REVIEW ARTICLE

VOL. 46 | NO. 1 | **JANUARY-APRIL 2025** | PP 1-18

Revista Mexicana de Ingeniería Biomédica

https://dx.doi.org/10.17488/RMIB.46.1.1472

E-LOCATION ID: e1472

Emerging Technologies as a Support for Proprioceptive Rehabilitation: a Scoping Review

Tecnologías Emergentes como Apoyo en la Rehabilitación Propioceptiva: una Revisión del Alcance

Uziel Trujillo Colón[1], *José Luis Hernández Hernández*[1], *Eduardo De La Cruz Gámez*[2], *Rayma Ireri Maldonado Astudillo*[1], *Ricardo Salazar*[3]

[1] Universidad Autónoma de Guerrero, Guerrero - México

[2] Tecnológico Nacional de México/Instituto Tecnológico de Acapulco, Guerrero -México

[3] Universidad Autónoma de Guerrero / CONAHCYT, Guerrero - México

ABSTRACT

Proprioceptive training encompasses interventions aimed at enhancing proprioceptive function to improve motor function performance. Three types of interventions are considered: Movement Training (MT); Somatosensory Stimulation Training (SST), and Force Reproduction Training (FRT). This study analyzes the potential of emerging technologies, such as exoskeletons, mechanical devices, Artificial Intelligence (AI), Virtual Reality (VR), the Internet of Things (IoT), and sensors, highlighting their application in proprioceptive therapies, with particular emphasis on MT, SST, and FRT. A total of 107 articles published in scientific journals were reviewed, of which 30 complied with inclusion criteria: 1) Implementation of proprioceptive intervention therapy; 2) use of technology; 3) publication after 2019, and 4) written in the English language. Of the studies analyzed, 43 % employed AI, indicating its increasing adoption, while IoT was the least utilized technology, with only 3 %. It is concluded that emerging technologies plays a crucial role in proprioceptive rehabilitation by enabling the analysis of data before and after surgical procedures, real-time pattern assessment, and the classification of sensory signals. Moreover, it offers alternatives to traditional measurement methods.

KEYWORDS: convolutional neural networks, exoskeletons, mechanical devices, therapies

RESUMEN

El entrenamiento propioceptivo representa cualquier intervención de la función propioceptiva que ayude a mejorar el desempeño de la función motora. Se consideran tres tipos de intervenciones: Entrenamiento de Movimiento (EM); Entrenamiento de Estimulación Somatosensorial (EES) y Entrenamiento de Reproducción de Fuerza (ERF). Este estudio analiza el alcance de las tecnologías emergentes, como los exoesqueletos, dispositivos mecánicos, Inteligencia Artificial (IA), Realidad Virtual (VR), el Internet de las Cosas (IdC) y sensores, destacando su aplicación en las terapias propioceptivas, con énfasis en el EM, EES, y ERF. Se revisaron 107 artículos publicados en revistas científicas, de los cuales 30 cumplieron los criterios de inclusión: 1) Implementación de terapia de intervención propioceptiva; 2) uso de tecnología; 3) publicación posterior al año 2019, y 4) redacción en inglés. De los estudios analizados, el 43 % empleó IA, mostrando su creciente adopción, mientras que el IdC fue la tecnología menos utilizada, con un 3 %. Se concluye que las tecnologías emergentes son fundamentales en la rehabilitación propioceptiva, al permitir el análisis de información antes y después de procedimientos quirúrgicos, la evaluación de patrones en tiempo real, y la clasificación de señales sensoriales. Además, ofrecen alternativas efectivas frente a métodos tradiciones de medición.

PALABRAS CLAVE: dispositivos mecánicos, exoesqueletos, redes neuronales convolucionales, terapias

Corresponding author

TO: José Luis Hernández Hernández

INSTITUTION: UNIVERSIDAD AUTÓNOMA DE GUERRERO

ADDRESS: TERCERA CALLE NO. 81, COL. VILLA MODERNA, CHILPANCINGO GUERRERO, C.P. 39070, MÉXICO.

EMAIL: joseluis.hernandez@itchilpancingo.edu.mx

Received:

30 September 2024

Accepted:

14 February 2025

Published:

20 March 2025

INTRODUCTION

Proprioception depends on sensory signals from muscle spindles, skin, and joint receptors. It refers to the body's ability to perceive limb position, detect movement (whether passive or active), and recognize the forces exerted[1]. Several factors can negatively the impact proprioceptive function, including typical aging[2], sport injuries[3], motor disorders[4], strokes[5], or numerous neurological and orthopedic conditions such as Parkinson's disease[6], focal dystonia[7], and sensory neuropathies[8]. Consequently, individuals with compromised proprioception often experience a deterioration in their quality of life. In this context and considering the critical role of proprioception in motor control, it has been proposed that therapies targeting motor function restoration should emphasize the enhancement of proprioceptive abilities. Thus, physical therapy rehabilitation is regarded as the most effective approach for this purpose[9].

In 2021, an analysis explored the potential of integrated Virtual Reality (VR) into physical therapies[10]. In the year 2022, a review was conducted on strokes, their rehabilitation, and the role of robotic technology, including its adoption and the barriers encountered during its implementation[11].

Currently, a wide range of therapies is available to enhance the proprioceptive system, and these should be administered by specialized professionals, such as Kinesiotherapists, Physiotherapists, or Traumatologists. Treatment modeling indicates that clinical assessment and data acquisition are followed by interpretation, which leads to diagnosis and prognosis. For interventions, it is sometimes necessary employ specialized medical instruments, such as goniometers, inclinometers, and scales, during evaluations[1]. Based on the latter, this article reviews the literature on various methods of proprioceptive intervention and the different technologies that can support rehabilitation therapies. It also examines the application of emerging technologies and identifies potential niches where these innovations could be utilized in the near future.

MATERIALS AND METHODS

This section outlines the process of gathering and analyzing relevant literature. A comprehensive search was conducted in indexed scientific journals using specific parameters to ensure the quality and relevance of the selected articles. Following the collection of articles, a detailed analysis and classification were performed based on the following key aspects: 1) Proprioception therapies applied in the studies; 2) technologies utilized in the intervention and evaluation, and 3) anatomical areas targeted for rehabilitation.

Literature search

The literature search for related works primarily involved scientific articles published in biomedical journals indexes, including PubMed, Google Scholar, MDPI, Science Direct, Web of Science, and Scopus. The parameters used in the searches included proprioception, physical rehabilitation therapy, movement training interventions, strength reproduction, somatosensory stimulation interventions, and technology in proprioceptive therapies. The following four criteria have been met for inclusion in the study: 1) the use of at least one proprioceptive intervention therapy; 2) the incorporation of some type of technology; 3) publication of the study must be from 2019 or later, and 4) the information consulted must be in English language. A total of 107 articles were reviewed, of which 30 met all the inclusion criteria.

