have a mechanism to detect instances of emergency. This was achieved using the Mediapipe library which is capable of real-time human pose estimation. [21] Although user-worn IMUs are available in our walker system, IMUs only detect a fall once it has occurred. Our requirement, however, is a system that can prevent falls and detect fatigue by analyzing the user's posture.

This was implemented using only two classes of classification 'No emergency', and 'Emergency'. By the extracted human landmarks the linear distances between each shoulder and the hip landmark on the respective side of the body are calculated. An emergency is declared if the lesser of the two values falls below a preset threshold.

4) User Database: Google Firebase serves as our real-time cloud storage database housing all the user data including biographical data, facial data, gait data, therapy history, and fall risk ratings. To ensure privacy protection, access to this data can be restricted based on different user authorization levels.

E. Walking rehabilitation assistance

The walker provides mobility aid in two modes. In the supported mode, the user leans on the walker to support their body weight. In contrast, the unsupported mode allows for hands-free walking, with no physical contact between the user and the walker. The walker follows the user's intended path at a close distance, minimizing obstruction to the user's gait. In the event of imbalance or fatigue during unsupported mode, the user can rely on the walker for emergency support. It has been observed that walkers can influence the natural (unassisted) gait [22]. This can be attributed to the walker acting as a payload to be pushed, thereby affecting the gait dynamics compared to normal walking. If the user progresses to a point where they can walk without external assistance (i.e., walker, rollator, etc.) they can still be aided by the unsupported mode of our walker acting as a fall-preventive companion.

1) Multiple modes of mobility aid: Several methods can be found in recent literature to realize robust human-front-following for robots. For instance, [23] uses a single Laser Range Finder (LRF) sensor to perform human following. Notably, one of the functionalities of our walker is estimating spatio-temporal gait parameters using LiDAR and IMU sensors. Thus, the same combination can be utilized for this control function. Inspiration drawn from [24] and [25] has been used to build the control logic of our robotic walker.

The Control Logic is the same for both supported and unsupported modes. As shown in Fig. 4 a Cascading Proportional-Derivative-Integral (PID) controller is implemented. The absolute heading (orientation) of the walker and the absolute heading of the user are obtained using an absolute orientation sensor by a method of dead reckoning [26] through an extended Kalman filter based on quaternion. The difference between two heading values is calculated which must asymptotically converge to zero to maintain the same orientation. Simultaneously, measurements taken from the LiDAR sensor monitor the shank position in real-time, and the peak values corresponding to each leg (Fig. 4) are obtained. The average of these two values is interpreted as the gap between the user and the walker. Error calculation is done between the predetermined setpoints for gap and heading difference and control adjustments are carried out through the PID control loop.

$$x_e = x_{set} - x_{measured} \quad (1)$$

$$\gamma(n) = K_{px} x_e(n) + K_{ix} \sum_{k=0}^{n} x_e(k) + K_{dx}[x_e(n) - x_e(n-1)] \quad (2)$$

x_{set} is the preset gap between the user and the walker. x_{measured} is the measured actual gap. x_e is the gap error. γ is the output of the gap PID controller. K_{px}, K_{ix}, and K_{dx} are the proportional, integral, and derivative components of the gap PID controller, respectively.

