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INNOVATIONS IN NEUROLOGICAL AND MUSCULOSKELETAL REHABILITATION: NEW FRONTIERS IN PAIN MANAGEMENT

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Abstract

Background

This thesis investigates innovative strategies for managing musculoskeletal disorders, chronic pain, and neurological rehabilitation, combining traditional and digital rehabilitation interventions. Through collaborations with international institutions, the research explores tele-rehabilitation and proprioceptive training aimed at improving functional outcomes and reducing chronic pain.

Methods

Clinical trials and cross-sectional studies were conducted, including a randomized controlled trial comparing tele-rehabilitation with conventional therapy for knee osteoarthritis. Outcomes were measured using pain, function, and quality of life scales (NPRS, WOMAC, SF-36). In addition, proprioception and balance were assessed in a cross-sectional study on healthy adults. Multimodal pain management strategies were also evaluated, including cognitive-behavioral therapy, neuromodulation (TENS, tDCS), and pharmacological treatments.

Results

Tele-rehabilitation demonstrated comparable effectiveness to conventional therapy in reducing pain and improving function, with NPRS and WOMAC scores showing significant improvements in both groups ($p < 0.001$). The proprioception study revealed age-related declines in balance, underscoring the importance of targeted training. Multimodal pain management approaches significantly reduced chronic pain and improved patient adherence to rehabilitation protocols, with neuromodulation techniques (TENS, tDCS) proving particularly effective.

Conclusion

Tele-rehabilitation emerges as a viable and accessible alternative for managing musculoskeletal disorders. Proprioceptive training is essential, especially for older adults or those with neurological impairments. The findings support the integration of traditional, digital, and psychological approaches to create a more comprehensive and personalized rehabilitation and pain management model.

Key words: Tele-rehabilitation, proprioception, chronic pain, neuromodulation, neurological rehabilitation.

Table of Contents

Chapter 1

Introduction

This doctoral thesis, titled "Innovative Approaches to Musculoskeletal Disorders, Pain Management, and Neurological Rehabilitation", encapsulates the comprehensive research undertaken in collaboration with various prestigious institutions. During my doctoral journey, I collaborated with the Istituto Ortopedico Rizzoli for research on musculoskeletal disorders, focusing on advanced rehabilitation techniques for fractures and related conditions. This partnership allowed for the investigation of effective interventions aimed at improving functional recovery and reducing disability. In the realm of pain management, significant insights were gained through collaboration with Prof. Marco Barbero in Lugano, Switzerland. Here, the focus was on neuropathic pain and innovative approaches such as the Drucebo effect. This collaboration enabled the development and testing of novel strategies for chronic pain management, contributing to the growing body of knowledge in this field. For neurological rehabilitation, I worked with the IRCCS Institute of Neurological Sciences. The primary focus was on migraine and other neurological conditions, with an emphasis on interventions that promote neuroplasticity and enhance functional outcomes. This research highlighted the importance of tailored rehabilitation programs in improving patient quality of life. Moreover, my work with the University Hospital of Modena on hand rehabilitation involved collaborating with a multidisciplinary team. This allowed for a comprehensive approach to treating hand injuries, utilizing advanced therapeutic techniques to restore function and dexterity. Additionally, the exploration of non-conventional therapies played a crucial role in this research. Techniques such as motor imagery and trigger point therapy were examined for their potential to complement traditional rehabilitation methods, offering patients alternative options for pain relief and functional improvement. These collaborations have fostered a multidisciplinary approach essential for addressing the diverse clinical challenges related to musculoskeletal disorders, pain management, and neurological rehabilitation. The research presented in this thesis aims to contribute significantly to the existing literature, providing new perspectives and methodologies based on robust clinical evidence. This work underscores the importance of an integrated approach in advancing the field of rehabilitation and improving patient outcomes.

Throughout this thesis, I will explore various innovative methodologies applied to chronic pain management and neuromusculoskeletal rehabilitation. The aim is to demonstrate how these interventions, integrating both traditional techniques and emerging technologies such as tele-rehabilitation and neuromodulation, can significantly improve patient outcomes. Each chapter represents a key element of a holistic and personalized approach to rehabilitation, highlighting the need for comprehensive and multidisciplinary treatment models.

Chapter 2

Musculoskeletal disorders

Musculoskeletal disorders (MSDs) encompass a wide range of conditions affecting the muscles, bones, tendons, ligaments, and nerves. These disorders may arise from trauma, repetitive strain, degenerative diseases, or inflammatory processes, significantly impacting an individual's quality of life. Clinically, MSDs can manifest as acute pain and inflammation or chronic stiffness and functional limitations. Early diagnosis and appropriate treatment are critical in preventing the progression of disability and improving therapeutic outcomes. Management strategies include conservative therapies such as physiotherapy and orthotic use, pharmacological interventions for pain and inflammation control, and surgical procedures for addressing complex structural issues. In the clinical setting, ongoing research continues to enhance our understanding of the underlying mechanisms of these disorders and the efficacy of various therapeutic options. Recent studies have investigated innovative approaches, such as ultrasound-guided hydrodistention for adhesive capsulitis and hydrodissection for De Quervain's tenosynovitis, demonstrating promising results in the management of these conditions. Additionally, the importance of early and individualized rehabilitation pathways has emerged as crucial for optimal functional recovery. This chapter delves into a series of cases and studies illustrating different musculoskeletal conditions, their clinical manifestations, and treatment strategies. Through a comprehensive analysis of available evidence, it aims to provide a scientific and technical guide for the effective management of MSDs, ultimately enhancing the quality of life for affected patients (table1).

Table 1 Summary Table

Article Title	Main Research Question	Body Part
Ultrasound Hydrodistention in Adhesive Capsulitis: Hospital versus Home-based Rehabilitation	Effectiveness of ultrasound-guided hydrodistention combined with hospital-based versus home-based rehabilitation in adhesive capsulitis.	Shoulder
Efficacy of Ultrasound-Guided Hydrodissection for Treating De Quervain's Tenosynovitis	Assessing the efficacy of ultrasound-guided hydrodissection in treating De Quervain's tenosynovitis.	Wrist
Treatment of Wrist Stiffness through Posture Orthosis and Active Exercise: A Case Report	Exploring the effectiveness of posture orthosis combined with active exercise in treating wrist stiffness post-fracture.	Wrist
Surgical Resolution of Chronic Thoracic Pain Stemming from a Rare Osteo-Muscular Conflict: A Case Report	Reporting a rare case of chronic thoracic pain caused by an osteo-muscular conflict and its	Thorax

	resolution through surgical intervention.	
Individuals with Chronic Ankle Instability Show Abnormalities in Maximal and Submaximal Isometric Strength	Investigating abnormalities in maximal and submaximal isometric muscle strength of knee extensor and flexor muscles in individuals with chronic ankle instability (CAI).	Ankle/Knee
Exploring the Impact of Rehabilitation on Post-Surgical Recovery in Elbow Fracture Patients: A Cohort Study	Evaluating the impact of rehabilitation on post-surgical recovery of elbow fracture patients.	Elbow
Adhesive Capsulitis: The Importance of Early Diagnosis and Treatment	Emphasizing the significance of early diagnosis and treatment in managing adhesive capsulitis.	Shoulder
A Case Series Analysis: Rehabilitation Pathway for Patients with Postsurgical Stener Lesions Treated with a Functional Thermoplastic Splint and Early Physiotherapy	Evaluating the effectiveness of postsurgical rehabilitation in patients with Stener lesions, focusing on hand functionality and pain management.	Hand

Effects of MLS Laser on Pain, Function, and Disability in Chronic Non-Specific Low Back Pain	Investigating the effects of MLS Laser therapy on pain, function, and disability in patients with chronic non-specific low back pain compared to a placebo treatment group.	Lower Back

This table summarizes the main research questions and the specific body parts studied in various articles related to different medical conditions and treatments. It highlights the focus of each study and the anatomical area affected, providing a quick reference for understanding the scope and objectives of the research.

1. Ultrasound Hydrodistention in Adhesive Capsulitis: Hospital versus Home-based Rehabilitation[20]

- **Objective:** To evaluate the effectiveness of ultrasound-guided hydrodistention combined with hospital-based versus home-based rehabilitation in patients with adhesive capsulitis (figure 1).
- **Findings:** Both groups showed significant improvements in range of motion (ROM) and pain reduction. The hospital-based group demonstrated more rapid improvements initially, but by the end of the study, the home-based group showed slightly better outcomes in some measures. Overall, both approaches were effective, highlighting the importance of hydrodistention in treatment strategies .

2. Efficacy of Ultrasound-Guided Hydrodissection for Treating De Quervain's Tenosynovitis[69]

- **Objective:** To assess the efficacy of ultrasound-guided hydrodissection in treating De Quervain's tenosynovitis.

- **Findings:** The study found that hydrodissection significantly reduced pain and improved functional outcomes in patients with De Quervain's tenosynovitis. Patients reported marked improvements in pain scores and grip strength post-treatment, suggesting that ultrasound-guided hydrodissection is an effective non-surgical treatment option

3. Treatment of Wrist Stiffness through Posture Orthosis and Active Exercise: A Case Report[11]

- **Objective:** To explore the effectiveness of posture orthosis combined with active exercise in treating wrist stiffness post-fracture.
- **Findings:** The case study of a 64-year-old woman showed significant improvement in active range of motion (AROM) through a modified treatment involving custom orthosis and active exercises. Although the results were promising, the study emphasized the need for larger studies to validate the treatment's efficacy

4. Surgical Resolution of Chronic Thoracic Pain Stemming from a Rare Osteo-Muscular Conflict: A Case Report[68]

- **Objective:** To report a rare case of chronic thoracic pain caused by an osteo-muscular conflict and its resolution through surgical intervention.
- **Findings:** A 33-year-old male with a decade-long history of chronic thoracic pain experienced significant symptom relief and improved quality of life following a partial costectomy of the right tenth rib. The case highlights the importance of advanced diagnostic evaluations and targeted surgical interventions in resolving complex musculoskeletal conditions .

5. Individuals with Chronic Ankle Instability Show Abnormalities in Maximal and Submaximal Isometric Strength of the Knee Extensor and Flexor Muscles[35]

- **Objective:** To investigate the abnormalities in maximal and submaximal isometric muscle strength of knee extensor and flexor muscles in individuals with chronic ankle instability (CAI)(figure2).
- **Findings:** The study revealed that individuals with CAI exhibited significant abnormalities in knee flexor strength and submaximal strength of the knee extensor muscles. These findings suggest that rehabilitation for CAI should also address neuromuscular control of proximal joints .

6. Exploring the Impact of Rehabilitation on Post-Surgical Recovery in Elbow Fracture Patients: A Cohort Study[19]

- **Objective:** To evaluate the impact of rehabilitation on the post-surgical recovery of elbow fracture patients.
- **Findings:** The study did not find statistically significant differences in ROM improvements between patients who underwent rehabilitation and those who did not. However, early rehabilitation appeared to help mitigate complications such as joint stiffness. The study underscores the importance of individualized rehabilitation plans and calls for further research with larger patient cohorts .