Analysis of parameters

To analyze the various related works according to the previously established criteria, a classification was performed based on the type of intervention: Movement Training (MT); Somatosensory Stimulation Training (SST), and Force Reproduction Training (FRT). The following categories were then considered: Artificial Intelligence (AI); mechanical devices; Virtual Reality (VR); exoskeletons; sensors, and IoT, with each of the related works was classified into one of these categories. Finally, the focus area of the rehabilitation work is categorized into: shoulders, arms, knees, feet, hands, gait re-education, upper limbs, and lower limbs, this serving as the third classification. The complete flow of the literature search and parameter selection are illustrated in Figure 1.

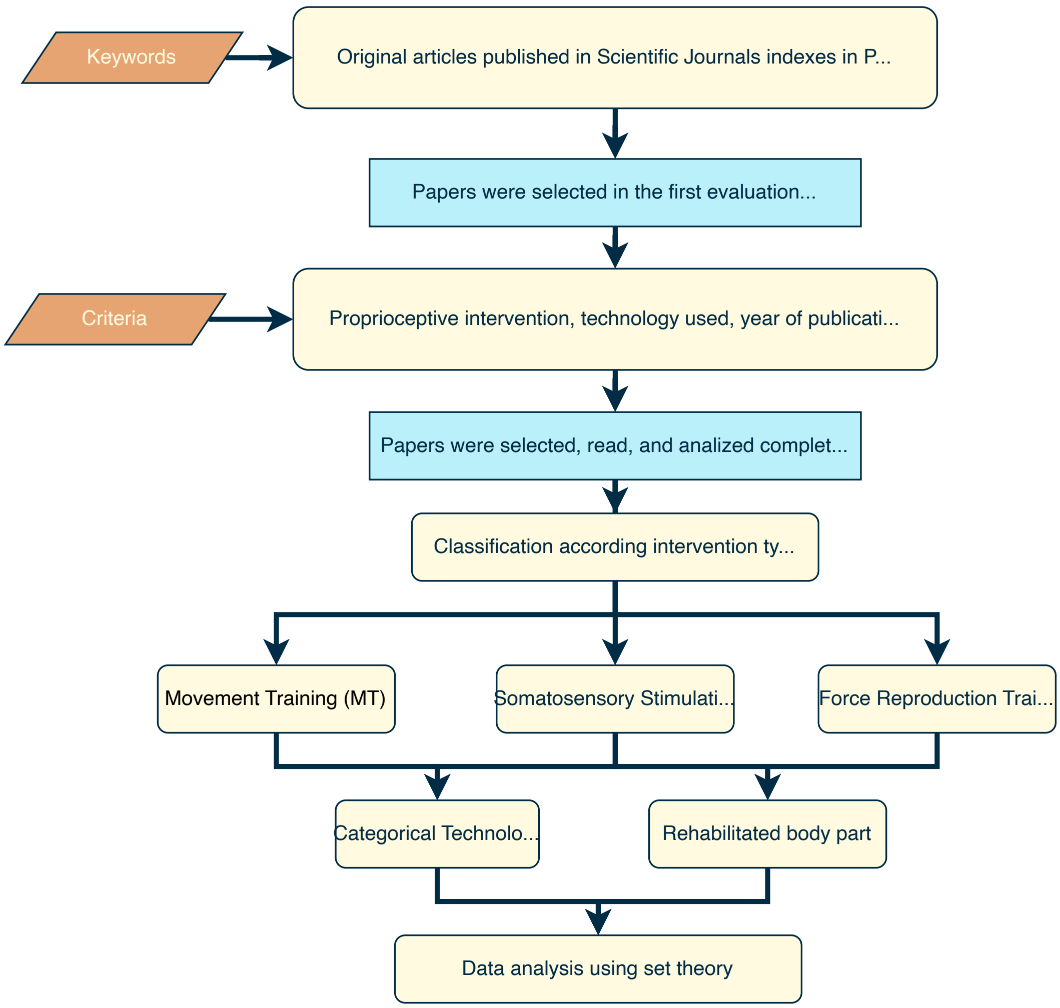

FIGURE 1. Search and criteria for related works.

Proprioceptive training refers to any intervention designed to enhance proprioceptive function, with the aim of recovering motor function and performance[9]. In clinical practice, there are various methods for proprioceptive interventions, including Movement Training (MT), Somatosensory Stimulation Training (SST), and Force Reproduction Training (FRT)[12], as shown in Figure 2. Additionally, various auxiliary technologies can be utilized at different phases of the evaluations.

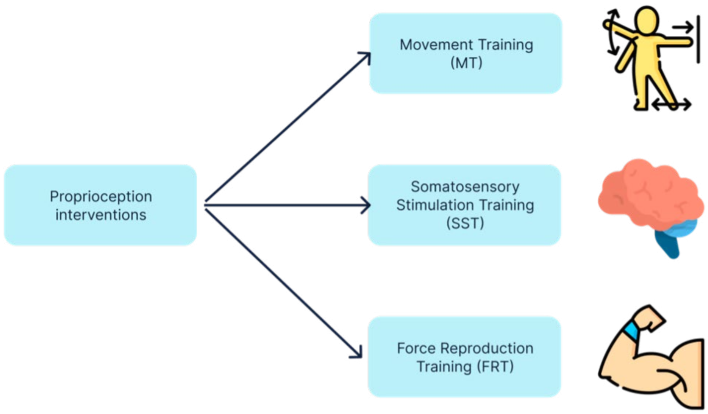

FIGURE 2. **Types of proprioceptive interventions.**

RESULTS AND DISCUSSION

a) Movement Training (MT)

Movement Training (MT) focuses on improving both the active and passive movement of a person's joints. Passive movement involves reaching a target at a specific position, and is assessed through a positional error test to determine whether the target has been successfully reached. Active movement, on the other hand, involves moving a body part from one position to another and assesses the accuracy of the Joint Position Sense (JPS). This assessment is conducted by measuring the movement threshold.

The compendium of Table 1 summarizes various studies utilizing interventions based on MT. These studies suggest the use of several technologies, including Convolutional Neural Network (CNN)[13], mechanical devices[14], Deep Neural Networks (DNN)[15], exoskeletons[16], linear regression[17], sensors[18] and Virtual Reality (VR)[19]. These technologies have been applied to different aspects of the rehabilitation or improvement of proprioceptive movement functioning, such as the elbow, shoulder, knee, hip, arms, upper limbs, lower limbs, gait re-education, and body.

