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Designing and Evaluating a Platform for Robot-Assisted Minimally Supervised Hand Therapy: A Pilot Study

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ABSTRACT

Background

Robot-assisted therapy has the potential to enhance therapy doses post-stroke, addressing the often insufficient treatment of hand function in clinical settings and after discharge. Traditionally, these systems have been complex and required therapist supervision. To better leverage robot-assisted therapy, we propose a platform designed for minimal therapist supervision and present a preliminary evaluation of its immediate usability, addressing a key challenge often neglected in real-world applications. This approach could increase therapy doses by enabling a single therapist to train multiple patients simultaneously, as well as supporting independent training in clinics or at home.

Methods

We implemented design changes on a hand rehabilitation robot, focusing on enabling minimally-supervised therapy. This involved developing new physical and graphical user interfaces and creating two functional therapy exercises aimed at training hand motor coordination, somatosensation, and memory. Ten participants with chronic stroke evaluated the platform's usability and reported their perceived workload during a minimally-supervised therapy session. The ability to use the platform independently was assessed using a checklist.

Results

After a brief familiarization period, participants were able to independently perform the therapy session, needing assistance in only 13.46% (range: 7.69–19.23%) of the tasks. They rated the user interface and exercises highly on the System Usability Scale, with scores of 85.00 (75.63–86.88) and 73.75 (63.13–83.75) out of 100, respectively. Nine

participants indicated they would use the platform frequently. The perceived workload was within acceptable ranges. The most challenging tasks identified were object grasping with simultaneous control of forearm pronosupination and stiffness discrimination.

Discussion

Our findings indicate that a robot-assisted therapy device can be safely and intuitively used with minimal supervision upon first exposure by adhering to usability and workload requirements. The preliminary usability evaluation highlighted specific challenges that need to be addressed to enable real-world minimally-supervised use. This platform could complement conventional therapy, providing increased therapy doses with existing resources and establishing a continuum of care that transitions from the clinic to the home.

Introduction:

Despite advances in neurorehabilitation, approximately one-third of stroke survivors suffer from chronic arm and hand impairments, limiting their ability to perform basic daily activities. Evidence suggests that intensive rehabilitation programs that maximize therapy doses—defined as the number of exercise task repetitions and total therapy time—can promote recovery and maintain upper limb function. Robot-assisted therapy is a promising approach to increasing therapy dose and intensity. Various robotic devices have been developed to train hand and wrist movements and provide objective evaluations of motor and sensory functions. However, robot-assisted therapy typically requires constant supervision by trained personnel to manage the equipment and set up therapy plans. Consequently, these devices are mostly used in short, supervised sessions in clinical settings, imposing organizational and economic constraints that limit their usage. This results in therapy doses that fall short of guidelines and pre-clinical evidence.

Minimally supervised therapy, where patients perform therapy independently with minimal external supervision, could better harness the potential of robot-assisted therapy. This approach would allow for the simultaneous training of multiple patients in clinics or enable patients to receive robot-assisted training at home. Several upper limb technology-supported therapies have been proposed for home use, allowing patients to benefit from additional rehabilitative services to increase therapy doses. However, few minimally supervised robotic devices capable of actively supporting or resisting patients during interactive therapy exercises have been proposed, and most of these do not focus on hand rehabilitation. Additionally, these devices often do not meet the complex requirements for minimally supervised use.

To be effective, motivating, and feasible, minimally supervised robot-assisted therapy platforms must meet a wide range of usability, human factors, and hardware requirements. They must provide engaging, physiologically relevant task-oriented exercises and continuously adapt therapy to the patient's ability level while ensuring ease of use. Specific hardware and software modifications are necessary to enable positive user experiences, compliance with therapy targets, and safe interactions in minimally supervised settings, both in clinics and at home. Integrating usability evaluations during the development of rehabilitation technologies can improve device design, user satisfaction, and overall usability. Unfortunately, the usability of robotic devices for upper-limb rehabilitation is rarely evaluated and documented in target user populations before clinical trials.