7. Adhesive Capsulitis: The Importance of Early Diagnosis and Treatment[70]

- **Objective:** To emphasize the significance of early diagnosis and treatment in managing adhesive capsulitis.
- **Findings:** Early diagnosis and intervention are crucial for better outcomes in adhesive capsulitis. Delayed treatment can lead to prolonged pain and limited shoulder movement. The study advocates for prompt therapeutic measures to prevent severe functional impairments

8. A Case Series Analysis: Rehabilitation Pathway for Patients with Postsurgical Stener Lesions Treated with a Functional Thermoplastic Splint and Early Physiotherapy[48]

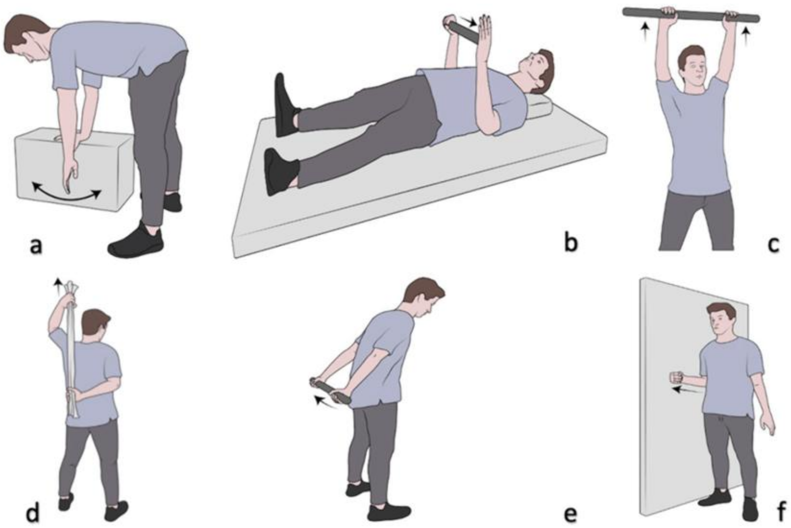
- **Objective:** To evaluate the effectiveness of postsurgical rehabilitation in patients with Stener lesions, focusing on hand functionality and pain management.
- **Findings:** The study showed significant improvements in range of motion (ROM) and grip strength, particularly in the early stages of rehabilitation. Pain levels remained low, and there was a notable decrease in disability in daily activities, suggesting the efficacy of early postoperative rehabilitation.

9. Effects of MLS Laser on Pain, Function, and Disability in Chronic Non-Specific Low Back Pain[33]

Objective: This double-blind placebo randomized-controlled trial aimed to investigate the effects of Multiwave Locked System (MLS) Laser therapy on pain, function, and disability in patients with chronic non-specific low back pain, compared to a placebo treatment group (figure 3).

Findings: The study involved 45 patients randomized into two groups: the MLS Laser group and the Sham Laser group. Both groups underwent 8 sessions of their respective treatments. Results showed a significant reduction in pain and disability in both groups immediately after the therapy and one month later. However, the MLS Laser group exhibited a significantly lower pain level compared to the Sham group one month after the end of therapy, indicating that MLS Laser therapy is more effective in reducing pain in the long term. No significant differences were found between the groups regarding function and disability.

Figure 1 Post-Hydrodistension Recovery Exercises for Frozen Shoulder



This illustration shows a series of exercises specifically designed to aid recovery following hydrodistension treatment for frozen shoulder (adhesive capsulitis):

- **a)** Lifting exercise with a box to enhance arm and shoulder strength and improve range of motion.
- **b)** Supine position shoulder press to strengthen the upper body and facilitate shoulder mobility.
- **c)** Overhead pull-up exercise to improve shoulder flexibility and arm strength.
- **d)** Stretching exercise using a pole to increase shoulder flexibility and reduce stiffness.
- **e)** Backward arm extension with a pole to enhance shoulder joint mobility and function.
- **f)** Rotational shoulder exercise using a wall for stability and to regain full range of motion in the shoulder.

These exercises are critical in the rehabilitation process, helping to restore function and reduce pain after hydrodistension treatment for frozen shoulder.

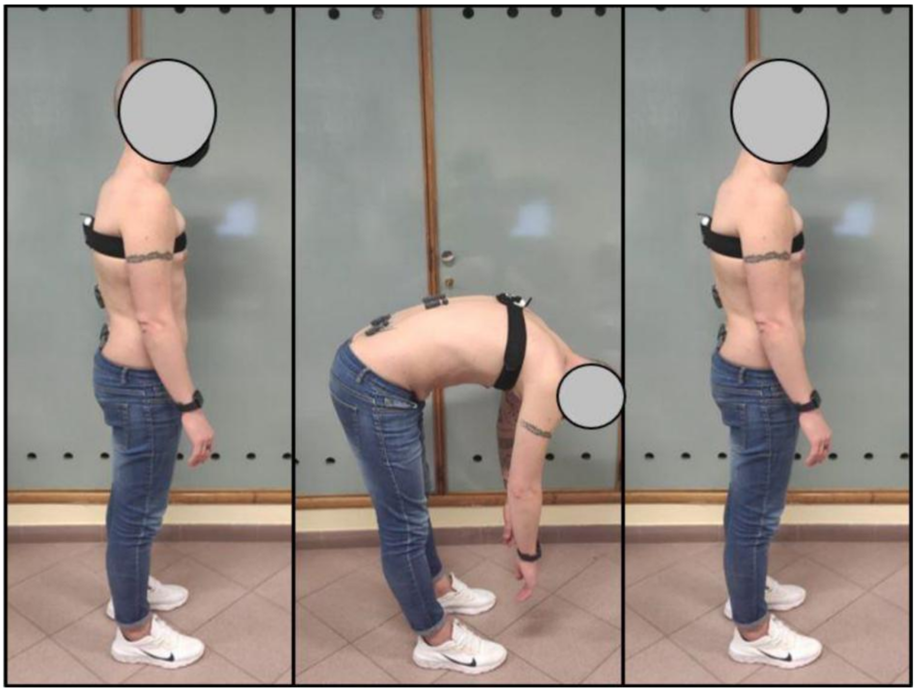
Figure 2 Thigh Muscle Force Evaluation for Ankle Instability Assessment

This image depicts a subject undergoing a thigh muscle force evaluation to assess the impact of chronic ankle instability. The evaluation involves:

- The subject seated in a specialized chair with their thigh muscles connected to sensors.
- A computer system recording and analyzing muscle force data during the test.

This procedure helps in understanding the neuromuscular control and strength of the thigh muscles, which is crucial for developing effective rehabilitation strategies for individuals with chronic ankle instability.

Figure 3 Muscle Activation Assessment with Forward Bending Test



One of the patients performing the forward bending with wireless EMG probes applied over the longissimus dorsi and the multifidus muscles, and an accelerometer placed in the middle of the shoulder blades.

Throughout this thesis, I will explore various innovative methodologies applied to chronic pain management and neuromusculoskeletal rehabilitation. The aim is to demonstrate how these interventions, integrating both traditional techniques and emerging technologies such as tele-rehabilitation and neuromodulation, can significantly improve patient outcomes. Each chapter represents a key element of a holistic and personalized approach to rehabilitation, highlighting the need for comprehensive and multidisciplinary treatment models.

Chapter 3

Neurological Rehabilitation

Neurological rehabilitation is an essential field dedicated to restoring and enhancing the functional abilities and quality of life of individuals suffering from neurological disorders. These disorders encompass a broad spectrum of conditions, including stroke, traumatic brain injury, Parkinson's disease, multiple sclerosis, spinal cord injuries, and other neurodegenerative diseases. The impairments resulting from these conditions often affect motor skills, cognitive functions, communication, and the ability to perform daily activities, necessitating a comprehensive and multidisciplinary approach to rehabilitation. The primary objective of neurological rehabilitation is to maximize the patient's functional independence and promote optimal recovery. This is achieved through a coordinated effort involving various healthcare professionals, including neurologists, physiatrists, physical therapists, occupational therapists, speech-language pathologists, neuropsychologists, and social workers. The rehabilitation process is highly individualized, taking into account the unique needs, capabilities, and goals of each patient. Recent advancements in technology and therapeutic techniques have significantly enhanced the efficacy of neurological rehabilitation. Robotic-assisted therapy, for example, provides precise and repetitive movements that aid in motor recovery. Virtual reality (VR) systems offer immersive environments for practicing motor and cognitive tasks, thereby improving engagement and outcomes. Non-invasive brain stimulation techniques, such as transcranial magnetic stimulation (TMS) and transcranial direct current stimulation (tDCS), have shown promise in modulating neural activity to enhance recovery processes. In addition to these technological innovations, evidence-based practices form the cornerstone of effective rehabilitation. Research has consistently demonstrated the benefits of early and intensive rehabilitation interventions. Neuroplasticity, the brain's ability to reorganize itself by forming new neural connections, plays a critical role in recovery. Rehabilitation strategies that leverage neuroplasticity include task-specific training, constraint-induced movement therapy, and mirror therapy. This chapter delves into the latest research and clinical applications in neurological rehabilitation. It examines a variety of innovative approaches and their outcomes, providing a comprehensive overview of how these techniques are integrated into patient care. By exploring the intersection of technology, therapy, and patient-centered care, this chapter aims to illuminate the pathways to enhanced recovery and improved quality of life for individuals affected by neurological conditions (table 2).

Table 2 Summary Table

Article Title	**Main Research Question**	**Body Part**
An Overview of Rehabilitation Approaches for Focal Hand Dystonia in Musicians: A Scoping Review	Effectiveness of rehabilitation approaches for focal hand dystonia in musicians.	Hand
Assessment of Postural Control and Proprioception Using the Delos Postural Proprioceptive System	Assessment of postural control and proprioception using DPPS.	Whole body

Automated Mechanical Peripheral Stimulation for Gait Rehabilitation in Parkinson's Disease: A Comprehensive Review	Impact of AMPS on gait rehabilitation in Parkinson's Disease.	Lower limbs
COVID-19-Associated Cerebellitis: A Case Report and Rehabilitation Outcome	Clinical presentation and rehabilitation outcomes of COVID-19-associated cerebellitis.	Cerebellum/Whole body
Is Physiotherapy in Migraines Known to Sufferers? A Cross-Sectional Study	Awareness and benefits of physiotherapy in migraine management.	Head/Neck

Kinematic and Plantar Pressure Analysis in Strumpell-Lorrain Disease: A Case Report	Gait abnormalities and plantar pressures in Strumpell-Lorrain disease.	Lower limbs
Harnessing Mirror Neurons: A New Frontier in Parkinson's Disease Rehabilitation—A Scoping Review of the Literature	Effectiveness of mirror neuron-based rehabilitation techniques in Parkinson's Disease.	Whole body

Gait Quality After Robot Therapy Compared with Physiotherapy in the Patient with Incomplete Spinal Cord Injury: A Systematic Review	Comparing the effectiveness of robot-assisted gait training combined with conventional physiotherapy versus conventional physiotherapy alone in improving gait quality in patients with incomplete spinal cord injury.	Lower limbs

This table provides a comprehensive overview of the main research questions addressed in recent studies on neurological rehabilitation, along with the specific body parts involved. Each study explores different therapeutic approaches and their impact on various neurological conditions, highlighting advancements in rehabilitation techniques and their effectiveness in improving patient outcomes.

1. An Overview of Rehabilitation Approaches for Focal Hand Dystonia in Musicians: A Scoping Review[13]

Objective: To compile and evaluate various rehabilitation approaches for focal hand dystonia (FHD) in musicians, with an emphasis on their efficacy and methodologies.

Findings: The review identified several rehabilitation methods, including sensory motor retuning, constraint-induced therapy, and transcranial magnetic stimulation. Each approach showed varying levels of success. Instrumental retraining emerged as particularly promising. The study highlighted the necessity of individualized treatment plans and called for more research on long-term outcomes and standardized protocols

2. Assessment of Postural Control and Proprioception Using the Delos Postural Proprioceptive System[51]

Objective: To assess the effectiveness of the Delos Postural Proprioceptive System (DPPS) in evaluating postural control and proprioception across different population groups.