TABLE 1. **Related works for proprioceptive interventions in MT (Continue in the next page).**

Ref.	Objective	Input data	Outcomes	Category	Applications
[13]	Develop a cost-efficient system for monitoring home-based rehabilitation using advanced technologies	Motion capture	The MLP algorithm effectively classified ROM and compensatory movements with accuracy in 89 %	AI	Elbow, shoulder, standing upright
[20]	Evaluate the validity and reliability of deep learning-based motion capture, such as DeepLabCut, for proprioception assessment compared to the gold-standard 3D optoelectronic system	Motion capture	DeepLabCut show a similar performance to that of Vicon to measure knee position	AI	Knee

TABLE 1. **Related works for proprioceptive interventions in MT (Continue in the next page).**

Ref.	Objective	Input data	Outcomes	Category	Applications
[21]	Validity OpenPose for knee range of motion assessment after TKA against radiography and goniometry	Motion capture, images, and goniometry	OpenPose showed higher ICC and narrower 95 % limits of agreement for ROM extension than goniometry	AI	Knee
[22]	Develop a computer vision-based method for real-time gait detection in patients using rehabilitation exoskeletons	Images	GaitPoseNet demonstrated a good percentage of correct keypoints, 95.77 %	AI, Exoskeleton	Hip, knee
[17]	Quantify lower limb proprioception and its correlation with clinical characteristics in SCA3 patients	Sensors	Lower limb proprioception in SCA3 patients was significantly impaired compared to the healthy control group, $p < 0.05$	Mechanical device	Lower limbs
[14]	Assess the impact of proprioceptive exercises on disease activity in postmenopausal women with RA	Sensors	The proprioceptive exercise program improved ankle function during gait in postmenopausal women with rheumatoid arthritis	Mechanical device	Gait re-education
[23]	Develop a framework for 3D user pose estimation from egocentric videos, utilizing proprioception as a key signal	Video	Experimental results show that the proposed framework significantly outperforms state-of-the-art methods	AI	Body
[24]	Evaluate shoulder proprioception after reverse shoulder arthroplasty for irreparable humeral fractures	Sensors	The results showed significant improvement in shoulder proprioception at 3, 6, and 12-months post-surgery	Mechanical device	Shoulder
[25]	The objective is real-time, on device rehabilitation assessments, overcoming the limitations of existing models such as PoseNet	Images	DeepRehab uses ResNet101, enabling more precise keypoint identification, particularly in the lower limbs	AI	Body
[26]	Develop a stimulation approach to assess the performance of the rehabilitation exoskeleton designed by the authors	Sensors	The exoskeleton improved gait training in stroke patients, enhancing kinematics, proprioception, metabolism, and muscle activation	Exoskeleton	Gait re-education
[27]	Evaluate the feasibility of predicting the KAM using anatomical landmarks that can be obtained from 2D video analysis	Video	KAM can be predicted with 95 % accuracy using a NN and video-based landmark positions	AI	Knee

TABLE 1. **Related works for proprioceptive interventions in MT (Continue from previous page).**

Ref.	Objective	Input data	Outcomes	Category	Applications
[15]	Propose a deep learning framework for automated evaluation of rehabilitation exercise quality	Kinect v2	The framework generates movement quality scores with 87 % accuracy, closely matching actual quality scores	AI	Body
[28]	Introduce an innovative and user-friendly system using M-IMUs for evaluating and rehabilitating patients with proprioceptive disorders	Sensors	Results in healthy subjects show that the VR game is easy to use and that it effectively captures the subject's attention	Sensors, VR	Arms, knee
[29]	Develop a real-time 3D proprioception system for soft bodies using computer vision and deep learning techniques	Motion capture	Experiments showed the methods high accuracy in 3D shape detection (dH: ≈1 mm, relative error: ≤1 %)	AI	Body
[19]	Evaluate the effect of VR-based proprioceptive training on postural stability in workers performing task at height	Sensors	The study provides evidence that VR can effectively improve postural stability and reduce fall risk in workers at height	Mechanical device, VR	Postural stability
[30]	Develop and assess a low-cost, portable system for measuring knee proprioception using inertial sensors	Sensors	Significant effects were observed for absolute error in 15-25° and 35-45°, and for variable error in 35-45°	Sensors	Knee
[31]	Investigate whether reward feedback can generate a lasting recalibration of vision and proprioception compared to error feedback	Handle of the robotic manipulator	Reward feedback reduced visuo-proprioceptive errors but did not improve retention compared to error-based feedback	Mechanical device	Arms
[2]	Determine the impact of movement speed and distance on upper limb in young and older adults	Handle of the robotic manipulator	The study found that faster speeds and longer distances increased proprioceptive error in both groups	Exoskeleton, VR	Upper limbs

The reviewed studies highlight a growing focus on the application of AI-based technologies, particularly Convolutional Neural Networks (CNN) and Deep Neural Networks (DNN). These technologies process input data from videos, images, or motion capture systems to generate 2D or 3D kinematic models[13][29], enabling precise digitization and mapping of the human body structure. This capability has proven valuable in evaluating parameters such as range of motion (ROM), achieving accuracies of 89 % and a Mean Per Joint Pose Error (MPJPE) of 57.4 %. In certain instances, these tools are specifically designed to assess the accuracy (95 %) of keypoint detection used by AI to estimate human posture or, alternatively, to classify movement patterns. On the other hand, the second most commonly used technology was exoskeletons. Their primary advantage lies in the integration of mechanical components, sensors, actuators and, in many cases, proprietary software, which allows the unification of these elements in a single device. Notable examples include KINARM, with an approximate commercial value of $ 189,000.00

USD[31], and BEAR-H1, which is currently under development[26]. Compare the performance of the exoskeleton with AI models, highlighting that significant discrepancies continue to exist between these technologies[22]. Specifically, the reported activation values were as follows: left hip (4.8); right hip (8.36); left knee (11.89), and right knee (17.75). Other studies focus on muscle activation, enhancing movement though targeted exercises, which improved the proprioceptive sense from 11.6 to 37.8[26].

In contrast, while mechanical devices can be costly, they are generally user-friendly. Some options available on the market include, for example, the Pro-Kin priced at approximately $ 22,499.00 USD[17], and the Human Norm II with an estimated cost of $ 79,995.00 USD[24]; these devices provide users with specialized tools that enable them to target specific areas and address deficiencies, such as those associated with total shoulder arthroplasty, Spinocerebellar Ataxia (SCA3), Rheumatoid Arthritis (RA), among other conditions. The studies analyzed include proprioception assessments utilizing these devices, reporting a range of results. Notable findings include significant values of $p < 0.005$, reductions in the Disease Activity Score (DAS) from 4.7 to 4.2[14], and improvements in the ROM of the treated areas, with an average of 31.1° ± 2.0, $p = 0.72$.

VR technologies are often integrated with recreational games[28], enabling users to perceive rehabilitation processes not as monotonous exercises, but as engaging activities. As games, these systems foster motivation, encouraging users to consistently improve and gradually progress in their recovery. The results of the reviewed studies indicate faster proprioception recovery in the affected areas. Another application of these systems involves their integration with external devices, such as balance platforms, to measure postural stability[19]. This integration allows for the acquisition of parameters such as the Center of Pressure (COP) and the evaluation of postural stability. In this regard, the use of sensors such as M-IMU is a low-cost alternative compared to exoskeletons and mechanical devices. The authors employed elastic bands positioned in areas requiring proprioceptive evaluation[30]. This technology facilitates the measurement of absolute and relative error, demonstrating significant effects in flexion and abduction movements within the ranges of 15° - 25° and 35° - 45°.

Categories, their primary applications, and input data were analyzed and represented in a network diagram (see Figure 3). Node sizes vary, indicating the relative importance or frequency of the use of each term.