$$\delta\theta_{measured} = |\theta_{walker} - \theta_{user}| \quad (3)$$

$$\delta\theta_e = \delta\theta_{set} - \delta\theta_{measured} \quad (4)$$

$$\alpha(n) = \delta\theta_e(n) + \gamma(n) \quad (5)$$

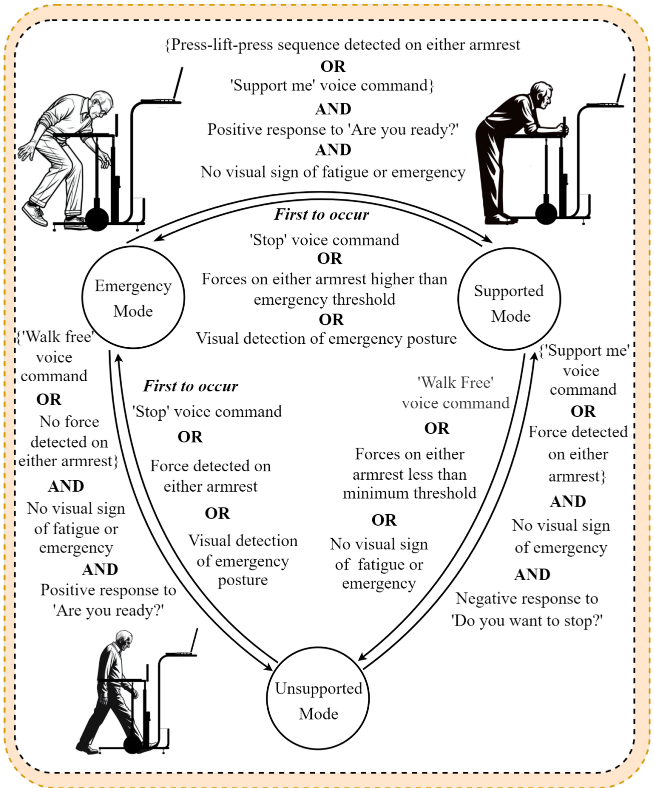

Fig. 5. Transition conditions for Finite State Machine (FSM) Model

$$v(n) = K_{px}\alpha(n) + K_{ix}\sum_{k=0}^{n}\alpha(k) + K_{dx}[\alpha(n) - \alpha(n-1)] \quad (6)$$

θ_{user} and θ_{walker} denote the absolute heading of the user and walker, respectively, while $\delta\theta_{\text{measured}}$ denotes their difference. $\delta\theta_{\text{set}}$ is the preset heading difference, and $\delta\theta_e$ is the heading error. α is the overall angle error. $K_{p\alpha}$, $K_{i\alpha}$, and $K_{d\alpha}$ are the proportional, integral, and derivative components of the heading PID controller, respectively, and v is the velocity output.

2) Standby emergency response: Emergency response is required at instances when the detection obtained through visual, inertial, or force-sensitive sensors exceeds a set emergency threshold. The response is not straightforward since the walker can be in any state (supported or unsupported) when an emergency event occurs. Given the multiple sensor modalities, responses for each on-off combination need to be considered, taking redundancy into account. To meet these requirements, we implement a finite-state machine (FSM) model (Fig. 5) to manage the transition condition between each state. This provides a responsive reaction with a minimal time gap between detection and response. Upon detecting an emergency, the walker will apply brakes, come to a stop, and simultaneously alert the caretaker.

F. Hardware

The robotic walker platform has been purposefully designed considering structural rigidity, interactive interface, user mobility intention, and emergency detection. The structure of the prototype used in this study was fabricated using stainless-steel tubes. Compliance with ISO safety standard requirements was tested.

Differential drive is selected over holonomic drive given that lateral (sideways) movement of walker user happens seldom. High-level control is done on a laptop running the Robot Operating System (ROS) while low-level control is handled by an Arduino Mega microcontroller. Brushless DC hub motors (ZLTECH ZLLG65ASM250-4096, ShenZhen ZhongLing Technology Co., Ltd, China) are used which in addition to meeting the power and torque requirements, give the ability to freewheel enabling the user to do corrections to the position or the orientation of the walker when not powered. A 2D LiDAR sensor (RPLIDAR A1, SLAMTEC Co., Ltd, China) has been placed on the walker facing the user for mobility control and gait data acquisition.

Since it is needed to implement walking intention detection for mobility control while simultaneously collecting gait data, from possible sensor combinations [23] the LiDAR and IMU combination proved to be the optimal one. In addition to the set of sensors mounted on the walker, our system features Inertial Measurement Units (IMU) worn by the user. Gait data and heading orientation data are obtained by these portable devices placed at key locations of the body. For heading orientation BNO055 absolute orientation sensor is used while MPU-6050 is used for gait monitoring. Portable, wearable data logger units are made using ESP-WROOM-32 module along with each IMU.