Findings: The DPPS was validated as a reliable tool for measuring postural stability and proprioception. It demonstrated sensitivity in detecting temporal changes and provided crucial data for developing targeted rehabilitation strategies. The system's ability to enhance the understanding and management of balance-related conditions was underscored (figure 4).

3. Automated Mechanical Peripheral Stimulation for Gait Rehabilitation in Parkinson's Disease: A Comprehensive Review[52]

Objective: To review the impact of Automated Mechanical Peripheral Stimulation (AMPS) on gait and motor performance in patients with Parkinson's Disease (PD).

Findings: The review included ten studies showing positive effects of AMPS on gait parameters such as walking speed, stride length, and stability. Improvements in functional performance and muscle activation during walking were noted. However, more robust randomized controlled trials are needed to confirm long-term efficacy and optimize treatment protocols.

4. COVID-19-Associated Cerebellitis: A Case Report and Rehabilitation Outcome[63]

Objective: To document the clinical presentation, treatment, and rehabilitation outcomes of a patient with cerebellitis associated with COVID-19.

Findings: The 22-year-old male patient presented with ataxia and dysarthria. Treatment included steroid therapy, vitamin supplementation, physiotherapy, and intravenous immunoglobulins. Significant improvements in balance, coordination, and daily activities were observed, though mild symptoms persisted. The case emphasizes the importance of a multidisciplinary approach for managing neurological complications associated with COVID-19 and calls for further research on pathogenesis and treatment strategies.

5. Is Physiotherapy in Migraines Known to Sufferers? A Cross-Sectional Study[65]

Objective: To investigate the awareness and experience of migraine patients regarding physiotherapy as a complementary treatment (figure 5).

Findings: The survey indicated that only 19.5% of migraine patients had undergone physiotherapy, but 56.4% reported benefits such as reduced attack intensity and frequency. Despite limited exposure, 90.1% of participants expressed interest in physiotherapy. The study highlights a significant gap in awareness and the potential of physiotherapy in managing migraines, suggesting increased accessibility and randomized controlled trials to validate its effectiveness.

6. Kinematic and Plantar Pressure Analysis in Strumpell-Lorrain Disease: A Case Report[53]

Objective: To assess spatial-temporal parameters and plantar pressures in a patient with Strumpell-Lorrain disease using motion sensors and a baropodometric platform(figure 6).

Findings: The analysis revealed significant gait abnormalities, including reliance on monopodal support during the swing phase and difficulty in ankle dorsiflexion due to spasticity. These findings provide insights into the specific gait impairments associated with Strumpell-Lorrain disease and emphasize the need for targeted rehabilitation strategies to address these issues and improve mobility.

7. Harnessing Mirror Neurons: A New Frontier in Parkinson's Disease Rehabilitation—A Scoping Review of the Literature

Objective: To map current evidence on the effectiveness of mirror neuron-based rehabilitation techniques in improving motor functions and quality of life in Parkinson's Disease (PD) patients.

Findings: The review included five studies focusing on action observation (AO) and motor imagery (MI). These techniques consistently demonstrated positive outcomes, such as reduced disease severity and improved gait, balance, and quality of life. Activation of mirror neurons through AO and MI facilitated motor learning and improved functional mobility. The study calls for more comprehensive research to integrate these techniques into standard physiotherapy routines for PD patients .

8. Gait Quality After Robot Therapy Compared with Physiotherapy in the Patient with Incomplete Spinal Cord Injury: A Systematic Review[21]

Objective: To compare the effectiveness of Robot-Assisted Gait Training (RAGT) combined with conventional physiotherapy versus conventional physiotherapy alone in improving gait quality in patients with incomplete spinal cord injury.

Findings: The systematic review included four studies with a total of 258 participants. RAGT combined with conventional physiotherapy showed greater improvements in locomotor function, lower limb muscle strength, and the need for assistance in walking. However, not all improvements were statistically significant. The review concludes that a rehabilitation protocol combining RAGT with conventional physiotherapy is more effective than isolated conventional physiotherapy in improving ambulation in the subacute phase

Figure 4 Delos Postural Proprioceptive System

An individual performing exercises using the Delos Postural Proprioceptive System (DPPS) to assess and improve postural control and proprioception. The DPPS aids in rehabilitation by providing feedback on balance and stability, essential for patients recovering from neurological conditions.

Figure 5 MINDS - Migraine and Physiotherapy Questionnaire

MINDS- MigraIne aND phySiotherapy

Ha mai eseguito della Fisioterapia per il suo mal di testa?

SÌ **NO**

Se SÌ: Si ricorda che tipo di fisioterapia e chi le ha proposto di farla?

____

Ne ha tratto beneficio?

SÌ **NO**

Se SÌ: In che termini (scelga una risposta):

- ☐ riduzione n° di attacchi
- ☐ riduzione dll'intensità degli attacchi
- ☐ ha ridotto i farmaci?
- ☐ Miglioramento della qualità di vita/riduzione della disabilità dovuta al mal di testa.
- ☐ Altro? Spieghi con parole su:

____

Se NO: Le hanno mai proposto di farla?

SÌ **NO**

Sarebbe interessato?

SÌ **NO**

Che trattamento pensa le proporrebbero in un ciclo di fisioterapia?

____

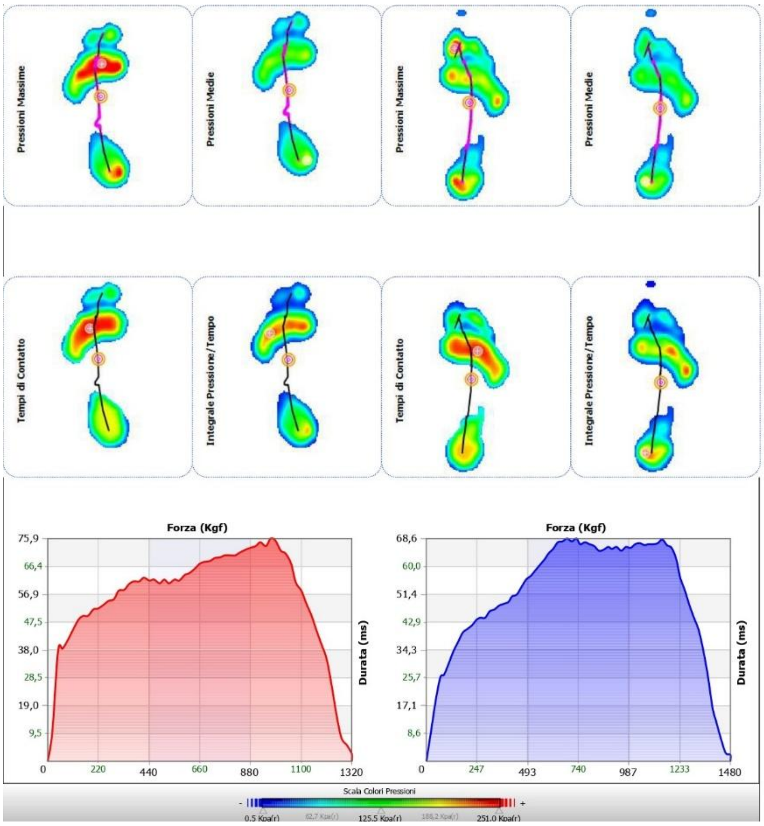
Cosa si aspetterebbe da un cilo di fisioterapia? (scelga l'opzione che ritiene più importante)

- ☐ riduzione n° di attacchi
- ☐ riduzione dll'intensità degli attacchi
- ☐ ha ridotto i farmaci?
- ☐ Miglioramento della qualità di vita/riduzione della disabilità dovuta al mal di testa.
- ☐ Altro? Spieghi con parole su:

____

This questionnaire is designed to assess the awareness, usage, and perceived benefits of physiotherapy among individuals suffering from migraines. It aims to gather information on whether patients have undergone physiotherapy for their headaches, the types of physiotherapy used, the benefits experienced, and their openness to considering physiotherapy if they haven't already. The survey also explores the expectations from a physiotherapy cycle in terms of migraine management.

Figure 6 Baropodometric Examination in Strumpell-Lorrain Disease



Baropodometric analysis in a patient with Strumpell-Lorrain disease. The top row shows the distribution of plantar pressures during different phases of the gait cycle, indicating areas of maximum and average pressure. The bottom row presents temporal parameters such as contact time and pressure-time integrals for each foot. The force-time graphs below display the exerted force over the duration of contact for both feet, highlighting gait asymmetries and abnormalities. This comprehensive analysis helps in identifying specific gait impairments and developing targeted rehabilitation strategies.

Following the examination of innovations in musculoskeletal and neurological rehabilitation, this chapter delves into the critical role of pain management within these rehabilitative processes. Pain, whether acute or chronic, is not merely a symptom but often a significant barrier to full patient engagement in rehabilitation therapies. Therefore, effective pain management is essential for optimizing rehabilitation outcomes.

Chapter 4

Pain Management

Pain is a complex and multifaceted phenomenon that significantly impacts an individual's physical, emotional, and psychological well-being. It is defined by the International Association for the Study of Pain (IASP) as "an unpleasant sensory and emotional experience associated with, or resembling that associated with, actual or potential tissue damage." In the context of rehabilitation, pain management is paramount as it influences patient outcomes, adherence to therapeutic protocols, and overall quality of life. Effective pain management strategies are crucial for facilitating recovery, improving functionality, and enhancing the rehabilitative process. Pain can be categorized into acute and chronic types. Acute pain serves as a warning signal of injury or disease, typically resolving as the underlying cause heals. Conversely, chronic pain persists beyond the normal healing period, often without a clear etiology, and can become a disease in its own right. Chronic pain conditions, such as low back pain, osteoarthritis, and neuropathic pain, pose significant challenges due to their persistent nature and complex underlying mechanisms. The role of pain in rehabilitation cannot be overstated. Pain often dictates the pace and extent of physical therapy, influencing both patient compliance and the efficacy of rehabilitative interventions. Inadequate pain management can lead to diminished motivation, reduced participation in therapeutic exercises, and ultimately, suboptimal rehabilitation outcomes. Therefore, integrating effective pain management strategies into rehabilitation protocols is essential for promoting recovery and improving patient functionality. Pain management in rehabilitation encompasses a diverse range of techniques and interventions, tailored to address the multifactorial nature of pain. These approaches can be broadly categorized into pharmacological and non-pharmacological strategies. Pharmacological treatments remain a cornerstone of pain management. Analgesics, anti-inflammatory drugs, and neuropathic pain medications are commonly employed to alleviate pain symptoms. However, the reliance on pharmacological solutions necessitates caution due to potential side effects and the risk of dependency, particularly with opioid medications. Non-pharmacological strategies are increasingly recognized for their efficacy and safety in pain management. These interventions include physical therapies, psychological approaches, and innovative neuromodulation techniques. Physical therapy interventions, such as exercise, manual therapy, and modalities like ultrasound and transcutaneous electrical nerve stimulation (TENS), play a vital role in managing pain and improving functional outcomes. The integration of aerobic activity, as seen in the management of post-surgical clavicle fractures, highlights the benefits of physical exercise in modulating pain and enhancing recovery. Techniques such as transcranial direct current stimulation (tDCS) and spinal cord stimulation (SCS) offer promising avenues for pain relief. For instance, tDCS has been shown to reduce pain intensity and improve functional outcomes in conditions like radial capitellum fractures and chronic foot pain, demonstrating its potential as a non-invasive, adjunctive treatment for pain management. Complementary approaches, including mindful breathing, music therapy, and trigger point therapy, provide additional avenues for pain management. Mindful breathing has been effective in reducing chronic low back pain, while 432 Hz frequency music has shown potential in alleviating anxiety and improving relaxation. Trigger point therapy is particularly beneficial in managing muscular spasticity, highlighting its role in comprehensive pain management strategies. Psychological interventions, such as cognitive-behavioral therapy (CBT), biofeedback, and relaxation techniques, address the emotional and cognitive aspects of pain. These methods are crucial for managing chronic pain, which often involves significant psychological components, including anxiety and depression. An integrative approach to pain management in rehabilitation involves combining multiple strategies to address the various dimensions of pain. This holistic perspective ensures that both the physiological and psychological aspects of pain are managed effectively, leading to improved patient outcomes. For example, integrating motor imagery techniques with traditional physical therapy can enhance pain relief and functional recovery in foot pain, providing a comprehensive treatment plan that addresses both the mental and physical components of rehabilitation. Pain management is a critical component of rehabilitation, encompassing a wide range of pharmacological and non-pharmacological approaches. By addressing the multifaceted nature of pain through an integrative and holistic framework, healthcare providers can optimize rehabilitation outcomes, improve patient quality of life, and foster a more effective recovery process (table 3).