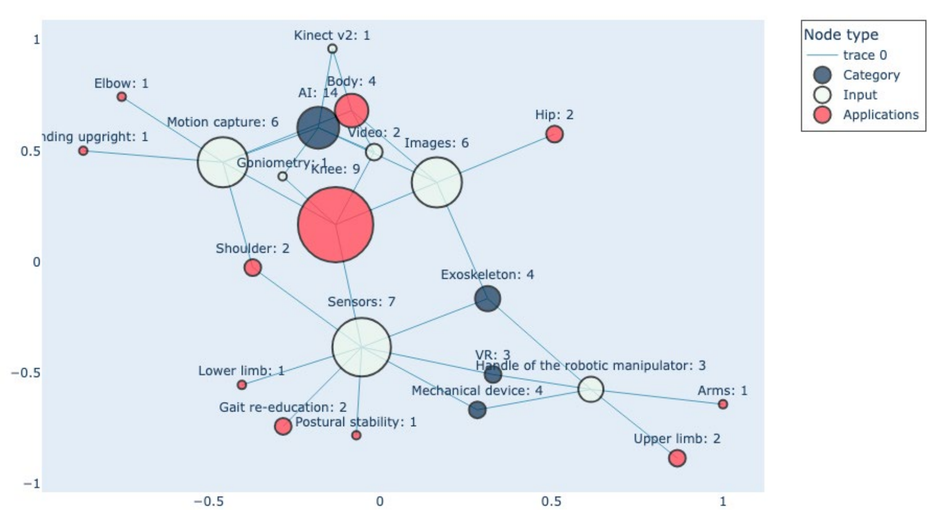

FIGURE 3. Network of related works in MT considering Category, Input data, and main Applications.

Rehabilitation therapies for MT revealed a predominant trend toward the adoption of Artificial Intelligence (AI), with 14 studies focusing on this approach. In contrast, niche opportunities were observed in the use of sensors, featured in one study, and Internet of Things (IoT) devices, which were not addressed in any study. In terms of input data, sensors were the most frequently employed, appearing in seven studies, followed by images and motion capture, each utilized in six studies. Regarding niche opportunities, robotics were the focus of three studies, while traditional devices were addressed in one study. Finally, trends in applications primarily targeted the knee (nine studies) and the whole body (four studies), whereas niche applications included standing upright and the elbow, with one study each.

b) Somatosensory Stimulation Training (SST)

Somatosensory Stimulation Training (SST) involves the application of a variety of methods, including vibrations, thermal stimulation, magnetic stimulation, electrical stimulation, or acupuncture[32][33]. To assess somatic proprioceptive sensitivity, evaluations usually consist of skin tests; for example, graphesthesia, which measures the ability to recognize handwriting on the skin, is assessed by having the patient blindfolded while the examiner writes numbers or letters on the palm of the hand or on the fingerprints using a relatively blunt instrument. Another example is the assessment of paresthesia, which involves evaluating abnormal sensations such as tingling or burning in the absence of specific stimuli, this evaluation is conducted through laboratory tests and physical examinations[34].

The technology employed for somatosensory stimulation is less varied compared to MT and typically includes electronic modules, exoskeletons and mechanical devices. These are commonly used elements in SST. Table 2 presents some related works associated with this type of intervention.

TABLE 2. **Related works for proprioceptive interventions in SST (Continue in the next page).**

Ref.	Objective	Input data	Outcomes	Category	Applications
[35]	Introduce and validate a new portable device for sensorimotor rehabilitation, combining MT and SST	Electromyography	The sensory training significantly improved two-point discrimination (TPD) on stimulated skin (p=0.047)	IoT	Arm
[36]	Investigate how the proprioceptive pathway processes muscle spindle signals to support various computational objectives	Musculoskeletal model	Models optimized for limb kinematics tasks best predicted neuronal activity in the cuneate nucleus	AI, Mechanical device	Shoulder, elbow
[32]	Investigate the proprioceptive system's role in action recognition, beyond its traditional function in representing bodily posture	Musculoskeletal model	Directional selective units were found only in models for action recognition, not in those for trajectory decoding	AI	Arm

TABLE 2. **Related works for proprioceptive interventions in SST (Continue from previous page).**

Ref.	Objective	Input data	Outcomes	Category	Applications
[18]	Evaluate the accuracy of perceiving different aspects of artificial proprioceptive feedback using a vibrotactor array	Interpretation of subjects' responses	The results showed over 90 % accuracy in recognizing proprioception components during single and dual tasks	Mechanical device	Forearm
[37]	Determine whether non-visual proprioceptive training can improve sensorimotor function in individuals who have suffered a stroke	Handle of the robotic manipulator	Seventy-three percent of stroke participants responded to the 2-day somatosensory training, improving wrist proprioceptive acuity by 30 %	Exoskeleton	Wrist
[38]	Present a new standardized psychometric platform for collecting data on somatosensory sensations evoked by neuroprosthesis	Software	The study found the platform easy to use and valuable for sensing electrical stimulation effects	Software	Arm, hand
[39]	Determine whether combining advanced and conventional rehabilitation therapy is more effective than treadmill training for improving proprioception and balance in subacute stroke patients	Sensors, software	The study showed a 43 % improvement in proprioceptive sensory changes through multisensory training	Mechanical device	Lower limb

Mechanical devices utilized in SST play a crucial role in rehabilitation by integrating advanced sensors capable of measuring and adjusting the patient's responses. Researchers combined IA with mechanical devices to investigate how proprioception processes signals from the muscle spindle[36]. This approach has resulted in the development of optimized models for kinematic tasks involving the upper limbs, achieving a 40 % increase in Explained Variance (EV). Other studies combined mechanical devices with strategically placed sensors for targeted evaluation[18]. Vibratory stimulations were subsequently applied to the muscle spindles, with sensors capturing and analyzing the emitted signals. By processing this data, the ROM was measured with 99 % accuracy, and the JPS with 91.7 %.

AI has the potential to significantly enhance somatosensory training by providing personalized and adaptive feedback. In the reviewed studies, AI was employed to generate a dataset representing the proprioceptive trajectories of characters, neural networks models were designed and trained, achieving accuracies of 97 %. Furthermore, the Temporal Convolutional Network (TCN) demonstrated superior performance, with an accuracy of 98.86 % [32].

Today, it is possible to construct devices that utilize electronic modules, microcontrollers, or microcomputers (such as, ESP32, Arduino, Raspberry Pi) to combine motor training with pattern recognition and myoelectric signals. These devices employ training sensors to transmit data, enabling the integration of output devices such as screens or monitors. The advantage of these technologies includes their low energy consumption and cost. Integration with other open source tools is usually simple, and the materials used for construction allow for flexible shaping and adapting different projects, ensuring ease-of-use based on specific needs. Research highlights wearable devices that integrate MT and SST with rehabilitation therapies[35]. The analysis demonstrated that proprioceptive exercises with these devices significantly improved Two-Point Discrimination (TDT) in the stimulated areas, achieving a p-value of 0.0021.

Exoskeletons, such as the WristBot, with an estimated market value of $ 17,831.00 USD[37], play a central role in studies investigating the efficacy of non-visual proprioceptive training in improving sensorimotor function among stroke survivors. The device facilitates movement execution through handle manipulation, effectively stimulating and enhancing sensorimotor function. Results indicate that 73 % of participants achieved a 30.2 % reduction in difference threshold and an average 22 % decrease in tracking error. A key advantage of the WristBot lies its all-in-one design, integrating essential components for regular measurement, analysis, and therapy evaluation based on the targeted body area. However, a notable limitation is its substantial size, which necessitates considerable space for installation. Figure 4 illustrates the relationship among the proposed technological categories, input data, and SST applications in the reviewed studies.