In this paper, we present the design of a platform for minimally-supervised robot-assisted therapy for hand function post-stroke and evaluate its short-term usability in a single experimental session with 10 chronic stroke survivors. The proposed platform builds on the existing high-fidelity, 2-degrees-of-freedom end-effector haptic device, ReHapticKnob (RHK), inspired by the HapticKnob concept. The RHK was previously used successfully in a clinical trial with subacute stroke subjects, showing equivalent therapy outcomes to dose-matched conventional therapy without adverse events. This success provided a foundation for exploring strategies to leverage the robot's unique features for minimally-supervised therapy.

To make the device suitable for minimally supervised settings, we developed an intuitive user interface—both physical/hardware and graphical/software—that allows chronic stroke survivors to perform therapy exercises independently, either in clinical settings or at home. Additionally, we created two new task-oriented therapy exercises designed for minimally supervised use, focusing on hand grasping and forearm pronosupination, which are functionally relevant movements.

The goal of this paper is to present the hardware and software modifications to the platform, including the robotic device, new physical and virtual user interfaces, and therapy exercises. We also report the results of a preliminary usability evaluation in which participants in the chronic stage of stroke independently used the device in a single session after a brief familiarization period. This work demonstrates that chronic stroke survivors can independently and safely use a powered robotic device for upper-limb therapy upon first exposure. It also highlights key design aspects that should be considered to maximize usability in real-world, minimally-supervised scenarios, providing a methodological basis that could be generalized to other platforms and applications.

Materials and Methods

ReHapticKnob and User Interface

The therapy platform proposed in this work consists of the existing robotic device ReHapticKnob (RHK) and includes a new user interface and two novel therapy exercises. The user interface comprises both physical components (hardware interfaces like finger pads and buttons of the RHK) and a graphical component (software), specifically the graphical user interface (GUI).

The RHK is a 2-degrees-of-freedom haptic device designed for the assessment and therapy of hand function post-stroke. It includes automated assessments to determine the baseline difficulty of therapy exercises and supports training in hand opening-closing (grasping) and forearm pronosupination through functionally relevant rehabilitative tasks rendered with high haptic fidelity. Users sit in front of the robot, positioning their hand inside two instrumented finger pads that slide symmetrically on a handlebar, as shown in Figure 1. VELCRO straps ensure contact between the user's fingers and the finger pads. The simple end-effector design of the robot, compared to the more complex donning and doffing of exoskeletons, makes it ideal for independent use. Proper limb positioning is initially instructed by a therapist to avoid misalignments and compensatory movements, which has proven effective in previous clinical trials.

Based on feedback from subjects and therapists in a previous clinical study, we developed a new therapy platform that is more user-friendly and suitable for minimally-supervised use. The novel GUI directly controls the execution of the therapy program and includes sections for both the user and the therapist. The "Therapist Section" is password-protected, allowing therapists to create or update subject profiles, including demographic data, impaired side, identification code, and a color sequence password for therapy plan access. Therapists can also select exercise parameters based on preliminary automated assessments to adapt the therapy exercises to the subject's ability level.

The "Patient Section" allows subjects to autonomously navigate their therapy plan using an intuitive colored pushbutton keyboard (Figure 1A). Subjects log in by selecting their identification code and entering the colored password. They can then manually navigate through a graphical list of available therapy exercises and select their preferred exercise.

To maximize usability, attention was given to the aesthetics and simplicity of all virtual displays and hardware components, guided by usability heuristics. These included visibility of feedback (performance feedback and unique identifiers on each user interface window), matching between virtual and haptic displays, user control and freedom (exit or stop buttons always available), consistency and standardization of display appearance, visibility and intelligibility of system instructions, fast system response, and simple error detection/warnings. Button placement, size, logical ordering, appearance, and color coding (e.g., red for quitting/exiting) were carefully designed to be easily visible and selectable, aiming to keep the number of buttons to a maximum of five for executing all exercises.

To ensure platform modularity, a state machine manages the low-level control of the robot (position, velocity, and force control implemented in LabVIEW 2016), while the GUI (Unity 5.6) guides the high-level control of the therapy session, allowing for the easy insertion or removal of different exercise types.