Table 3 Summary Table

Article Title	**Main Research Question**	**Body Part**
Adapting RegentK Principles for Non-Surgical Meniscal Tear Management: An Innovative Case Report	How can RegentK principles be adapted for non-surgical management of meniscal tears?	Knee (Meniscus)

An Overview and Critical Analysis of the Graston Technique for Foot-Related Conditions: A Scoping Review	What is the effectiveness of the Graston technique for foot-related conditions?	Foot
Can Beneficial Frequencies in Physiotherapy Help Treatment? Scoping Review	What is known from the existing literature on the use of 432Hz frequency music and rehabilitation?	General (Physiotherapy)
Case Report: Integrating Aerobic Activity in Post-Surgical Management of Plurifragmentary Distal Clavicle Fractures	How can aerobic activity be integrated into post-surgical management of distal clavicle fractures?	Shoulder (Clavicle)

Mindful Breathing as an Adjunctive Approach to Chronic Low Back Pain Management: A Scoping Review	How can mindful breathing be used as an adjunctive approach to manage chronic low back pain?	Back (Low Back Pain)
Transcranial Direct Current Stimulation (tDCS) in Managing Pain and Recovery: A Clinical Case of Radial Capitellum Fracture	What is the efficacy of tDCS in managing pain and facilitating recovery in radial capitellum fractures?	Elbow (Radial Capitellum)

Unveiling the Potential of Trigger Point Therapy: Exploring Its Efficacy in Managing Muscular Spasticity: A Scoping Review	What is the efficacy of trigger point therapy in managing muscular spasticity?	Muscles
Unlocking the Power of Motor Imagery: A Comprehensive Review on Its Application in Alleviating Foot Pain	How can motor imagery be applied to alleviate foot pain?	Foot
Transcranial Direct Current Stimulation for Chronic Foot Pain: A Comprehensive Review	What is the efficacy, safety, and mechanism of tDCS in managing chronic foot pain?	Foot

Summary of the main research questions and targeted body parts for the selected articles on various rehabilitation techniques and treatments. Each article explores different approaches for managing specific conditions, ranging from non-surgical methods for meniscal tears to the use of transcranial direct current stimulation (tDCS) for chronic foot pain.

1. Adapting RegentK Principles for Non-Surgical Meniscal Tear Management: An Innovative Case Report[58]

Objective: To investigate the application of RegentK principles for non-surgical management of meniscal tears and evaluate its impact on pain alleviation and functional enhancement (figure 7).

Findings: The application of RegentK principles led to significant improvements in pain reduction and functional outcomes in patients with meniscal tears. The case report demonstrated that patients experienced decreased pain levels and increased mobility, suggesting that RegentK could be a viable non-surgical treatment option for meniscal injuries.

2. An overview and critical analysis of the Graston technique for foot-related conditions: a scoping review[59]

Objective: To critically analyze the efficacy of the Graston technique in the treatment of foot-related conditions and identify existing research gaps.

Findings: The Graston technique showed promise in improving pain and functional outcomes in patients with various foot-related conditions, including plantar fasciitis and Achilles tendinopathy. However, the review highlighted a lack of standardized protocols and the need for more rigorous, high-quality studies to confirm these findings and establish consistent treatment guidelines.

3. Can beneficial frequencies in physiotherapy help treatment? Scoping Review[54]

Objective: To systematically review the literature on the therapeutic effects of 432 Hz frequency music in physiotherapy and rehabilitation.

Findings: Listening to music at 432 Hz was associated with positive effects on sleep quality, anxiety reduction, and heart rate. Studies included in the review reported that patients experienced improved relaxation and reduced stress levels. Despite these promising results, the evidence base remains limited, necessitating further research to validate these findings and explore the underlying mechanisms.

4. Case report: Integrating aerobic activity in post-surgical management of plurifragmentary distal clavicle fractures[55]

Objective: To evaluate the role of aerobic exercise in the post-surgical management of plurifragmentary distal clavicle fractures and its influence on pain and recovery outcomes (figure 8).

Findings: Integrating aerobic activity into the rehabilitation program for patients with distal clavicle fractures significantly improved pain modulation and overall recovery. The case report showed enhanced functional outcomes and faster return to daily activities, supporting the incorporation of aerobic exercise as a beneficial component of post-surgical rehabilitation.

5. Mindful Breathing as an Adjunctive Approach to Chronic Low Back Pain Management: A Scoping Review[60]

Objective: To assess the adjunctive use of mindful breathing techniques in chronic low back pain management and their effectiveness in improving patient outcomes.

Findings: Mindful breathing techniques were effective in reducing chronic low back pain and improving functional outcomes. Patients practicing mindful breathing reported lower pain levels, increased mobility, and enhanced quality of life. The review suggests that mindful breathing can be a valuable addition to comprehensive pain management strategies.

6. Transcranial Direct Current Stimulation (tDCS) in managing pain and recovery: A clinical case of radial capitellum fracture[64]

Objective: To examine the effectiveness of transcranial Direct Current Stimulation (tDCS) in the management of pain and functional recovery in patients with radial capitellum fractures (figure 9).

Findings: The application of tDCS significantly reduced pain and improved functional recovery in a patient with a radial capitellum fracture. The case study indicated notable improvements in pain scores and range of motion, suggesting that tDCS could be a promising non-pharmacological intervention for pain management in orthopedic injuries.

7. Unveiling the Potential of Trigger Point Therapy: Exploring its Efficacy in Managing Muscular Spasticity: A Scoping Review[56]

Objective: To explore the efficacy of trigger point therapy in the management of muscular spasticity and the necessity for standardized treatment protocols.

Findings: Trigger point therapy was effective in reducing muscular spasticity and improving mobility in patients with spasticity-related conditions. The review highlighted significant reductions in muscle tightness and pain, but also pointed out the need for standardized treatment protocols to ensure consistent and reproducible outcomes.

8. Unlocking the power of motor imagery: a comprehensive review on its application in alleviating foot pain[61]

Objective: To review the application and effectiveness of motor imagery techniques in the alleviation of foot pain and enhancement of functional rehabilitation.

Findings: Motor imagery techniques effectively reduced foot pain and improved functional outcomes in patients. The review found that patients using motor imagery experienced less pain and better performance in physical activities, supporting the integration of these techniques into standard physiotherapy practices for foot pain management.

9. Transcranial direct current stimulation for chronic foot pain: A comprehensive review[62]

Objective: To provide a comprehensive review of the efficacy, safety, and mechanisms of transcranial direct current stimulation (tDCS) in managing chronic foot pain, including conditions like plantar fasciitis.

Findings: The review demonstrated significant reductions in pain intensity and improvements in related outcomes following tDCS treatment for chronic foot pain. Patients reported decreased pain levels, enhanced foot function, and reduced pain-related anxiety. The review supports tDCS as a promising neuromodulation approach for chronic foot pain management, highlighting its potential to improve patient outcomes and quality of life. Further research is needed to optimize treatment parameters and evaluate long-term effects.

Figure 7 Sagittal MRI of Complex Meniscal Tear

This sagittal MRI image shows a complex fissure of the meniscus, illustrating the intricate nature of the tear and its potential impact on knee joint function and stability. Complex meniscal tears often require detailed assessment to determine the appropriate non-surgical or surgical intervention for optimal patient outcomes.

Figure 8 3D CT Reconstruction of Displaced Clavicle Fracture

This 3D CT reconstruction image demonstrates a displaced fracture of the clavicle. The image clearly shows the misalignment of the fractured bone segments, providing crucial information for the planning of surgical intervention and rehabilitation strategies. Displaced clavicle fractures often require detailed imaging to assess the extent of displacement and to guide appropriate treatment.

Figure 9 Application of Transcranial Direct Current Stimulation (tDCS)

right images depict the proper placement of the electrodes on a patient's scalp. tDCS is a non-invasive brain stimulation technique used to modulate neuronal activity, often employed in the management of chronic pain, neurological rehabilitation, and cognitive enhancement. Proper electrode placement is crucial for the efficacy and safety of the treatment.