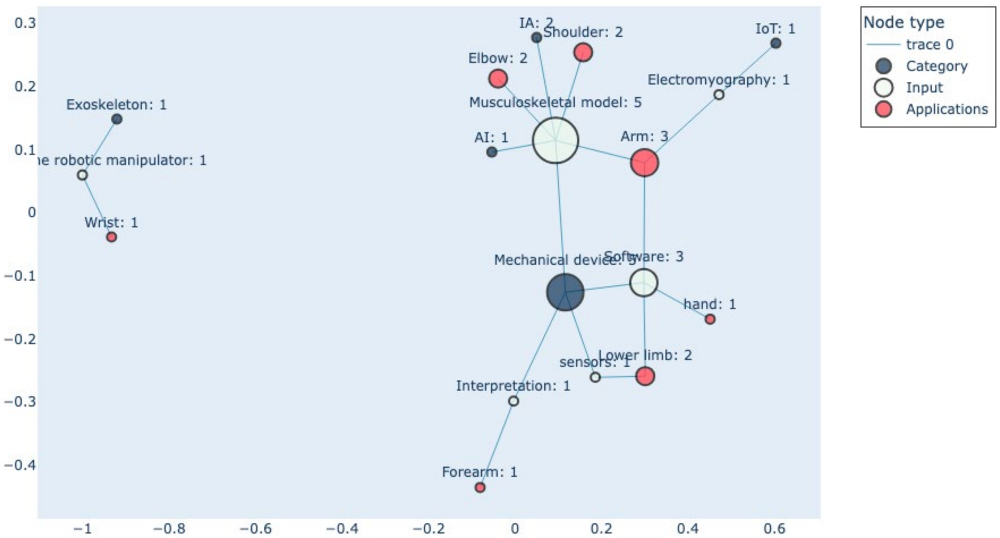

FIGURE 4. **Network of related works in SST considering Category, Input data and main Applications.**

A clear trend emerges toward the use of mechanical devices, which account for a total of five studies, while emerging low-cost niches such as IoT are represented by a single study within the technological categories. Additionally, musculoskeletal models, featured in five studies, emerged as the preferred type of data input, closely associated with mechanical devices. These are followed by proprietary software, utilized in three studies. Opportunities for further exploration were identified in the use of electromyography tests, which were featured in only one study.

Finally, the majority of on SST primarily focus on applications involving the arms, elbows, hands, and wrist. However, a notable gap remains in research addressing the lower limbs.

c) Force Reproduction Training (FRT)

Tension and strength are commonly used to measure proprioception and are often evaluated during Force Reproduction Training (FRT). Contralateral limb matching has become the preferred method for assessing force reproduction. This method usually involves applying the Maximum Voluntary Isometric Contraction (MVIC) measurement force and attempting to replicate it. The coincidence forces can occur either in the same limb or in the contralateral limb[40]. Within the clinical environment, the dynamometer (such as grip, hand, or traction dynamometers) is the most commonly used device for conducting force reproduction assessments[41]. In this context, emerging technologies utilized to assess FRT predominantly include exoskeletons and mechanical devices, has gained popularity in recent years. The main advantage of these technologies is their ability to evaluate multiple areas of the body with a single device. However, their main disadvantages are the high costs of acquisition, maintenance, administration, and the space required for their use. Table 3 presents a selection of studies focused on FRT.

TABLE 3. **Related works for proprioceptive interventions in FRT**

Ref.	Objective	Input data	Outcomes	Category	Applications
[5]	Investigate the relationship between proprioceptive deficits and motor functions in chronic stroke survivors	Handle of the robotic manipulator	Stroke participants had greater errors and variability in the passive position matching test	Mechanical device	Arm
[42]	Create a simulation framework for a lower-limb model with CNS signals and proprioceptive feedback	Images	Incorporating proprioceptors enhances simulation realism and enables more accurate analysis of human movement mechanisms	Software	Leg
[43]	Develop a bionic knee joint structure based on tensegrity for high-efficiency rehabilitation knee exoskeleton	Images	Simulations and experiments validated the NTZNN controllers' performance and noise resistance in noisy environments	IA	Knee
[16]	Evaluating the effectiveness of ML and DL methods in detecting stroke presence using kinematic data from a robotic APM task	Handle of the robotic manipulator	ML and DL models outperformed the traditional cutoff scoring technique in stroke classification	IA, exoskeleton	Upper limb
[44]	Investigate how gender and grip types affect the accuracy of grip force reproduction in healthy individuals	Dynamometer	Women are more accurate or consistent in detecting pinch force changes than men	Electronic device	Finger

AI is revolutionizing strength training by integrating with technologies such as computer vision and wearable sensors to enhance proprioception. Recent studies highlight the use of neural networks (NN) combined with biomechanical devices to improve knee tensegrity[43], These studies involve torque testing and represent various rehabilitation states (-40 N, -150 N, or 0 N), achieving improved knee flexion in older adults, with ranges reaching 130°-140°. Another study demonstrates the use of AI in conjunction with exoskeletons, focusing on a robotic arm that assists patients in performing kinematic movements[16]. The data is processed by a DNN, comparing technological applications against traditional methods. The DL models outperformed conventional cut-off scoring techniques for stroke patients, achieving an accuracy of 86 % and a logistic regression score of 86.6 %.

It should be emphasized that the visualization of information in a user-friendly and comprehensible manner is crucial in the development of technologies, as it facilitates the rapid integration of processed data from sensors, AI, and mechanical devices. Among the reviewed works, a framework stands out that simulates a musculoskeletal model of the lower limbs, processing signals from the nervous system[42]. This study performs a Golgi evaluation, enabling the detection of force tensions ranging from 0.4 N - 7.2 N. The ability to present this data clearly and accessibly is essential for accurate interpretation and decision-making in applications related to proprioception and strength training. In this regard, dynamometers have undergone significant evolution through the integration of advanced technologies such as digital sensors, wireless connectivity, and proprietary software, enabling more precise measurements and real-time force analysis. Research has concentrated on using these devices to measure pinch strength in older adults, particularly to assess MVIC in both men and women[44]. The findings suggest that women exhibit greater accuracy and sensitivity in detecting changes in pinch strength compared to men. This difference may have important implications for designing proprioceptive training programs and strength assessments tailored to specific populations.

Figure 5 illustrates the relationship among the suggested technological categories, the processed input data, and their main applications across different areas of the body. This visual representation reveals how different technologies, including AI, electronic devices, exoskeletons, and software, interact with the data generated by the body during exercises. Additionally, it details how each technology is applied to specific areas, enabling a more precise and personalized analysis of strength.