A force-sensitive resistor (FSR) matrix is placed on each armrest to detect instances of emergency. A wearable haptic feedback device made from Micro-vibration motors is used for haptic rhythmic cueing. To facilitate remote therapy and user monitoring multi-degree-of-freedom camera is designed which can perform pan, tilt, and up-and-down linear motion. This provides multiple viewing angles for remote therapy and to observe both the upper body and lower body which would otherwise be difficult for a static camera with a narrow field of view.

G. EXPERIMENTAL SETUP

A pilot study was conducted with five healthy subjects in the age range of 25 ± 1.6 years. Prior to experimentation. written consent was obtained from each participant. All data were gathered in a way that maintained the anonymity of the participants. An 8-camera Simi-Reality Motion capture system served as the ground truth while data were recorded by LiDAR and IMU for post-processing. An oblong-shaped track was used for the evaluation of overall user movement patterns during interaction with the robotic setup.

In the motion capture area, the stainless steel structure of the walker prototype gave false readings due to the reflections of the active illumination interfering with sensor readings. A mobile robotic platform in Fig. 6 was used in lieu, with the same sensor arrangement and relative positions of sensors and motors. Reflective markers were placed on specific anatomical landmarks of the user and key positions of the mobile robot to ensure accurate tracking by the motion capture system. The study investigated the accuracy of the

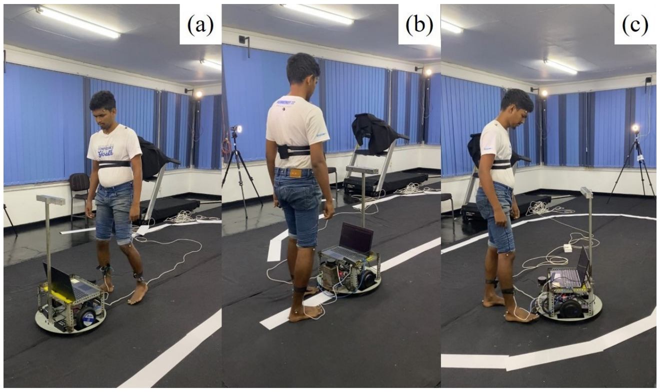

Fig. 6. Experimentation done using the mobile robotic platform (a) Walking straight on the guided path (b) Walking straight on the unguided path (c) Turning on the guided path

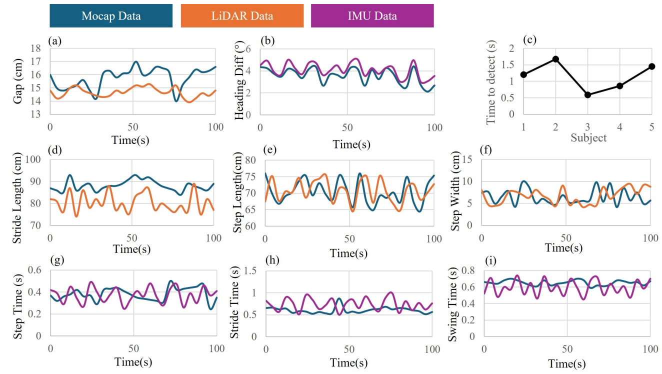

Fig. 7. Time variance of (a) Gap between user and walker (b) Heading difference (d) Stride length (e) Step length (f) Step width (f) Step time (g) Stride time (i) Swing time. (c) shows the time to detect an emergency.