Chapter 5

Advanced Approaches to Pain Control in Rehabilitation

5.1 Mechanisms, Implications, and Strategies

Pain is a complex and multifaceted phenomenon that significantly impacts an individual's physical, emotional, and psychological well-being. In the context of rehabilitation, effective pain management is crucial for optimizing recovery, enhancing functionality, and ensuring adherence to therapeutic interventions. Understanding pain from a neurophysiological perspective provides insights into its mechanisms and informs the development of comprehensive management strategies. Pain perception, or nociception, begins with the activation of nociceptors, which are specialized sensory receptors located in the skin, muscles, joints, and certain internal organs. These receptors respond to potentially harmful stimuli such as mechanical pressure, extreme temperatures, and chemical irritants. When activated, nociceptors generate electrical signals that are transmitted via peripheral nerve fibers to the spinal cord and brain. There are two primary types of nerve fibers involved in pain transmission: A-delta fibers and C fibers. A-delta fibers are myelinated, allowing for fast transmission of sharp, acute pain signals. In contrast, C fibers are unmyelinated and conduct signals more slowly, resulting in a dull, throbbing pain sensation. Upon reaching the dorsal horn of the spinal cord, these signals are processed and relayed to higher brain centers for further interpretation. The spinal cord serves as a critical relay and processing center for pain signals. Here, the initial pain signal can be amplified or dampened through various mechanisms. One such mechanism is the gate control theory of pain, which proposes that non-painful input can close the "gates" to painful input, thereby preventing pain sensation from traveling to the central nervous system. This theory highlights the role of interneurons in the dorsal horn that can inhibit the transmission of pain signals, providing a potential target for pain management interventions. Upon reaching the brain, pain signals are processed in several regions, including the thalamus, somatosensory cortex, limbic system, and prefrontal cortex. The thalamus acts as a central relay station, directing signals to the appropriate cortical areas for perception and interpretation. The somatosensory cortex is responsible for the localization and intensity of pain, while the limbic system and prefrontal cortex are involved in the emotional and cognitive aspects of pain, respectively. This complex network explains why pain is not merely a physical sensation but also an emotional and psychological experience. Chronic pain, which persists beyond the normal healing period, often involves changes in the nervous system that contribute to its persistence. These changes can include sensitization, where the nervous system becomes more responsive to pain stimuli, and maladaptive neuroplasticity, where the brain's pain pathways are altered, leading to sustained pain perception even in the absence of an obvious physical cause. Understanding these neurophysiological changes is critical for developing effective pain management strategies in rehabilitation. Effective pain management in rehabilitation encompasses both pharmacological and non-pharmacological strategies. Pharmacological treatments, including analgesics, anti-inflammatory drugs, and neuropathic pain agents, are commonly used to alleviate pain. However, their use must be carefully managed to avoid side effects and potential dependency, particularly with opioids. Non-pharmacological interventions are increasingly recognized for their efficacy and safety. These strategies include physical therapies, psychological approaches, and innovative neuromodulation techniques. Physical therapy interventions such as exercise, manual therapy, and modalities like ultrasound and transcutaneous electrical nerve stimulation (TENS) play a critical role in pain management by reducing pain, improving mobility, and enhancing overall physical function. Psychological interventions, including cognitive-behavioral therapy (CBT), biofeedback, and relaxation techniques, address the emotional and cognitive aspects of pain, which are particularly important for managing chronic pain. Innovative neuromodulation techniques, such as transcranial direct current stimulation (tDCS) offer promising avenues for pain relief. tDCS has been shown to reduce pain intensity and improve functional outcomes in various conditions, including chronic pain syndromes. These advanced techniques highlight the importance of a comprehensive approach to pain management that integrates multiple modalities to address both the physical and psychological dimensions of pain. The placebo and nocebo effects are powerful examples of how psychological and contextual factors can influence pain perception. The placebo effect refers to the beneficial outcomes resulting from a patient's expectations of treatment, even when the treatment is inactive. Conversely, the nocebo effect occurs when negative expectations lead to worse outcomes. These effects underscore the importance of patient-provider interactions and the therapeutic environment in pain management. The drucebo effect, a term recently introduced in pain management research, refers to the enhancement of placebo effects through digital and remote interventions. This effect leverages modern technology to provide supportive and therapeutic communication, enhancing patients' expectations and outcomes without direct physical interaction. Technological advancements have significantly enhanced the tools available for pain management in rehabilitation. Robotic-assisted therapy, virtual reality (VR) systems, and wearable devices offer new opportunities for managing pain and improving functional recovery. Robotic-assisted therapy provides precise and repetitive movements that aid in motor recovery and pain reduction, particularly beneficial for patients with severe physical impairments. VR systems offer immersive environments for practicing motor and cognitive tasks, improving engagement and outcomes in rehabilitation, and can also be used to distract patients from pain during therapeutic exercises. Wearable technology can monitor physiological parameters related to pain, such as muscle tension and heart rate, providing real-time feedback and enabling personalized pain management strategies. Pain management is a critical component of effective rehabilitation, requiring a comprehensive and multidisciplinary approach. By understanding the complex neurophysiological nature of pain and integrating advanced pharmacological and non-pharmacological strategies, healthcare providers can optimize patient outcomes, enhance recovery, and improve the quality of life for individuals undergoing rehabilitation. The integration of psychological factors, such as placebo and nocebo effects, along with technological advancements, further enriches the therapeutic arsenal available to clinicians. Future research should continue to explore innovative pain management techniques and their integration into rehabilitation protocols to address the diverse challenges presented by musculoskeletal and neurological disorders.

5.2 Musculoskeletal Disorders and Pain in Rehabilitation

Musculoskeletal disorders (MSDs) encompass a broad range of conditions affecting the muscles, bones, tendons, ligaments, and nerves. These disorders can arise from trauma, repetitive strain, degenerative diseases, or inflammatory processes, significantly impacting an individual's quality of life. Pain is a predominant symptom in many MSDs and poses substantial challenges in rehabilitation. Effective management of musculoskeletal pain is essential for improving functional outcomes and enhancing the overall rehabilitation process. Pain in MSDs involves complex neurophysiological mechanisms that begin with the activation of nociceptors, specialized sensory receptors located in the skin, muscles, joints, and certain internal organs. These receptors respond to potentially harmful stimuli such as mechanical pressure, extreme temperatures, and chemical irritants. When activated, nociceptors generate electrical signals transmitted via peripheral nerve fibers to the spinal cord and brain. Two primary types of nerve fibers are involved in pain transmission: A-delta fibers and C fibers. A-delta fibers are myelinated, allowing for fast transmission of sharp, acute pain signals. In contrast, C fibers are unmyelinated and conduct signals more slowly, resulting in a dull, throbbing pain sensation. Upon reaching the dorsal horn of the spinal cord, these signals are processed and relayed to higher brain centers for further interpretation. Upon reaching the brain, pain signals are processed in several regions, including the thalamus, somatosensory cortex, limbic system, and prefrontal cortex. The thalamus acts as a central relay station, directing signals to the appropriate cortical areas for perception and interpretation. The somatosensory cortex is responsible for the localization and intensity of pain, while the limbic system and prefrontal cortex are involved in the emotional and cognitive aspects of pain, respectively. This complex network explains why pain is not merely a physical sensation but also an emotional and psychological experience.

One common MSD is low back pain, which affects a significant portion of the population at some point in their lives. Low back pain can be acute, resulting from a sudden injury or strain, or chronic, often linked to conditions such as degenerative disc disease, spinal stenosis, or spondylolisthesis. The management of low back pain in rehabilitation involves a combination of pharmacological treatments, physical therapies, and lifestyle modifications. Effective interventions include exercise programs designed to strengthen the core muscles, improve flexibility, and enhance overall spinal stability. Manual therapies, such as spinal manipulation and mobilization, have also shown benefits in reducing pain and improving function in patients with low back pain. Osteoarthritis (OA), a degenerative joint disease characterized by the breakdown of cartilage and underlying bone, leads to pain, stiffness, and reduced mobility. OA commonly affects the knees, hips, hands, and spine. Pain management in OA is multifaceted, involving pharmacological treatments such as nonsteroidal anti-inflammatory drugs (NSAIDs) and analgesics, along with non-pharmacological approaches like physical therapy, weight management, and assistive devices. Physical therapy for OA focuses on exercises to maintain joint flexibility, muscle strength, and overall functional ability. Aquatic therapy is particularly beneficial for OA patients as it allows for low-impact exercise that reduces joint stress while improving cardiovascular fitness and muscle strength. Tendinopathies, such as Achilles tendinitis and rotator cuff tendinopathy, are also common MSDs characterized by pain and functional impairment. These conditions result from overuse or acute injuries leading to inflammation or degeneration of the tendon. Rehabilitation for tendinopathies involves a combination of rest, targeted exercises, and manual therapies. Eccentric strengthening exercises have been shown to be particularly effective in treating tendinopathies by promoting tendon remodeling and reducing pain. Additionally, modalities such as ultrasound therapy and shockwave therapy can be used to enhance the healing process and alleviate pain. Inflammatory conditions, such as rheumatoid arthritis (RA), are another category of MSDs that cause significant pain and disability. RA is an autoimmune disorder characterized by chronic inflammation of the joints, leading to pain, swelling, and eventual joint destruction. Rehabilitation for RA focuses on controlling inflammation, managing pain, and maintaining joint function. Pharmacological treatments, including disease-modifying antirheumatic drugs (DMARDs) and biologics, play a central role in controlling disease activity. Physical therapy interventions aim to maintain joint mobility and muscle strength, prevent deformities, and promote overall physical fitness. Joint protection techniques and assistive devices can help reduce joint stress and preserve function. Central sensitization and maladaptive neuroplasticity are key concepts in understanding chronic pain in MSDs. Central sensitization refers to the increased responsiveness of neurons in the central nervous system to normal or subthreshold afferent input, resulting in heightened pain sensitivity and perception. This phenomenon is often seen in chronic pain conditions, such as fibromyalgia and chronic low back pain, where the pain experience becomes disproportionate to the actual tissue damage. Maladaptive neuroplasticity involves changes in the brain and spinal cord that reinforce chronic pain pathways, making the pain persistent and difficult to treat. Addressing these central mechanisms is essential for effective pain management in chronic MSDs. Integrating psychological approaches into the management of MSDs is crucial for addressing the multifaceted nature of pain. Cognitive-behavioral therapy (CBT) helps patients modify negative thoughts and behaviors related to pain, improving their coping strategies and reducing the impact of pain on their daily lives. Mindfulness-based stress reduction (MBSR) and other relaxation techniques can also be beneficial in managing chronic pain by reducing stress and enhancing emotional well-being. Managing pain in musculoskeletal disorders is a complex and multifaceted process that requires a comprehensive approach. Effective rehabilitation strategies must address the underlying causes of pain, incorporate both pharmacological and non-pharmacological treatments, and consider the psychological aspects of pain. By adopting a multidisciplinary approach and integrating advanced therapeutic techniques, healthcare providers can optimize pain management, improve functional outcomes, and enhance the quality of life for individuals with musculoskeletal disorders.

5.3 Pain and Rehabilitation

Tele-rehabilitation and Balance Assessment in the Management of Pain: Comparative Studies on Knee Osteoarthritis and Postural Control

Knee osteoarthritis (OA) is a major cause of disability among the elderly, with significant implications for patients' quality of life due to chronic pain and reduced physical function. In recent years, new therapeutic approaches have emerged, such as tele-rehabilitation, which has garnered increasing interest for its potential applications in OA patients. At the same time, balance assessment, particularly in individuals with musculoskeletal conditions, has become critical for understanding functional and biomechanical impairments. Balance plays a key role in both rehabilitation and daily functioning, particularly in older adults or those recovering from injuries. In this context, two pivotal studies provide valuable insights: a randomized controlled trial on the effectiveness of tele-rehabilitation in managing knee OA pain, and a cross-sectional study evaluating balance performance during a single-limb stance (SLS) task in healthy adults. These studies offer complementary perspectives on pain management and functional recovery, with one focusing on the therapeutic impact of remote rehabilitation, and the other exploring proprioception and postural control, two key factors that may influence rehabilitation outcomes.

Study 1: Effectiveness of tele-rehabilitation in patients with knee osteoarthritis. A Randomized Controlled Trial

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Abstract

Objective: The primary objective of this randomized controlled trial was to evaluate the effectiveness of tele-rehabilitation (TR) compared to conventional rehabilitation (CT) in reducing pain (as measured by the Numeric Pain Rating Scale, NPRS) in patients with knee osteoarthritis. Secondary objectives included assessing changes in physical function and quality of life, as measured by the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) and the Short Form-36 (SF36) health survey, respectively.

Methods: Fifty-five patients diagnosed with knee osteoarthritis were randomly allocated to either the TR group (n=29), receiving remote physiotherapy sessions three times a week for four weeks, or the CT group (n=26), undergoing traditional outpatient rehabilitation with the same exercise regimen. Outcomes were measured at baseline and after a 3-month follow-up period.

Results: At baseline, there were no significant differences between groups in terms of NPRS and WOMAC scores. After 3 months, both the CT and the TR groups showed significant improvements in pain reduction (NPRS, $p<0.001$), WOMAC score ($p<0.001$), and in some subscales of the SF-36 (i.e. physical functioning, role limitation attributable to physical problems, energy and pain).

Conclusion: Tele-rehabilitation is an effective alternative to conventional rehabilitation for reducing pain and improving quality of life in patients with knee osteoarthritis. These findings suggest that TR can be incorporated alongside conventional approaches to provide a comprehensive treatment strategy for managing knee osteoarthritis, enhancing patient outcomes in various dimensions of well-being.