Exercises for Robot-Assisted Minimally-Supervised Therapy

The ReHapticKnob (RHK) initially featured seven assessment-driven therapy exercises developed according to Perfetti's neurocognitive therapy approach, which combines motor training with somatosensory and cognitive tasks. These exercises focused on isolated movements, such as grasping or pronosupination, and were administered under therapist supervision【Metzger et al., 2014b; Ranzani et al., 2020】.

To expand the exercise repertoire and optimize it for minimally-supervised use, we implemented two new exercises designed to facilitate the transition to activities of daily living. These exercises emphasize synchronous movements and integrate sensory, cognitive, and motor cues.

Tunnel Exercise

The tunnel exercise is designed to enhance the synchronous coordination of grasping and pronosupination while improving sensory perception of haptic cues. In this exercise, users control two symmetric avatars (representing the finger pads of the robot as purple triangles) that progress through a virtual tunnel. The goal is to avoid obstacles and collect rewards (e.g., coins) by maneuvering the avatars.

Key features of the tunnel exercise include:

- Sensory Cues: Hand vibrations indicate the correct position to avoid obstacles.

- Haptic Feedback: Stiff virtual walls constrain the movement of avatars within the tunnel, and changes in viscosity (velocity-dependent resistance) challenge the stabilization of hand movements.

- Difficulty Levels: As difficulty increases, avatar speed within the tunnel increases, the range of pronosupination required expands, and changes in environment viscosity become more pronounced. Additionally, the space between obstacles narrows and the intensity of haptic vibrations decreases.

Each exercise block involves a 1-minute progression through the virtual tunnel, during which users must avoid up to 30 obstacles. A complete exercise session consists of ten 1-minute blocks.

These newly developed exercises are tailored to be user-friendly and effective in a minimally-supervised setting, thereby enhancing the potential for patients to perform independent therapy both in clinical environments and at home.

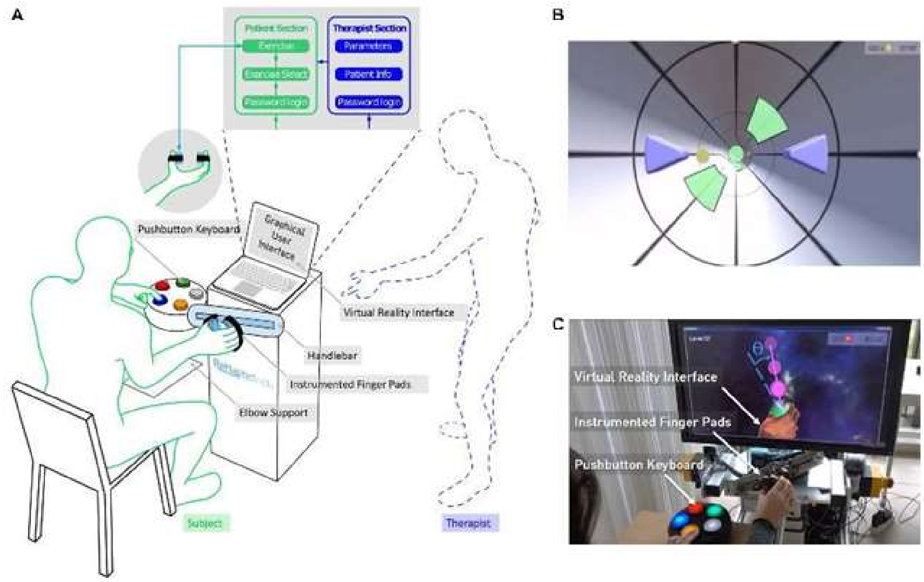

FIGURE 1 | The ReHapticKnob therapy platform. (A) The platform consists of a haptic rehabilitation device - the ReHapticKnob - with physical (i.e., instrumented finger pads, colored pushbutton keyboard) and graphical user interfaces (GUIs) and a set of therapy exercises that can be used with minimal supervision. The GUI includes a section for the therapist to initially customize the therapy plan and a patient section through which the user can autonomously perform predefined therapy exercises. (B) Virtual reality interface of the tunnel exercise. The subject has to drive a set of purple avatars by opening-closing and pronosupinating the finger pads. The goal is to avoid the green obstacles and collect as many coins as possible. (C) A subject performing the sphere exercise on the ReHapticKnob. During the testing phase shown, the subject has to catch a falling sphere halo by rotating the finger pads (pronosupination). The object is caught if the hand orientation (dotted line) is aligned with the falling direction (continuous line), within a certain angular range θ. Once the object is caught, the subject selects the sphere stiffness he/she perceives while squeezing the object by pressing the corresponding color on the pushbutton keyboard.