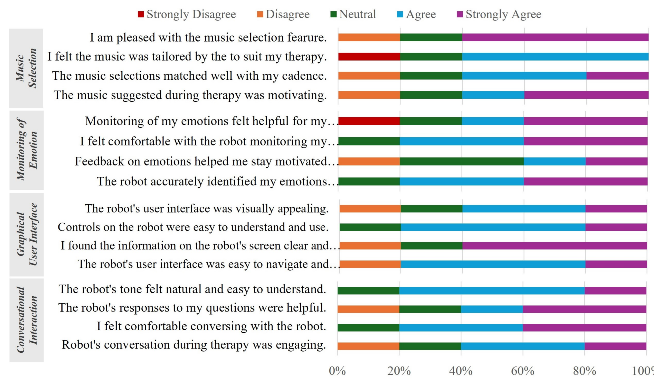

Fig. 8. User opinion on socially assistive features

supported and unsupported modes of mobility aid and determined the feasibility of using LiDAR and IMU sensors to track gait parameters. User opinions on the socially assistive features were collected using a 5-point Likert scale.

III. RESULTS

Time variation of recorded data is given by Fig. 7. The Root Mean Square Error (RMSE) and Pearson Correlation between the ground truth (Motion Capture Data) and sensor data (LiDAR/IMU) are presented in Table 2. The results show good agreement with the ground truth for the experimental criteria. The criteria include control parameters (gap between robot and human, angle between robot and human, emergency response), spatial gait parameters (step length, stride length, step width), and temporal gait parameters (step time, stride time, swing time). These results suggest that LiDAR and IMU sensors are promising alternatives to motion capture for gait analysis during robotic walker use. A majority of acceptance of the functionalities of the walker is seen on the Likert scale (Fig. 8).

This preliminary study did not assess the impact of Rhythmic Auditory Stimulation (RAS) on gait rehabilitation performance, as it solely involved healthy subjects to validate the concept. The next phase of our research will include healthy subjects with induced gait abnormalities, providing valuable insights into the system's capacity to manage deviations from normal gait patterns. Future studies should encompass a larger and more diverse group to generalize these findings to the target population, thereby establishing the system's effectiveness in real-world rehabilitation scenarios.

TABLE II

EXPERIMENTAL RESULTS IN COMPARISON TO THE GROUND TRUTH

Type	Criteria	RMSE (Mean ± SD)	Pearson Correlation (Mean ± SD)
Mobility Control	Gap between walker & user(m)	6.78 ± 2.4	0.73 ± 0.03
	Heading Difference(°)	1.32 ± 0.43	0.24 ± 0.06
Gait Analysis (Spatial)	Stride length (m)	0.08 ± 0.02	0.87 ± 0.02
	Step length (m)	0.04 ± 0.02	0.77 ± 0.03
	Step width (m)	0.02 ± 0.03	0.75 ± 0.02
Gait Analysis (Temporal)	Stride Time (s)	0.04 ± 0.01	0.66 ± 0.07
	Step time (s)	0.02 ± 0.01	0.42 ± 0.04
	Swing time (s)	0.02 ± 0.01	0.53 ± 0.08

The current study focused on monitoring gait, posture, and emotions to track the user's physical and mental state. Future enhancements to the walker could enable the collection of additional user data, such as brain and heart activity, to provide a more comprehensive picture. If all this information could be processed and visualized in real-time, the insights derived would be even more valuable.

Longitudinal studies are crucial to understanding user acceptance, adaptation, and the role of robotic walkers in promoting independent living. These studies should investigate how user demographics, including age, gender, and type of disability, influence rehabilitation progress and user experience.

IV. CONCLUSION

This study establishes the successful development of the initial version of an intelligent robotic walker for gait rehabilitation. The walker uniquely integrates social assistive robotics and Rhythmic Auditory Stimulation (RAS) based music therapy principles. The challenge of limited access to music therapists is addressed by developing a platform equipped with user monitoring and interface technologies enabling both robot-facilitated therapy and remote therapy. The preliminary study, conducted with healthy subjects, demonstrated satisfactory system performance. The analysis of motion capture data (considered as the ground truth) against data from LiDAR and IMU sensors shows a good correlation indicating the system's effectiveness in user monitoring, mobility control, and emergency response. User opinions on the system's social interaction capabilities such as personified RAS, social interaction had a majority of acceptance but highlighted some areas for improvement. While limitations like sample size necessitate further research, this initial success demonstrates the potential to create a system that can deliver RAS therapy beyond therapist-supervised sessions, thereby providing access to effective gait rehabilitation.