Trial registration NCT05719350; Telerehabilitation in Patients With Osteoarthritis (TABLET)

Keywords: Knee Osteoarthritis, Tele-Rehabilitation, Pain Management, Physical Functioning, Physical Therapy.

Introduction and background

Osteoarthritis (OA) poses a significant public health challenge, being one of the primary causes of disability among the elderly population in developed countries and adversely affecting patients' quality of life. During the COVID-19 pandemic, the need for safe and effective alternatives for OA management has become even more evident. [1] Knee OA, in particular, afflicts over 32.5 million adults in the United States alone, making it the second most costly health condition treated in American hospitals.[2] In Italy, the prevalence of symptomatic knee OA was estimated to be around 29.8% among the elderly aged over 65.[30]

The latest guidelines from the American College of Rheumatology/Arthritis Foundation (ACR)[3] and the Osteoarthritis Research Society International (OARSI)[4,5] have highlighted a range of therapeutic options, including specific exercise programs that have proven effective in reducing pain and slowing OA progression.[6-10] Traditionally, these treatments are delivered in outpatient clinical settings with the support of rehabilitation professionals. [6]

The emergence of tele-rehabilitation (TR) programs has responded to the growing demand for treatment methods that ensure safety and therapeutic continuity.[11] TR allows the remote delivery of rehabilitation programs, in accordance with the Individual Rehabilitation Project (PRI) guidelines, proving especially useful in both post-acute and chronic phases of patient neuromuscular recover.[12 -15] In this context, TR emerges as a promising solution, offering patients with chronic diseases the opportunity to follow personalized rehabilitation programs from their own home, as an alternative or in addition to traditional treatment.[16]

The aim of this study is to assess whether an evidence-based exercise program, targeted at elderly individuals with knee OA and delivered through tele-rehabilitation, can be as effective, if not more, compared to conventional rehabilitation in terms of pain reduction and quality of life improvement. Furthermore, the study seeks to explore the impact of TR on treatment adherence and patient satisfaction, potentially offering a more accessible and flexible solution for OA management.

METHODS

Study Design and Population

The study is as a randomized controlled trial. It was registered on ClinicalTrials.gov (code NCT05719350). The study population was composed of individuals diagnosed with knee osteoarthritis, identified according to the American College of Rheumatology (ACR) and NICE criteria, [3,17-18] and with Kellgren–Lawrence grade ≥2. Eligibility criteria included individuals aged over 18 years, able to provide informed consent for participation in the study, and capable of using electronic devices such as PCs, tablets, or smartphones. Subjects with a Numeric Pain Rating Scale (NPRS) value >3[19-22] indicating moderate to severe knee pain, were included. Subjects who have participated in any rehabilitation exercise programs, whether in an outpatient setting or via remote care, within the last 6 months prior to enrollment in the study were excluded. Subjects were randomized assigned to either TR or CT group using a 1:1 allocation ratio. Subject allocation to treatments occurred sequentially as each participant entered the study. Both the TR group and the CT group received the same protocol of land-based therapeutic exercises. TR group received the rehabilitation program through video-call (WhatsApp, FaceTime applications) and communicated with healthcare providers throughout the duration of the exercise session.

The research protocol received approval from the Ethics Committee AVEC (Comitato Etico Area Vasta Emilia Centro) under protocol code CE AVEC: /Sper/IOR806/2022. Written informed consent was obtained from all participants. No devices were provided to the participants, which used their own equipment for the TR sessions.

Recruitment and allocation

Patient recruitment took place in February 2023 and lasted one month. were contacted by phone call and invited to participate in the study by physiotherapists who were affiliated with the institution.

In the Sport Activities section, different levels of physical activity are listed: "Absent" (0 physical activity sessions per week), "Low" (1 physical activity session per week), "Moderate" (2-3 physical activity sessions per week), and "High" (more than 3 physical activity sessions per week).

Randomization Procedure

To ensure a fair and unbiased allocation of participants to the Tele-Rehabilitation (TR) group and the Conventional Therapy (CT) group, our study utilized the online tool available at www.randomizer.org. This website is known for providing simple yet effective randomization services, suitable for various research settings.

Implementation: An independent member of our research team, who was not involved in participant recruitment, treatment, or assessment, used www.randomizer.org to generate the randomization sequence. This process was conducted by entering the total number of participants and specifying two equal groups, which facilitated a balanced distribution between the TR and CT groups.

Allocation Concealment: The use of www.randomizer.org contributed to allocation concealment by ensuring that the sequence was immediately applied without revealing future allocations. This procedure was strictly followed to prevent any potential bias, with group assignments being disclosed to the research team only after each participant's enrolment and initial assessment were complete.

Blinding: Given the nature of the interventions, it was not possible to blind participants or therapists to group assignments. However, to mitigate any risk of bias in outcome assessment, the researchers responsible for evaluating the study outcomes were kept blind to group allocations. This was achieved by keeping the randomization sequence and resulting group assignments confidential, accessible only to the independent team member who performed the randomization.

Data collection was carried out by a team of physiotherapists, who underwent prior training for the assessments. This approach aimed to minimize bias in data collection and analysis.

Intervention

In both the experimental (TR) and conventional (CT) groups, the rehabilitation sessions were systematically supervised by a physiotherapist who attended small groups with a maximum of five subjects. The sessions took place three days a week, with the schedule set on Mondays, Wednesdays, and Fridays, spanning a period of four weeks for a total 12 sessions.

The decision to measure pain intensity four weeks after intervention is based on expected therapeutic effects, literature evidence, and practical research considerations. This timeframe aligns with when noticeable improvements from rehabilitation exercises are typically observed, allowing for an assessment of immediate post-treatment outcomes.[23] It balances the need to detect changes due to the intervention against the potential for external factors to influence results over longer periods.[19] Furthermore, a four-week assessment provides timely feedback on treatment efficacy, supporting informed decisions about future therapeutic directions. This approach is underpinned by both the cumulative nature of the interventions and existing research findings on pain management and rehabilitation effectiveness within a similar period.[24]

The knee joint exercises comprised four land-based exercises, lasting approximately 20 to 25 minutes in total. Each exercise targeted specific muscle strengthening and joint mobility, with intervals of approximately 1-2 minutes between exercises.

The knee exercises for the experimental group included the following:

1. Knee flexion/extension in a seated position.
2. Quadriceps strengthening with isometric contraction in a seated position.
3. Sit-to-Stand (squat) from a chair.
4. Squat isometric exercise in an upright standing position.

Conventional group (CT): subjects received the same rehabilitation (exercise) program described above, but they were supervised by a physiotherapist, as outpatient setting at the Istituto Ortopedico Rizzoli (IOR), Bologna, Italy.

Outcomes

The primary outcome measure was the change in pain levels as measured by the NPRS. NPRS is a commonly used pain assessment tool in both clinical and research settings. The scale ranges from 0 (no pain) to 10 (worst imaginable pain). It provides a simple and effective method to measure the intensity of pain perceived by an individual at a specific moment.[20] All subjects' pain level was assessed by NPRS at three different time points: baseline (T0, i.e. before the start of the treatment), at the end of the treatment (T1, i.e. after four weeks of intervention), and at three-month follow-up (T2). In addition to the primary outcome, secondary outcomes were evaluated using the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) and the Short Form Health Survey (SF-36) survey. The WOMAC is a validated questionnaire that assesses pain, stiffness, and physical functioning designed to assess the health status and functional limitations of individuals with osteoarthritis, particularly affecting the knee and hip joints. The score range 0-96, with higher values indicating worse function.[25,26] The SF-36 is a widely used health-related quality of life questionnaire that measures various aspects of physical and mental health. It consists of 36 items that cover eight distinct health domains, providing a comprehensive assessment of the individual's health status and functional outcomes. The score range 0-100, with higher values indicating better quality of life[7, 12][,28]. Outcome data regarding NPRS, WOMAC index and Short Form 36 Health Survey (SF-36), are reported in Table 2 at different time points: T0 (baseline), T1 (post-intervention), and T2 (follow-up).

Neither serious medical conditions, nor side effects were reported during the study. Minor issues included fatigue, transient articular and muscular discomfort, and initial difficulties with certain exercises, highlighting the safety and feasibility of both rehabilitation methods.

Sample size

The power analysis for sample size definition was performed, considering the NPRS score as the primary endpoint in the follow-up. Assuming the scores are normally distributed, the comparison between the two groups was based on an unpaired t-test. Based on the literature,[29] the standard deviation was estimated to be 1.7. Assuming that the minimum clinically significant difference between the two groups is 2 points (effect size = 1.178) and considering a two-sided t-test for non-inferiority design, the minimum sample size required, with an alpha error of 0.05 ($Z\ 1\text{-}\alpha = 1.645$) and a power of at least 0.9 ($Z\ 1\text{-}\beta = 1.282$), $\delta 0 = 1$, and $\sigma = 1.7$, the minimum number of participants needed in each group was 25, for a total sample size of 50 cases. Accounting for a 5% dropout rate, the sample size was set to maintain statistical power with at least 48 completing participants, i.e., 24 per group, thereby ensuring the validity of the statistical analyses relative to the study’s objectives.

Statistical analyses

To address the primary research question, an independent two-sample t-test was employed to compare the mean NPRS scores between the experimental and control groups at the conclusion of the treatment phase and the follow-up assessment. Additionally, paired t-tests were conducted to investigate within-group changes in pain scores from baseline to the respective time points. To answer the primary research question, a two-sample independent t-test was used to compare the mean NPRS scores between the experimental and control group at baseline, at the end of the treatment phase and at the follow-up assessment. In addition, paired t-tests were conducted to examine within-group variations in pain scores from baseline to the respective time points. At baseline, we conducted a frequency distribution analysis to examine the relationships between the qualitative variables in our study. This allowed us to assess the initial distribution of participant characteristics, such as gender, age, work activity, school education and sporting activity performed in the two study groups. These data were used to ensure the initial comparability of the groups. Secondary outcome measures, encompassing functional status and quality of life, were assessed using the WOMAC and the Short Form 36 Health Survey (SF-36), respectively. Independent t-tests were conducted to determine differences in mean scores between the two groups at the different time points, and paired t-tests to assess within-group changes from baseline. Post hoc pair-wise comparison was assessed with ANOVA repeated measures with Šidák correction. Prior to statistical analysis, data were tested for normality as per the assumptions of parametric statistics. The statistical significance level for all analyses was set at $\alpha = 0.05$, ensuring robust and accurate inference. For MCID evaluation, the total WOMAC scores were normalized as a percentage and converted in a reverse format ranging from 0 (worst) to 100 (best).[25]

The Shapiro-Wilk test results indicate that the Numeric Pain Rating Scale (NPRS) scores for both the Tele-Rehabilitation (TR) and Conventional Therapy (CT) groups, at baseline (T0) and after intervention (T1), follow a normal distribution. This is because the p-values for all tests are above 0.05, suggesting no significant deviation from normality. TR group at T0: Statistic = 0.944, p-value = 0.131; TR group at T1: Statistic = 0.966, p-value = 0.460; CT group at T0: Statistic = 0.984, p-value = 0.918; CT group at T1: Statistic = 0.970, p-value = 0.548.

Advanced statistical software packages (SPSS Statistics, version 24, IBM Corp., Armonk, NY, USA) were used.

RESULTS

Flow- chart of patient's recruitment is shown in Figure 1.