Sphere Exercise

The sphere exercise focuses on enhancing hand coordination during grasping and pronosupination, with an emphasis on somatosensation and memory for identifying objects based on their stiffness. Each exercise block consists of a training phase followed by a testing phase.

Training Phase

In the training phase, the user moves a virtual hand to squeeze a series of virtual spheres (three to five), each with a different stiffness. The user must memorize the color associated with each stiffness, switching spheres by pressing a predefined button on the colored pushbutton keyboard.

Testing Phase

In the testing phase, semi-transparent spheres (halos) fall radially from a random initial position toward the virtual hand. The user must rotate the robot and adjust hand opening to catch the falling halo. A halo is successfully caught if the hand aperture matches the sphere diameter within an error margin of ±10 mm, and the hand pronosupination angle aligns with the falling direction within an error band of ±40° to ±15°, depending on the difficulty level (Figure 1C). Once a halo is caught, the user squeezes it, identifies its stiffness, and indicates the corresponding color using the pushbutton keyboard. Each testing phase lasts 3 minutes. As difficulty increases, the number and speed of falling halos increase, hand positioning tolerance decreases in the pronosupination degree of freedom, and the relative change in object stiffness decreases based on the subject's stiffness discrimination ability (determined by initial robotic assessments).

Exercise Session

An exercise session consists of three blocks, each including a training phase and a testing phase, lasting between 10 and 15 minutes in total.

Difficulty Adaptation

In both the tunnel and sphere exercises, difficulty is adapted based on the subject's initial abilities assessed through robotic evaluations. These evaluations determine the subject's active range of motion (AROM) in grasping and pronosupination, and their ability to discriminate stiffnesses (expressed as the "Weber fraction"). For the tunnel exercise, AROM scales the positioning and size of the virtual walls, determining the tunnel's size. For the sphere exercise, AROM scales the workspace within which the halos fall. The Weber fraction scales the initial stiffness difference between spheres.

Performance is summarized at the end of each exercise block, displaying a score that helps further adapt the exercise difficulty. This adaptation aims to maintain a performance level around 70%, which is optimal for engagement and minimizes frustration from either overly easy or overly difficult tasks【Adamovich et al., 2009; Cameirão et al., 2010; Choi et al., 2011; Lambercy et al., 2011; Metzger et al., 2014b; Wittmann et al., 2016】. Although this study tested only a single session, and therefore did not extensively evaluate performance-based difficulty adaptation, these aspects are integral to the exercise design and future evaluations.

Participants

Ten individuals with chronic stroke (>6 months) participated in a pilot study to assess the usability of the proposed minimally-supervised therapy platform, reflecting potential future users. Inclusion criteria were set at 18 years or older, the ability to lift the arm against gravity, residual finger flexion and extension, capability to provide informed consent, and understanding of two-stage commands. Exclusion criteria comprised clinically significant non-related pathologies (e.g., severe aphasia, cognitive deficits, or pain), ethical contraindications, and suspected non-compliance (e.g., substance abuse).

Pilot Study Design

Conducted at ETH Zurich, Switzerland, over a 2-week period, the pilot study involved a single test session (see Figure 2). The session comprised a supervised and a minimally-supervised segment. During the supervised phase, a professional therapist assessed baseline ability levels through standard clinical and robotic assessments, customized exercise difficulty levels, and provided instructions while guiding the subject through one block of each exercise. Subjects were encouraged to ask questions related to device use. In the subsequent minimally-supervised segment, subjects independently performed the tunnel exercise (10 blocks) and the sphere exercise (3 blocks) using the therapy platform. The therapist observed silently, intervening only in case of risk or explicit request. Subjects independently initiated exercises, tested them, and logged out. Post-experimental, subjects completed usability questionnaires.