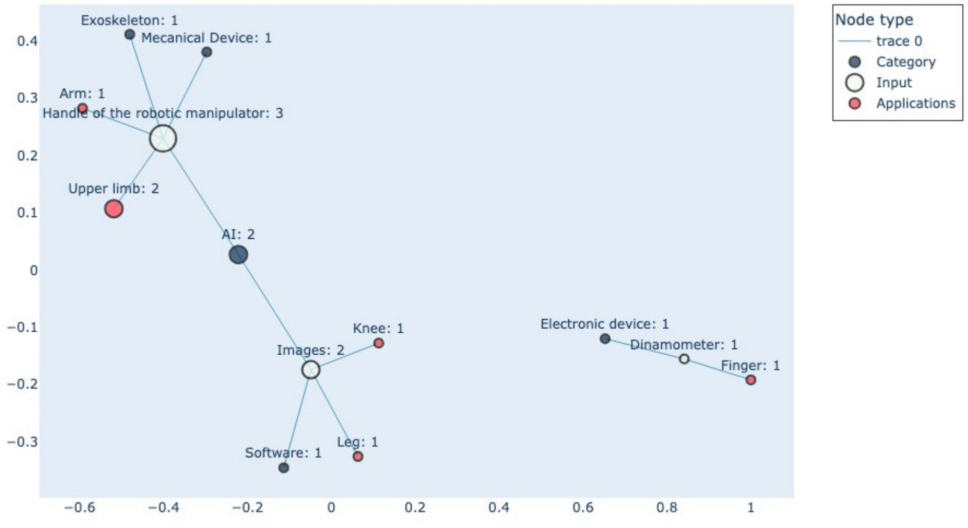

FIGURE 5. Network of related works in FRT considering Category, Input data, and main Applications

Studies focused on improving proprioception in strength training remain limited, although there is a growing trend in the use of AI. However, VR represents an area of opportunity that remains underexplored. The primary sources of data input in the studies derive from robotic devices, which enable real-time measurement and analysis of forces and movements. The applications identified in the studies mainly focus on the upper extremities, including the fingers and arms, as well as the knees and legs—key areas for enhancing proprioception in strength training.

d) Gaps and limitations detected

Emerging technologies applied to proprioceptive rehabilitation exhibit significant potential. However, it is essential to recognize their current limitations and take proactive steps toward addressing these. Several studies have identified the following gaps:

- AI: Despite being the most widely used technology, there is a need to improve the accuracy of various elements, such as classification, keypoint detection, ROM, JRE and MAE

- Exoskeletons: while showing promise for rehabilitation and the improvement of proprioception, they tend to be costly, limiting their accessibility for many users. Additionally, their size and weight can make them challenging to use in certain environments or for specific patients, especially those with reduced mobility. The setup and operation of these devices may also require specialized personnel and increases complexity and operational costs, rendering their implementation in low-budget clinical or rehabilitation settings more difficult

- Mechanical devices: It is necessary to reduce the cost of these devices, as they are effective for specific needs but require a broader range of applicable situations

- VR: users with ophthalmic issues may experience difficulties when using VR devices, as these can affect vision or exacerbate certain visual conditions. The majority of studies utilizing VR employ games, prioritizing patient-friendliness rather than increasing the difficulty of movement

- Sensors: although these devices are typically low-cost, they require the support of the remaining technologies to perform proprioceptive assessment. Examples include actuators, elastic bands, microcontrollers, AI, and proprietary software, among others

Based on the aforementioned analysis, the gaps and limitations identified in MT, SST, and FRT indicate that, despite the existence of various supporting technologies, further work is needed in real-world validation, particularly with patients who have diverse conditions and needs. While these technologies have applications across different parts of the body, the reviewed studies highlight limited research in key areas such as the fingers, wrist, ankle, hip, and elbow. These underexplored body areas present an opportunity to expand the application of these technologies in proprioceptive rehabilitation and training.

e) Challenges

Despite technological advancements across various fields, continuous improvements are essential in each of the emerging technologies identified. The main challenges include:

1. AI: enhancing the precision of its algorithms, exploring different techniques, and reducing the amount of information required to generate the dataset

2. Exoskeletons, Mechanical devices, and VR: principally focusing on reducing costs, improving ergonomics, and refining their design
3. Sensors: focusing on improving accuracy, simplifying calibration and configuration processes, and reducing energy consumption

Thus, the challenges for MT, SST, and FRT may lie in the integration of multiple technologies, such as AI with sensors or electronic devices with software. The goal is to reduce the costs associated with more complex solutions, such as exoskeletons, mechanical devices, or VR.

f) Trends

As illustrated in Figures 3-5, IA is a contemporary approach that addresses various proprioceptive interventions from multiple perspectives, proving to be particularly useful when budget constraints are present by offering a wide range of solutions. On the other hand, home devices (computers, telephones, tablets) are accessible tools that are capable of processing substantial amounts of information, making the use of artificial vision algorithms (CNN, DNN) feasible for image processing. It is evident that current technological access, combined with the ease of acquisition and integration with smart tools, facilitates the development of low-cost solutions that do not require specialized spaces or complex structures, this presenting a promising area for future exploration.

IoT can make communication possible among devices developed by different teams, storing information in the cloud, and constantly generating data regarding the use of the device. This opens a world of possibilities for communication among different device architectures that were initially incompatible or designed for a single purpose.

CONCLUSIONS

This article aims to provide an overview of emerging technologies and their applications within proprioceptive training. There is a significant opportunity for growth in MT, SST, and FRT, as the studies presented are limited, underscoring the need for more in-depth exploration. It is recommended to conduct comprehensive analyses of each type of rehabilitation therapy, focusing on specific areas of application (e.g., arm, leg, hip) or particular techniques (e.g., ROM, JPS, JRE). This approach will enable a more focused and detailed examination.

Technology has been employed to enhance proprioception in various ways, encompassing both the pre- and post-operative periods. In the field of MT, studies have been conducted to assess various aspects of mobility, such as Range of Motion (ROM), Joint Position Sense (JPS), Joint Reproduction Error (JRE), Percentage of Correct Keypoints (PCK), Mean Absolute Error (MAE), Knee Adduction Moment (KAM), and Center of Pressure (COP). A similar approach is observed in SST, where Two-Point Discrimination (TPD), accuracy, and usability have been evaluated. Last, FRT evaluates the absolute error, knee torque, and Maximum Voluntary Isometric Contraction (MVIC). All of these studies employed various emerging technologies applied to different areas of the body.

AI is a key technological trend that complements other technologies in rehabilitation therapies. Due to its cost-effectiveness, ease-of-implementation, and flexibility, AI is increasingly adopted in therapies such as Movement Training (MT), Somatosensory Stimulation (SST), and Force Reproduction Testing (FRT). AI is utilized for tasks such as posture classification, keypoint detection, signal and pattern analysis, recognition, and correlation detection. In addition, when adequate space and budget are available, mechanical devices, exoskeletons, or virtual reality can serve as a viable and effective alternative, tailored to the specific needs of each patient. Thus, devices that operate with IoT or sensors are presented as a low-cost alternative that must be integrated with other technologies to serve as a viable solution for proprioceptive rehabilitation.

It is possible to affirm that emerging technologies currently play a crucial role in Medicine. They serve as a support throughout various stages of rehabilitation therapies, allowing for the development of modern and innovative alternatives that enhance and elevate an individual's quality of life.