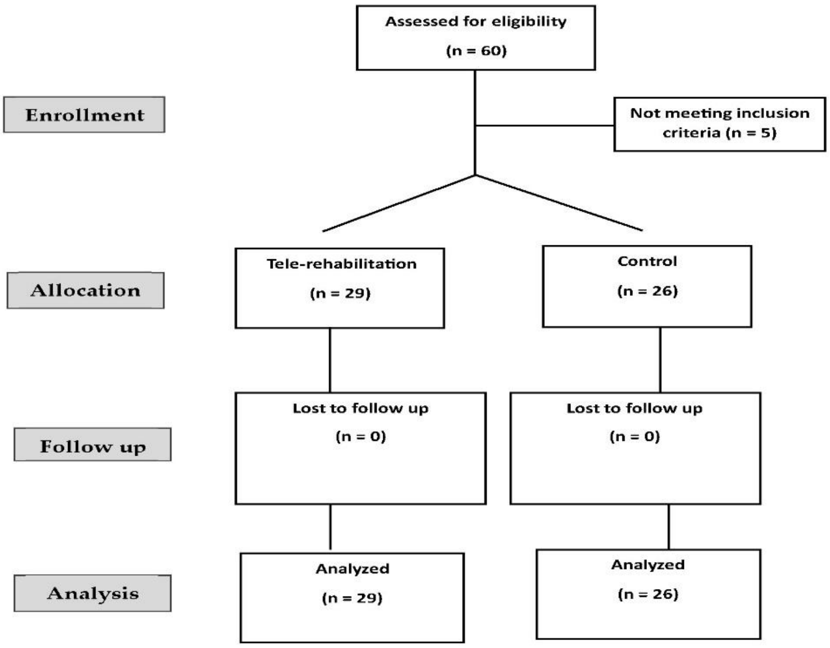

Figure 1. Flow- chart of patients' recruitment.

Demographics and characteristics of the studied subjects are reported in TABLE 1.

TABLE 1. Baseline characteristics of the sample, tele-rehabilitation and conventional rehabilitation group.

	All sample (n = 55)	TR (n = 29)	CT (n = 26)	*p*
Age (years)	61.0 ± 14.8	58.6 ± 17.4	63.6 ± 11.0	0.248
Body mass index (kg/m^2)	26.2 ± 4.0	27.1 ± 3.9	25.5 ± 4.1	0.111
Gender				
Men	21 (38%)	12 (41%)	9 (35%)	
Women	34 (62%)	17 (59%)	17 (65%)	
Education				0.285
Primary School	3 (5.5%)	2 (6.9%)	1 (3.8%)	
Secondary School	9 (16.4%)	2 (6.9%)	7 (26.9%)	
High School	26 (47.3%)	15 (51.7%)	11 (42.3%)	
Degree	17 (30.9%)	10 (34.5%)	7 (26.9%)	
Work Activities				0.688
Employee	22 (40.0%)	11 (37.9%)	11 (42.3%)	
Professional	9 (16.4%)	5 (17.2%)	4 (15.4%)	
Retiree	22 (40.0%)	11 (37.9%)	11 (42.3%)	
Student	2 (3.6%)	2 (6.9%)	0 (0.0%)	
Sport Activities				**0.002**
Absent	29 (52.7%)	13 (44.8%)	16 (61.5%)	
Low	15 (27.3%)	5 (17.2%)	10 (38.5%)	
Moderate	10 (18.2%)	10 (34.5%)	0 (0.0%)	
High	1 (1.8%)	1 (3.4%)	0 (0.0%)	

Regarding the Kellgren-Lawrence classification, subjects were graded as follows: 16 scored 2 (n=9 CT; n=7 RT), 34 scored 3 (n=16 CT; n=18 RT), and 6 subjects scores 4 (n=2 CT; n=4 RT). Outcome data regarding NRS, WOMAC index and Short Form 36 Health Survey (SF-36), are reported in TABLE 2 at different time points: T0 (baseline), T1 (post-intervention), and T2 (follow-up).

TABLE 2. Differences among groups and during the follow up for the outcome variables. Data collected at T0, T1, and T2 are represented as mean values ± SD. In the post-hoc analysis, the significance of comparisons within groups (and between groups) is highlighted through p-values. Significant results are italicized. (*p<0.05; **p<0.01). Nv= not evaluable.

	T0	*T1*	*T2*	*ANOVA repeated measures (p)*	*Post hoc analysis with Sidack multiple comparison*		
					T0 vs T1	*T0 vsT2*	*T1 vsT2*
NPRS (0-10)							
TR group	4.3 (1.6)	1.6 (1.9)	1.3 (2.1)	**<0.0005**	*<0.0001*	*<0.0001*	*ns*
CT group	4.4 (1.4)	1.4 (1.8)	1.5 (2.0)	**<0.0005**	*<0.0001*	*<0.0001*	*ns*
Difference among groups (p)	*0.703*	*0.735*	*0.553*				
WOMAC (0-96)							
TR group	27.4(17.8)	14.4(15.8)	8.9(15.2)	**<0.0005**	*<0.0001*	*<0.0001*	*<0.0001*
CT group	35.5(21.0)	23.0(15.9)	14.2 (14.5)	**<0.0005**	*<0.0001*	*<0.0001*	*<0.0001*
Difference among groups (p)	*0.157*	***0.019***	***0.008***				
SF36 (0-100)							
Physical Functioning							
TR goup	71.2(20.1)	75.0(16.7)	76.0 (16.0)	**<0.0005**	*ns*	*=0.024*	*ns*
CT group	59.8(27.7)	70.2(21.9)	71.9(21.4)	**<0.0005**	*<0.0001*	*<0.0001*	*ns*
Difference among groups (p)	*0.147*	*0.592*	*0.766*				
Role limitations attributable to physical problems							
TR group	69.8(34.6)	78.4(23.6)	79.2(22.9)	**=0.046**	=0.20	=0.10	*ns*
CT group	66.0(29.2)	72.7(30.2)	73.5(29.9)	**=0.014**	=0.33	=0.40	*ns*
Difference among groups (p)	*0.478*	*0.545*	*0.522*				
Role limitations attributable to emotional problems							

TR group	91.0(23.8)	94.9(12.1)	95.0(12.0)	0.174	-	-	-
CT group	79.4(28.1)	79.4(28.6)	78.6(30.8)	0.830	-	-	-
Difference among groups (p)	***0.031***	***0.017***	***0.017***				
Energy							
TR group	65.0(18.5)	70.2(13.5)	70.7(13.2)	**0.021**	*=0.026*	*=0.037*	*ns*
CT group	57.9(20.4)	67.0(15.0)	68.9(14.0)	**0.001**	*=0.05*	*=0.01*	*ns*
Difference among groups (p)	*0.134*	*0.460*	*0.747*				
Emotional Well-Being							
TR group	79.0(17.5)	79.0(17.5)	79.0(17.5)	nv	-	-	-
CT group	73.7(16.9)	74.1(16.2)	73.9(16.0)	0.611	-	-	-
Difference among groups (p)	*0.149*	*0.189*	*0.159*				
Social Functioning							
TR group	83.2(15.4)	83.2(15.4)	83.2(15.4)	nv	-	-	-
CT group	66.7(26.6)	72.7(17.9)	72.8(18.0)	0.085	-	-	-
Difference among groups (p)	***0.012***	***0.035***	***0.040***				
Pain							
TR group	59.9(17.6)	88.0(17.2)	90.3(19.1)	**0.0005**	*<0.0001*	*<0.0001*	*ns*
CT group	49.4(18.3)	85.1(21.0)	89.7(16.1)	**0.0005**	*<0.0001*	*<0.0001*	*ns*
Difference among groups (p)	*0.123*	*0.768*	*0.673*				
General Health							
TR group	66.6(17.6)	70.0(15.5)	71.0(15.5)	**0.019**	*=0.029*	*=0.014*	*ns*
CT group	57.5(18.3)	61.0(15.0)	66.7(14.3)	**0.001**	*ns*	*<0.0001*	*=0.025*

Difference among groups (p)	***0.038***	***0.010***	*0.117*				

<u>*Numeric Pain Rating Scale (NPRS) (Tab.2).*</u>

Patients in both groups (TR and CT) reported a significant reduction in pain value after the exercise program (T1), and the reduction was maintained in the follow up (p=0.0005). The post hoc pairwise comparison with Šidák correction showed significant differences of NPRS values between T0 and T1 (p<0.001), and between T0 and T2 (p<0.001) in TR. Similarly, in the CT, NPRS value was statistically lower in T1 vs T0 (p<0.001), and T2 vs T0 (p=<0.001). No differences were found in NRS values when comparing tele-rehabilitation vs standard protocol at the tested time points.

<u>*Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) (Tab.2).*</u>

A significantly lower WOMAC score was found for both experimental TR and CT at T1 and T2 (p=0.0005). The post hoc pairwise comparison with Šidák correction showed significant differences of WOMAC index between T0 and T1 (p<0.001), and between T0 and T2 (p=<0.001) in the TR. Similarly, in the CT group, WOMAC score was statistically lower in T1 vs T0 (p<0.001), and T2 vs T0 (p<0.001).

The analysis of differences of WOMAC score among groups showed that TR subjects had significant lower values both at T1 (p=0.019) and T2 (p=0.008).

The statistical analysis performed for each subscale of WOMAC (pain, stiffness and function) did not found significant differences between groups at the baseline (data not shown).

The between-group analysis at the baseline showed significantly higher sports activities in the tele-rehabilitation group than in the conventional group, and therefore we performed further analysis to evaluate a possible role of individuals' sport activity on outcomes. Patients were divided according to their level of sports activities (none, level 1, and level ≥2); because the sport activity of level 3 was reached only by one individual, it was included in the group of level 2. Since the subgroup analysis with very few cases is not highly reliable, we performed a multivariate analysis with sport activity correction on the improvements of the scores of the two outcomes. The multivariate analysis adjusted for sport activity showed that the intervention has a significant influence on outcomes when considered across the levels, while its effect alone was only tendential ($p<0,1$) for NPRS (data not shown). The post hoc pairwise analysis spread by sport level showed non difference in the improvement of 0 level of sport, but a better improvement in the level 1 of sport in the TR group. No comparisons can be made for the higher level.

<u>*Short Form 36 Health Survey (SF-36) (Tab.2)*</u>

SF36 – physical functioning. As shown in table 2, the score of Physical Functioning significantly increased in both TR and CT subjects after the exercise program ($p=0.0005$). The post hoc pairwise comparison with Sidak test showed a significant difference of the score between T0 and T1 ($p<0.05$), and between T0 and T2 ($p<0.01$) in the CT. In TR group, we found statistical difference of the score in the comparison between T0 and T2 ($p<0.05$)

SF36- Role limitation attributable to physical problems. After the exercise program, the score significantly increased in both TR ($p<0.05$) and CT ($p<0.05$). The post hoc pairwise comparison with Sidak test showed a significant difference of the score between T0 and T1 ($p<0.05$), and between T0 and T2 ($p=0.01$) in the CT. In TR subjects we found statistical difference of the score in the comparison between T0 and T1 ($p<0.05$), and between T0 and T2 ($p<0.05$)

SF36- Role limitation attributable to emotional problems. In the domain of Role Emotional the exercise protocol did not cause modification in reported value during the follow up both for TR and CT patients.

Comparing the different protocols (TR vs standard care) we found statistically higher values in the subject who follow the TR protocol vs the standard care at all the time points T0 ($p<0.05$), T1 ($p<0.05$), and T2 ($p<0.05$).