The evaluation focused on new, more complex exercises that train coordinated movements and sensory, cognitive, and motor functions. These exercises presented cognitive challenges, essential for assessing device usability under demanding conditions. Simpler exercises were avoided to prevent bias, as they are better suited for earlier rehabilitation stages. The chosen exercises are ideal for individuals with mild to moderate impairments, aligning with previous studies indicating their suitability for minimally-supervised therapy. Moreover, compared to simpler exercises, these exercises fostered greater subject engagement in minimally-supervised therapy, lacking additional encouragement from a supervising therapist.

The study received approval from the Cantonal Ethics Committee in Zurich, Switzerland (Req-2017-00642).

Baseline Assessments

At baseline, subjects' upper limb impairment was evaluated using the Fugl-Meyer Assessment of the Upper Extremity (FMA-UE) (Fugl-Meyer et al., 1975) along with its wrist and hand subscore (FMA-WH). Gross manual dexterity was assessed via the Box and Block test (BBT) (Mathiowetz et al., 1985). In addition to clinical assessments, robotic evaluations were conducted to determine the initial difficulty level of therapy exercises based on subjects' abilities. Robotic assessments included measuring the active range of motion (AROM) to evaluate hand opening, closing, and pronosupination of the forearm. The stiffness discrimination ability, expressed as the "Weber fraction," characterized the smallest discernible difference between two object stiffnesses. Further details on these assessments can be found in the referenced literature.

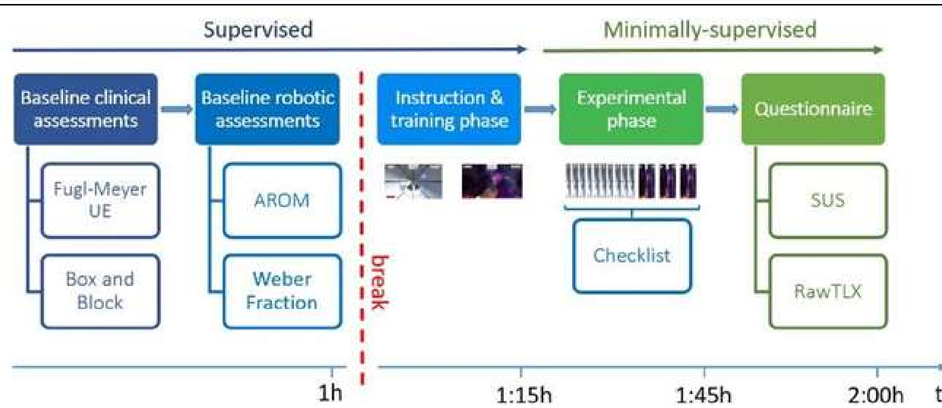

FIGURE 2 | Study protocol. Abbreviations: UE, Upper Extremity; AROM, Active Range of Motion; SUS, System Usability Scale; RawTLX, Raw Task Load Index.

Outcome Measures and Statistical Analysis

The primary outcome measures aimed to assess the ability of chronic stroke subjects to independently utilize the therapy platform and identify any remaining usability challenges. These measures included:

1. Percentage of tasks requiring external intervention: Recorded using a performance checklist documenting tasks/actions that required therapist intervention or external support.

2. Usability and perceived workload: Evaluated through two standardized questionnaires assessing the user interface and exercise components separately.

The performance checklist comprised 26 items, covering aspects related to the use of user interfaces, the tunnel exercise, and the sphere exercise. The percentage of items requiring intervention was calculated for each subject.

The standardized usability questionnaires employed were:

1. System Usability Scale (SUS): A ten-item questionnaire gauging the overall usability of the system, including the user interface and each exercise individually. SUS scores above 50 out of 100 indicated satisfactory usability. Two items specifically addressed system "learnability," crucial for evaluating minimally-supervised usage scenarios.

2.Raw Task Load Index (RawTLX): A six-item questionnaire assessing workload during system use across domains such as mental demand, physical demand, temporal demand, overall performance, effort, and frustration level.