It can be concluded that there currently exists a greater technological demand oriented towards MT, followed by SST and finally FRT. The review found that multiple factors must be assessed when selecting the appropriate support technology for rehabilitation, including: the type of intervention required (MT, SST, or FRT), input data, application, rehabilitation site (clinic or home), budget constraints, available space (suitability and adaptation of the area), and whether specialized supervision is needed. Therefore, the final selection will depend on what the user can afford and the specialist's recommendation.

ACKNOWLEDGMENTS

We would like to express our gratitude to the Universidad Autónoma de Guerrero for providing the facilities and resources necessary for conducting postgraduate studies in Innovation Sciences. We also extend our thanks to CONAHCyT for grant number 421452, which supported this research.

DECLARATION OF CONFLICT OF INTEREST

The authors declares that they have no financial or personal relationship with organizations or individuals that could unnaturally influence or interfere in the work.

CONTRIBUTIONS OF THE AUTHORS

U. T. C. conceptualization, investigation, methodology, formal analysis, visualization and writing of the original draft; J. L. H. H. conceptualization, methodology, validation, supervision; E. D. G. conceptualization, methodology, references, supervision; R. I. M. A. conceptualization, supervision, methodology; R. S. conceptualization, methodology, validation, visualization, supervision. All authors reviewed and approved the final version of the manuscript.

REFERENCES

[1] A.-V. Bruyneel, "Evaluación de la propiocepción: pruebas de estatestesia y cinestesia," EMC - Kinesiter. - Med. Fis., vol. 37, no. 4, pp. 1-11, 2016, doi: https://doi.org/10.1016/S1293-2965(16)78903-1

[2] D. T. Tulimieri and J. A. Semrau, "Aging increases proprioceptive error for a broad range of movement speedand distance estimates in the upper limb," Front. Hum. Neurosci., vol. 17, 2023, art. no. 1217105, doi: https://doi.org/10.3389/fnhum.2023.1217105

[3] M. L. Alfonso Mora, et al., "Métodos de evaluación de la propiocepción en deportistas. Revisión de la Literatura," Rev. Digi. Act. Fís. Deport., vol. 4, no. 1, pp. 69-82, 2018. doi: https://doi.org/10.31910/rdafd.v4.n1.2018.415

[4] A. E. Khrulev, et al., "Modern Rehabilitation Technologies of Patients with Motor Disorders at an Early Rehabilitation of Stroke (Review)," Sovrem Tekhnologii Med., vol. 14, no. 6, pp. 64-78, doi: https://doi.org/10.17691/stm2022.14.6.07

[5] A. Cherpin, et al., "A preliminary study on therelationship between proprioceptive deficits and motor functions in chronic stroke patients," 2019 IEEE 16th International Conference on Rehabilitation Robotics (ICORR), Toronto, Canada, 2019, pp. 465-470, doi: https://doi.org/10.1109/ICORR.2019.8779447

[6] V. Suglia et al., "A Serious Game for the Assessment of Visuomotor Adaptation Capabilities during Locomotion Tasks Employing an Embodied Avatar in Virtual Reality," Sensors, vol. 23, no. 11, 2023, art. no, 5017, doi: https://doi.org/10.3390/s23115017

[7] L. Avanzino and M. Fiorio, "Proprioceptive dysfunction in focal dystonia: From experimental evidence to rehabilitation strategies," Front. Hum. Neurosci., vol. 8, 2014, art. no. 1000, doi: https://doi.org/10.3389/fnhum.2014.01000

[8] H. Shibasaki et al., "A new form of congenital proprioceptive sensory neuropathy associated with arthrogryposis multiplex," J. Neurol., vol. 251, no. 11, pp. 1340-1344, 2004, doi: https://doi.org/10.1007/s00415-004-0539-4

[9] J. E. Aman, N. Elangovan, I. L. Yeh, and J. Konczak, "The effectiveness of proprioceptive training for improving motor function: A systematic review," Front. Hum. Neurosci., vol. 8, 2015, art. no. 1075, doi: https://doi.org/10.3389/fnhum.2014.01075

[10] A. Vladimirovich Zakharov, et al., "Proprioception in Immersive Virtual Reality," in Proprioception, 2021, p. 668, doi: https://doi.org/10.5772/intechopen.96316

[11] A. Sidarta, et al., "Current clinical practice in managing somatosensory impairments and the use of technology in stroke rehabilitation," PLoS One, vol. 17, no. 8, 2022, art. no. e0270693, doi: https://doi.org/10.1371/journal.pone.0270693

[12] K. Valdes, K. C. Manalang, and C. Leach, "Proprioception: An evidence-based review," J. Hand Ther., 2023, art. no. 00142-4, doi: https://doi.org/10.1016/j.jht.2023.09.015

[13] C. Mennella, U. Maniscalco, G. De Pietro, and M. Esposito, "A deep learning system to monitor and assess rehabilitation exercises in home-based remote and unsupervised conditions," Comput. Biol. Med., vol. 166, 2023, art. no. 107485, doi: https://doi.org/10.1016/j.compbiomed.2023.107485

[14] P. Aleixo, T. Atalaia, J. V. Patto, and J. Abrantes, "The Effect of a Proprioceptive Exercises Programme on Disease Activity and Gait Biomechanical Parameters of Post-Menopausal Women with Rheumatoid Arthritis," in Rheumatoid Arthritis, 2022, doi: https://doi.org/10.5772/intechopen.99462

[15] Y. Liao, A. Vakanski, and M. Xian, "A Deep Learning Framework for Assessing Physical Rehabilitation Exercises," IEEE Trans. Neural Syst. Rehabil. Eng., vol. 28, no. 2, pp. 468-477, 2020, doi: https://doi.org/10.1109/tnsre.2020.2966249

[16] D. Hossain, S. H. Scott, T. Cluff, and S. P. Dukelow, "The use of machine learning and deep learning techniques to assess proprioceptive impairments of the upper limb after stroke," J. Neuroeng. Rehabil., vol. 20, no. 1, 2023, art. no. 15, doi: https://doi.org/10.1186/s12984-023-01140-9

[17] X. H. Liu, et al., "Impaired Lower Limb Proprioception in Spinocerebellar Ataxia Type 3 and Its Affected Factors," Front. Neurol., vol. 13, 2022, art. no. 833908, doi: https://doi.org/10.3389/fneur.2022.833908

[18] L. Vargas, H. H. Huang, Y. Zhu, and X. Hu, "Static and dynamic proprioceptive recognition through vibrotactile stimulation," J. Neural. Eng., vol. 18, no. 4, 2021, art. no. 046093, doi: https://doi.org/10.1088/1741-2552/ac0d43

[19] M. Cyma-Wejchenig, J. Tarnas, K. Marciniak, and R. Stemplewski, "The influence of proprioceptive training with the use of virtual reality on postural stability of workers working at height," Sensors, vol. 20, no. 13, 2020, art. no. 3731, doi: https://doi.org/10.3390/s20133731

[20] M. Van Den Bogaart, et al., "Validity of deep learning based motion capture using DeepLabCut to assess proprioception," Gait Posture, vol. 106, no. 1, 2023, art. no. S212, doi: https://doi.org/10.1016/j.gaitpost.2023.07.255