References

[1] J. Rusowicz, J. Szczepańska-Gieracha, and P. Kiper, "Neurologic music therapy in geriatric rehabilitation: A systematic review," *Healthcare*, vol. 10, no. 11, 2022.

[2] S. Scataglini, Z. Van Dyck, V. Declercq, G. Van Cleemput, N. Struyf, and S. Truijen, "Effect of music based therapy rhythmic auditory stimulation (ras) using wearable device in rehabilitation of neurological patients: A systematic review," *Sensors*, vol. 23, no. 13, 2023.

[3] J. Hussain, A. Mangiacotti, F. Franco, and E. Chinellato, "Robotic music therapy assistant: A cognitive game playing robot," in *Social Robotics* (A. A. Ali, J.-J. Cabibihan, N. Meskin, S. Rossi, W. Jiang, H. He, and S. S. Ge, eds.), (Singapore), pp. 81–94, Springer Nature Singapore, 2024.

[4] H. Feng, M. H. Mahoor, and F. Dino, "A music-therapy robotic platform for children with autism: A pilot study," *Frontiers in Robotics and AI*, vol. 9, 2022.

[5] H.-Y. Lee, B.-W. Ko, W.-K. Song, H. Kim, and J.-H. Shin, "Rhythmic auditory stimulation for robot-assisted gait rehabilitation: A preliminary study," in *2015 IEEE International Conference on Advanced Intelligent Mechatronics (AIM)*, pp. 422–426, 2015.

[6] R. M. S. Yap, K.-i. Ogawa, Y. Hirobe, T. Nagashima, M. Seki, M. Nakayama, K. Ichiryu, and Y. Miyake, "Gait-assist wearable robot using interactive rhythmic stimulation to the upper limbs," *Frontiers in Robotics and AI*, vol. 6, 2019.

[7] D. H. Langbecker, L. Caffery, M. Taylor, D. Theodoros, and A. C. Smith, "Impact of school-based allied health therapy via telehealth on children's speech and language, class participation and educational outcomes," *Journal of Telemedicine and Telecare*, vol. 25, no. 9, pp. 559–565, 2019. PMID: 31631760.

[8] N. Céspedes, D. Raigoso, M. Múnera, and C. A. Cifuentes, "Long-term social human-robot interaction for neurorehabilitation: Robots as a tool to support gait therapy in the pandemic," *Frontiers in Neurorobotics*, vol. 15, 2021.

[9] L. P. Cole, T. L. Henechowicz, K. Kang, M. Pranjić, N. M. Richard, G. L. J. Tian, and C. Hurt-Thaut, "Neurologic music therapy via telehealth: A survey of clinician experiences, trends, and recommendations during the covid-19 pandemic," *Frontiers in Neuroscience*, vol. 15, 2021.

[10] L. P. Cole, T. L. Henechowicz, M. Pranjić, and G. L. J. Tian, "Neurologic Music Therapy via Telehealth: A Survey of Clinician Experiences, Trends, and Recommendations During the COVID-19 Pandemic," *Frontiers in Neuroscience*, vol. 15, Apr. 2021. Publisher: Frontiers.

[11] L.-A. Leow, C. Rinchon, and J. Grahn, "Familiarity with music increases walking speed in rhythmic auditory cuing," *Annals of the New York Academy of Sciences*, vol. 1337, no. 1, pp. 53–61, 2015. _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1111/nyas.12658.

[12] "GitHub - plamere/SortYourMusic: A web app that sorts your playlists by a wide range of Echo Nest parameters — github.com." https://github.com/plamere/SortYourMusic. [Accessed 20-03-2024].

[13] L.-A. Leow, T. Parrott, and J. A. Grahn, "Individual Differences in Beat Perception Affect Gait Responses to Low- and High-Groove Music," *Frontiers in Human Neuroscience*, vol. 8, Oct. 2014. Publisher: Frontiers.