Pearson’s correlation coefficients were calculated between SUS scores and baseline characteristics of subjects (age, FMA-UE, FMA-WH, and BBT score), resulting in 12 comparisons. The statistical significance threshold was adjusted using Bonferroni correction for multiple comparisons.

For the user interface, a minimal workload target (≤25%) was set for all domains except temporal demand, where an intermediate workload level (25–75%) was acceptable.

Results

Experiment Characteristics

Ten subjects (four female, six male) in the chronic stage after ischemic stroke (median 39.5 months post-event) participated. Their median age was 60.5 years, with four right and six left hemisphere lesions, and all were right-handed. Initial upper-limb impairment ranged from mild to moderate, with median Fugl-Meyer Assessment of the Upper Extremity (FMA-UE) score of 41.5 out of 66 points and FMA-Wrist and Hand (FMA-WH) score of 17.0 out of 24 points. In the Box and Block test (BBT), subjects transported a median of 39.5 blocks/min using their impaired limb. All participants provided written consent before enrollment.

The experiment lasted a median of 111.5 minutes, including 79.1 minutes of robot use and 34.8 minutes for assessments, breaks, and questionnaires. During robot use, subjects spent 16.0 minutes on baseline robotic assessments and 59.9 minutes learning to use the user interface and exercises. During the experimental phase, minimal therapist intervention was required, with a median of 3.5 interventions per subject. No serious adverse events related to the intervention were observed, but two subjects reported mild temporary increases in hand muscle tone.

User Interface

The user interface received a System Usability Scale (SUS) score between good and excellent (median 85.0 out of 100), with nine subjects rating it as excellent. Most subjects found the interface intuitive and the colored button interfaces easy to use. However, the oldest subject (age 87) rated the interface lower. SUS scores showed an inverse relationship with age but no significant correlation with ability level.

Raw Task Load Index (RawTLX) results indicated perceived workload levels within target bands, although the third quartile exceeded the target band in mental demand, physical demand, and effort.

Subjects required external assistance for 14.3% of user interface checklist items. Common issues included difficulty inserting the hand into the finger pads and remembering the colored password.

Implications and Conclusions

This study aimed to develop and assess the usability of a minimally-supervised therapy platform, enabling personalized and engaging task-oriented exercises for hand rehabilitation. Our findings indicate that a powered robot-assisted therapy device, meeting usability and workload criteria, can be safely and easily used by chronic stroke patients with minimal supervision in a single session. Through this pilot evaluation, we identified areas for further design refinement to enhance platform usability and user acceptance. These results suggest the potential for active robotic devices to complement conventional therapies in real-world settings, optimizing resource utilization, increasing therapy dosage, and fostering a continuum of care that promotes patient engagement and autonomy from clinical to home environments.

References List:

[1]. Prakash, S., Malaiyappan, J. N. A., Thirunavukkarasu, K., & Devan, M. (2024). Achieving Regulatory Compliance in Cloud Computing through ML. AIJMR-Advanced International Journal of Multidisciplinary Research, 2(2).

[2]. Malaiyappan, J. N. A., Prakash, S., Bayani, S. V., & Devan, M. (2024). Enhancing Cloud Compliance: A Machine Learning Approach. AIJMR-Advanced International Journal of Multidisciplinary Research, 2(2).

[3]. Devan, M., Prakash, S., & Jangoan, S. (2023). Predictive Maintenance in Banking: Leveraging AI for Real-Time Data Analytics. Journal of Knowledge Learning and Science Technology ISSN: 2959-6386 (online), 2(2), 483-490.

[4]. Eswaran, P. K., Prakash, S., Ferguson, D. D., & Naasz, K. (2003). Leveraging Ip For Business Success. International Journal of Information Technology & Decision Making, 2(04), 641-650.

[5]. Prakash, S., Malaiyappan, J. N. A., Thirunavukkarasu, K., & Devan, M. (2024). Achieving Regulatory Compliance in Cloud Computing through ML. AIJMR-Advanced International Journal of Multidisciplinary Research, 2(2).

[6]. Malaiyappan, J. N. A., Prakash, S., Bayani, S. V., & Devan, M. (2024). Enhancing Cloud Compliance: A Machine Learning Approach. AIJMR-Advanced International Journal of Multidisciplinary Research, 2(2).