[21] Y. Saiki, et al., "Reliabitily and validity of pose estimation algorithm for measurement of knee range of motion after total knee arthroplasty," Bone Joint Res., vol. 12, no. 5, pp. 313-320, 2023, doi: https://doi.org/10.1302/2046-3758.125.bjr-2022-0257.r1

[22] Y. Wang, Z. Pei, C. Wang, and Z. Tang, "Depth-aware pose estimation using deep learning for exoskeleton gait analysis," Sci Rep, vol. 13, no. 1, 2023, art. no. 22681, doi: https://doi.org/10.1038/s41598-023-50207-z

[23] W. Su, Y. Liu, S. Li, and Z. Cai, "Proprioception-Driven Wearer Pose Estimation for Egocentric Video," in 2022 26th International Conference on Pattern Recognition (ICPR), Montreal, Canada, 2022, pp. 3728-3735, doi: https://doi.org/10.1109/ICPR56361.2022.9956092

[24] Y. Guler, et al., "Shoulder Proprioception Following Reverse Total Shoulder Arthroplasty for Unreconstructable Upper Third Fractures of the Humerus: 2-Year Outcomes 2022," Indian J. Orthop., vol. 56, no. 12, pp. 2245-2252, 2022, doi: https://doi.org/10.1007/s43465-022-00769-3

[25] Dos Santos Melício, et al., "DeepRehab: Real Time Pose Estimation on the Edge for Knee Injury Rehabilitation," in Artificial Neural Networks and Machine Learning - ICANN 2021, Bratislava, Slovakia, 2021, doi: https://doi.org/10.1007/978-3-030-86365-4_31

[26] F. Mo, et al., "A simulation-based framework with a proprioceptive musculoskeletal model for evaluating the rehabilitation exoskeleton system," Comput. Methods Programs Biomed., vol. 208, 2021, art. no. 106270, doi: https://doi.org/10.1016/j.cmpb.2021.106270

[27] M. A. Boswell, et al., "A neural network to predict the knee adduction moment in patients with osteoarthritis using anatomical landmarks obtainable from 2D video analysis," Osteoarthritis Cartilage, vol. 29, no. 3, pp. 346-356, 2021, doi: https://doi.org/10.1016/j.joca.2020.12.017

[28] M. Lapresa, et al., "A Smart Solution for Proprioceptive Rehabilitation through M-IMU Sensors," in 2020 IEEE International Workshop on Metrology for Industry 4.0 & IoT, Roma, Italy, 2020, pp. 591-595, doi: https://doi.org/10.1109/MetroInd4.0IoT48571.2020.9138193

[29] R. Wang, et al., "Real-time Soft Body 3D Proprioception via Deep Vision-based Sensing," IEEE Robot Autom. Lett., vol. 5, no. 2, pp. 3382-3389, 2020, doi:

https://doi.org/10.1109/LRA.2020.2975709

[30] A. L. Rahlf, et al., “Validity and Reliability of an Inertial Sensor-Based Knee Proprioception Test in Younger vs. Older Adults,” Front. Sports Act. Living., vol. 1, 2019, art. no. 27, doi: https://doi.org/10.3389/fspor.2019.00027

[31] I. A. Kuling, A. J. de Brouwer, J. B. J. Smeets, and J. R. Flanagan, “Correcting for natural visuo-proprioceptive matching errors based on reward as opposed to error feedback does not lead to higher retention,” Exp. Brain Res., vol. 237, no. 3, pp. 735-741, 2019, doi: https://doi.org/10.1007/s00221-018-5456-3

[32] K. J. Sandbrink, et al., “Contrasting action and posture coding with hierarchical deep neural network models of proprioception,” Elife, vol. 12, 2023, art. no. e81499, doi: https://doi.org/10.7554/elife.81499

[33] L. Winter, Q. Huang, J. V. L. Sertic, and J. Konczak, “The Effectiveness of Proprioceptive Training for Improving Motor Performance and Motor Dysfunction: A Systematic Review,” Front. Rehabil. Sci., vol. 3, 2022, art. no. 830166, doi: https://doi.org/10.3389/fresc.2022.830166

[34] P. Mehta, et al., “Paresthesias and dysesthesias,” in Imaging Acute Neurologic Disease: A Symptom-Based Approach, Cambridge University Press, 2014, pp. 332-346, doi: https://doi.org/10.1017/CBO9781139565653.022

[35] M. Buist, et al., “Novel Wearable Device for Mindful Sensorimotor Training: Integrating Motor Decoding and Somatosensory Stimulation for Neurorehabilitation,” IEEE Trans. Neural Syst. Rehabil. Eng., vol. 32, pp. 1515-1523, 2024, doi: https://doi.org/10.1109/TNSRE.2024.3379996

[36] A. Marin Vargas, A. Bisi, A. S. Chiappa, C. Versteeg, L. E. Miller, and A. Mathis, “Task-driven neural network models predict neural dynamics of proprioception,” Cell, vol. 187, no. 7, pp. 1745-1761.e19, 2024, doi: https://doi.org/10.1016/j.cell.2024.02.036

[37] I. L. Yeh, et al., “Effects of a robot-aided somatosensory training on proprioception and motor function in stroke survivors,” J. Neuroeng. Rehabil., vol. 18, no. 1, 2021, art. no. 77, doi: https://doi.org/10.1186/s12984-021-00871-x

[38] G. Valle, et al., “A Psychometric Platform to Collect Somatosensory Sensations for Neuroprosthetic Use,” Front. Med. Technol., vol. 3, 2021, art. no. 619280, doi: https://doi.org/10.3389/fmedt.2021.619280

[39] C. Lim, “Multi-sensorimotor training improves proprioception and balance in subacute stroke patients: A randomized controlled pilot trial,” Front. Neurol., vol. 10, 2019, art. no. 157, doi: https://doi.org/10.3389/fneur.2019.00157

[40] G. Dover and M. E. Powers, “Reliability of Joint Position Sense and Force-Reproduction Measures During Internal and External Rotation of the Shoulder,” J. Athl. Train., vol. 38, no. 4, pp. 304-310, 2003.

[41] G. Coskun, B. Talu, and A. Cools, “Proprioceptive force-reproduction of the rotator cuff in healthy subjects before and after muscle fatigue,” Isokinet. Exerc. Sci., vol. 26, no. 3, pp. 175-181, 2018, doi: https://doi.org/10.3233/IES-173206

[42] H. Zhang, et al., “A Framework of a Lower Limb Musculoskeletal Model with Implemented Natural Proprioceptive Feedback and Its Progressive Evaluation,” IEEE Trans. Neural Syst. Rehabil. Eng., vol. 28, no. 8, pp. 1866-1875, 2020, doi: https://doi.org/10.1109/tnsre.2020.3003497

[43] C. Xu, et al., “An advanced bionic knee joint mechanism with neural network controller,” Front. Neurorobot, vol. 17, 2023, art. no. 1178006, doi: https://doi.org/10.3389/fnbot.2023.1178006

[44] L. Li, et al., “Effect of pinch types on pinch force sense in healthy adults,” Front. Hum. Neurosci., vol. 16, 2022, art. no. 990431, doi: https://doi.org/10.3389/fnhum.2022.990431