[14] T. Georgiou, S. Holland, and J. van der Linden, "Wearable haptic devices for post-stroke gait rehabilitation," in *Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing: Adjunct*, UbiComp '16, (New York, NY, USA), pp. 1114–1119, Association for Computing Machinery, Sept. 2016.

[15] N. Céspedes, M. Múnera, C. Gómez, and C. A. Cifuentes, "Social Human-Robot Interaction for Gait Rehabilitation," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 28, pp. 1299–1307, June 2020. Conference Name: IEEE Transactions on Neural Systems and Rehabilitation Engineering.

[16] "ReSpeaker Mic Array v2.0 — Seeed Studio Wiki — wiki.seeedstudio.com." https://wiki.seeedstudio.com/ReSpeaker$_{M}ic_{A}rray_{v}2.0.[Accessed 20-03-2024].$

[17] H. Prasanth, M. Caban, U. Keller, G. Courtine, A. Ijspeert, H. Vallery, and J. von Zitzewitz, "Wearable Sensor-Based Real-Time Gait Detection: A Systematic Review," *Sensors*, vol. 21, p. 2727, Jan. 2021. Number: 8 Publisher: Multidisciplinary Digital Publishing Institute.

[18] F. Deligianni, Y. Guo, and G.-Z. Yang, "From Emotions to Mood Disorders: A Survey on Gait Analysis Methodology," *IEEE Journal of Biomedical and Health Informatics*, vol. 23, pp. 2302–2316, Nov. 2019. Conference Name: IEEE Journal of Biomedical and Health Informatics.

[19] S. I. Serengil and A. Ozpinar, "HyperExtended LightFace: A Facial Attribute Analysis Framework," in *2021 International Conference on Engineering and Emerging Technologies (ICEET)*, pp. 1–4, Oct. 2021. ISSN: 2409-2983.

[20] D. S. Cortes, C. Tornberg, T. Bänziger, H. A. Elfenbein, H. Fischer, and P. Laukka, "Effects of aging on emotion recognition from dynamic multimodal expressions and vocalizations," *Scientific Reports*, vol. 11, p. 2647, Jan. 2021. Publisher: Nature Publishing Group.

[21] C. Lugaresi, J. Tang, H. Nash, C. McClanahan, E. Uboweja, M. Hays, F. Zhang, C.-L. Chang, M. G. Yong, J. Lee, W.-T. Chang, W. Hua, M. Georg, and M. Grundmann, "MediaPipe: A Framework for Building Perception Pipelines," June 2019. arXiv:1906.08172 [cs].

[22] X. Wan and Y. Yamada, "Changes in the Determinism of the Gait Dynamics with the Intervention of a Robotic Walker," *Applied Sciences*, vol. 10, p. 4939, Jan. 2020. Number: 14 Publisher: Multidisciplinary Digital Publishing Institute.

[23] Q. Yan, J. Huang, Z. Yang, Y. Hasegawa, and T. Fukuda, "Human-Following Control of Cane-Type Walking-Aid Robot Within Fixed Relative Posture," *IEEE/ASME Transactions on Mechatronics*, vol. 27, pp. 537–548, Feb. 2022. Conference Name: IEEE/ASME Transactions on Mechatronics.

[24] C. A. Cifuentes, A. Frizera, R. Carelli, and T. Bastos, "Human–robot interaction based on wearable IMU sensor and laser range finder," *Robotics and Autonomous Systems*, vol. 62, pp. 1425–1439, Oct. 2014.

[25] I.-S. Choi and J.-S. Choi, "Leader-Follower Formation Control Using PID Controller," in *Intelligent Robotics and Applications* (C.-Y. Su, S. Rakheja, and H. Liu, eds.), (Berlin, Heidelberg), pp. 625–634, Springer, 2012.

[26] I.-S. Weon and S.-G. Lee, "Intelligent robotic walker with actively controlled human interaction," *ETRI Journal*, vol. 40, no. 4, pp. 522–530, 2018. _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.4218/etrij.2017-0329.