[7]. Biswas, A. (2019). Media Insights Engine for Advanced Media Analysis: A Case Study of a Computer Vision Innovation for Pet Health Diagnosis. International Journal of Applied Health Care Analytics, 4(8), 1-10.

[8] Chopra, B., & Raja, V. (2024). Toward Enhanced Privacy in Digital Marketing: An Integrated Approach to User Modeling Utilizing Deep Learning on a Data Monetization Platform. Journal of Artificial Intelligence General science (JAIGS) ISSN: 3006-4023, 1(1), 91-105.

[9]. Raja, V. (2024). Fostering Privacy in Collaborative Data Sharing via Auto-encoder Latent Space Embedding. Journal of Artificial Intelligence General science (JAIGS) ISSN: 3006-4023, 4(1), 152-162.

[10]. Raja, V. ., & chopra, B. . (2024). Exploring Challenges and Solutions in Cloud Computing: A Review of Data Security and Privacy Concerns. Journal of Artificial Intelligence General Science (JAIGS) ISSN:3006-4023, 4(1), 121–144. https://doi.org/10.60087/jaigs.v4i1.86

[11]. SARIOGUZ, O., & MISER, E. (2024). Data-Driven Decision-Making: Revolutionizing Management in the Information Era. Journal of Artificial Intelligence General science (JAIGS) ISSN: 3006-4023, 4(1), 179-194.

[12]. Raja, V. (2024). Exploring Challenges and Solutions in Cloud Computing: A Review of Data Security and Privacy Concerns. Journal of Artificial Intelligence General science (JAIGS) ISSN: 3006-4023, 4(1), 121-144.

[13]. Biswas, A. (2019). Media Insights Engine for Advanced Media Analysis: A Case Study of a Computer Vision Innovation for Pet Health Diagnosis. International Journal of Applied Health Care Analytics, 4(8), 1-10.

[14]. Talati, D. (2023). Telemedicine and AI in Remote Patient Monitoring. Journal of Knowledge Learning and Science Technology ISSN: 2959-6386 (online), 2(3), 254-255.

[15]. Talati, D. (2023). Artificial Intelligence (Ai) In Mental Health Diagnosis and Treatment. Journal of Knowledge Learning and Science Technology ISSN: 2959-6386 (online), 2(3), 251-253.

[16]. Talati, D. (2023). AI in healthcare domain. Journal of Knowledge Learning and Science Technology ISSN: 2959-6386 (online), 2(3), 256-262.

[17]. Talati, D. (2024). AI (Artificial Intelligence) in Daily Life. Authorea Preprints.

[18]. Tembhekar, P., Malaiyappan, J. N. A., & Shanmugam, L. (2023). Cross-Domain Applications of MLOps: From Healthcare to Finance. Journal of Knowledge Learning and Science Technology ISSN: 2959-6386 (online), 2(3), 581-598.

[19]. Malaiyappan, J. N. A., Karamthulla, M. J., & Tadimarri, A. (2023). Towards Autonomous Infrastructure Management: A Survey of AI-driven Approaches in Platform Engineering. Journal of Knowledge Learning and Science Technology ISSN: 2959-6386 (online), 2(2), 303-314.

[20]. Karamthulla, M. J., Malaiyappan, J. N. A., & Tillu, R. (2023). Optimizing Resource Allocation in Cloud Infrastructure through AI Automation: A Comparative Study. Journal of Knowledge Learning and Science Technology ISSN: 2959-6386 (online), 2(2), 315-326.

[21]. Althati, C., Tomar, M., & Malaiyappan, J. N. A. (2024). Scalable Machine Learning Solutions for Heterogeneous Data in Distributed Data Platform. *Journal of Artificial Intelligence General science (JAIGS) ISSN: 3006-4023*, *4*(1), 299-309.

[22]. Althati, C., Tomar, M., & Shanmugam, L. (2024). Enhancing Data Integration and Management: The Role of AI and Machine Learning in Modern Data Platforms. Journal of Artificial Intelligence General science (JAIGS) ISSN: 3006-4023, 2(1), 220-232.