SF36-Energy. After the exercise program, the score of Energy significantly increased in both TR ($p<0.05$) and CT groups ($p=0.001$). The post hoc pairwise comparison with Sidak test showed a significant difference of the score between T0 and T1 ($p=0.05$), and between T0 and T2 ($p=0.01$) in the CT. In TR group we found statistical difference of the score in the comparison between T0 and T1 ($p<0.05$) and between T0 and T2 ($p<0.05$).

SF36- Emotional well-being. There was no significant difference of this item score along the follow-up, for both experimental groups. No significant differences were found between TR and CT, either.
SF36-Social Functioning: There was no significant difference of Social Functioning score along the follow-up, for both experimental groups.
Comparing the different protocols (TR vs standard care) we found statistically higher values in the subject who follow the TR protocol vs the standard care at all the time points T0 ($p<0.05$), T1 ($p<0.05$), and T2 ($p<0.05$).
SF36- Pain. After the exercise program, the score of Pain significantly ameliorated in both TR ($p=0.0005$) and CT subjects ($p=0.0005$). The post hoc pairwise comparison with Sidak test showed a significant difference between T0 and T1 ($p<0.001$), and T0 and T2 ($p<0.001$) in both groups.
SF36- General Health. A significant increase in GH value after the exercise program and in the follow up was reported by subjects in both TR ($p<0.05$) and CT ($p=0.001$) groups. The post hoc pairwise comparison with Šidák test showed a significant difference between T0 and T1 ($p<0.001$) in the CT and between T0 and T1 ($p=0,029$), and T0 and T2 ($p<0.05$) in the TR group.

Comparing the different protocols (TR vs standard care) we found statistically higher values in the subject who follow the TR protocol vs the standard care one at T0 ($p<0.05$), and T1 ($p=0.010$).
The comparison between the Tele-Rehabilitation (TR) and Conventional Therapy (CT) groups was actually conducted at the end of the 12th session, i.e. four weeks from the beginning of the treatment. This timing was aimed to assess the immediate effects of the interventions directly after their completion.
The analysis of effect sizes is reported in TABLE 3.

TABLE 3. Analysis of Effect Sizes of Tele-Rehabilitation Versus Conventional Therapy in Knee Osteoarthritis.

Outcome Measure	Group	Pre-Intervention Mean (SD)	Post-Intervention Mean (SD)	Cohen's d
NPRS	TR	4.3 (1.6)	1.6 (1.9)	1.5
	CT	4.4 (1.4)	1.4 (1.8)	1.8
WOMAC	TR	27.4 (17.8)	14.4 (15.8)	0.8
	CT	35.5 (21.0)	23.0 (15.9)	0.7
SF36 Physical Functioning	TR	71.2 (20.1)	76.0 (16.0)	-0.3
	CT	59.8 (27.7)	71.9 (21.4)	-0.5

The Cohen's d values show significant improvements within both groups for the NPRS and WOMAC measures, indicating effective pain management and functional improvement. The negative signs for Cohen's d values in the SF-36 Physical Functioning measure are due to the direction of improvement (increase in scores), which does not align with the convention used in calculating Cohen's d. The SF-36 Physical Functioning scores also improved, with moderate effect sizes, suggesting enhanced physical functioning post-intervention. The magnitude of these values still provides useful information about the size of the effect.

DISCUSSION

The main finding of the present study is that a home physiotherapy exercise protocol that is supervised by a therapist via tele-rehabilitation is not inferior to the same protocol delivered as outpatient treatment in improving pain levels and functional outcomes in patients with symptomatic knee osteoarthritis.

Former research investigated the role and efficacy of remote care in managing chronic musculoskeletal pain and function. According to previous studies[15, 36] we observed a significant reduction in pain and an increase in patients' self-assessment of their general function, health status and quality of life, after the physiotherapy program, and the beneficial effects were maintained at three-month follow up. Unlike other studies, however, we evaluated the bare effect of an exercise protocol supervised by a physiotherapist without confounding factors like additional physical o pharmacological therapies, different number of sessions, or the use of assistive devices. In the study by Azma et al. 2017[33] on pain and physical function of patients with knee OA, no differences were found between tele rehabilitation and office-based physiotherapy up to six months after treatment, but the outpatient group was subjected to additional passive physiotherapeutic interventions (i.e. transcutaneous electrical nerve stimulation, ultrasound, and thermo-therapies). Similarly, Das et al., 2023[15] reported no differences in pain and functional scores in early-knee OA patients who underwent teleconsultation (including remote examination) vs outpatient consultation, but the management protocol included heat therapy, calcium and vitamin D supplementation, and oral NSAIDs for 10 days, besides physiotherapy exercises.

Considering patient's education, a recommendation by OARSI guideline for OA management, the rehabilitation supervised by a physiotherapist (using video or phone calls) likely increase patient's participation and adherence to treatment and self- care. Remote physiotherapist interventions with digital tools commonly used for communication can help to improve home exercise adherence.[10] Compared to the home-based home exercise program, the supervision of a physiotherapist prevents the risks of adverse effects (wrong postures, excessive articular load, muscular stains), and ensures the accuracy of the exercise performance. In our study, patients were assisted by a physiotherapist throughout the sessions. In the case of standard rehabilitation protocols and following adequate education, caregiver may support tele-rehabilitation as well. In a study by Ortiz-Piña et al. (2021)[24] a 12-week tele-rehabilitation program supervised by family caregivers had better outcomes in terms of functional independence and physical condition (self-assessment and performance-based) for elderly individuals with hip fractures compared to traditional home-based rehabilitation. These findings suggest that tele-rehabilitation could be a valid option for managing the recovery process in older patients when perceived barriers limit the access to outpatient care.

At the baseline, no difference in the scores on pain and physical functioning evaluated by NPRS, WOMAC, and corresponding specific domains in the SF-36 questionnaire, were found between CT and RT groups. The WOMAC index is a disease specific questionnaire accounting for the three cardinal clinical hallmarks of the osteoarthtritis (ie. pain, stiffness and physical function) and therefore, it is the best tool to describe the study population. Indeed, we observed few significant differences among the groups at the baseline, specifically in the *role limitations attributable to emotional problems*, in the *social functioning* and in the reported *general health*, of the SF-36. The latter could represent a bias in the study, still we believe that they are likely the expression of individuals' psychologic rather than physical traits, and therefore should not influence the effects of a rehabilitation program. We have also found that TR subjects were more physically active, than controls. Specifically, the above features could impact the compliance with remote training and should be taken into account in programs of telerehabilitation that are not supervised by a physiotherapist, as in our study.

Rehabilitation (either RH or TR) improves outcomes across all groups and at all levels of sports activity, and, at a low level of sport activity, TR subjects showed a significantly better improvement (note that low level sport activity subgroup, level 1, comprised only 5 subjects in the TR group on a total of 15 subjects, i.e. 27.3%). Further studies with larger samples across different levels of sports activity could investigate whether active individuals might benefit the most from tele-rehabilitation, but this was beyond the scope of this study.

In our study, pain levels decreased statistically in both the tele-rehabilitation and traditional rehabilitation groups, after the 4-week exercise protocol and at the 3-month follow up; there was no statistical difference between the two experimental groups at all time points, confirming the comparable efficacy in pain improvement using the two approaches. Regarding self-reported function, both WOMAC index and SF-36 specific items (i.e. physical functioning, role limitations attributable to physical problems, energy) resulted statistically improved in both experimental groups. The total WOMAC score were statistically lower in the TR group after the treatment suggesting a better health status of this group. Interestingly, TR subjects reported significantly higher score in the subscale of general health, emotional problems, and social functioning at the baseline, and this may correlate to the incidental observation that they were also more physically active. Moreover, we found that the difference in the mean change of the normalized total WOMAC score improved of 22,2% in control and 19,2% in TR subjects, following the physiotherapy protocol. These values are far above the minimal clinical important difference (MCID) required for knee OA (i.e. 17%, Clement at al., 2018.[25] MCID is an indicator of the perceived effect size, and in the case of WOMAC score, it is the smallest change in score perceived by patients about their general function following a treatment. These results also suggest that tele-rehabilitation may have a positive impact on specific aspects of functionality, offering additional benefits compared to traditional rehabilitation. Although the tele-rehabilitation program was indeed conducted under the supervision of a physical therapist, similar to traditional outpatient care, tele-rehabilitation can significantly reduce operating costs of healthcare facilities keeping patients at their home. In this view, tele-rehabilitation could reduce the burden on healthcare facilities and on patients, who could benefit from logistic opportunities and a reduction in travel and social efforts to reach rehabilitation centers.

In conclusion, our data indicate that tele-rehabilitation is as effective as traditional physiotherapist-led rehabilitation in mitigating pain and ameliorating function in individuals with knee osteoarthritis. These findings affirm tele-rehabilitation not only as a non-inferior but also as valid alternative to conventional rehabilitation.

Limitations

Limitations of our study are crucial for contextualizing its findings. The short duration of the follow-up period limited our ability to assess the long-term sustainability of the improvements gained through tele-rehabilitation. Additionally, the absence of a non-treated control group prevents a comprehensive understanding of the natural progression of knee osteoarthritis without intervention, which could have provided valuable baseline data for comparison. The small sample size also poses constraints on the generalizability of our results, potentially limiting the statistical power to detect significant differences or subtle effects of the TR intervention. Future research should aim to include longer follow-up periods to better evaluate the lasting impact of TR, incorporate a non-treated control group for more in-depth comparisons, and increase sample sizes to enhance the robustness and applicability of findings.

Conclusions

The study concludes that tele-rehabilitation is an effective and viable alternative to conventional physiotherapist-led rehabilitation for managing knee osteoarthritis, demonstrating comparable outcomes in pain reduction and functional improvement. This underscores tele-rehabilitation's strength not in surpassing conventional therapy in efficacy, but in offering a flexible, accessible, and potentially resource-efficient option for knee osteoarthritis care.

AUTHORS'CONTRIBUTION STATEMENT

RT proposed the revision project and identified the framework. RT, MGB and PP proposed the methodology. RT, DP and LB identified the research strategy. RT, PD, MGB extracted and analyzed the data. RT, PD and MGB supervised the methodology. All authors conducted the revision and developed the first and subsequent drafts of the manuscript.

MANUSCRIPT CONFLICT OF INTEREST

The Authors declares that there is no conflict of interest.

FUNDING

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Study 2: Assessment of Balance During a Single-Limb Stance Task in Healthy Adults: A Cross-Sectional Study

Roberto Tedeschi, Luciana Labanca, Daniela Platano, Maria Grazia Benedetti

Abstract

Single-limb stance (SLS) is a demanding postural task, widely used for balance assessment in both research and clinical practice. Despite extensive data on elderly and clinical populations, less is known about younger and healthier adults. Our aim in this study was to assess balance during a SLS task among a cohort of healthy adults to determine whether there are age or sex group or testing condition differences in performances. In this cross-sectional study, we involved 120 participants aged 30 to 65 years and divided them into four age sub-groups with equal numbers of males and females in each. We assessed balance during a 45-second SLS task on a Delos Postural System for both lower limbs in two conditions - open eyes (OE) and closed eyes (CE). We calculated stability (SI) and autonomy (AU) indices and used analysis of variance to determine that there was no significant effect of limb dominance or sex on balance parameters. However, there was a significant interaction effect between age group and testing condition for both SI and AU ($p < 0.001$ for both), with balance worsening as age increased only in the CE condition.. These results highlight a pattern of balance decline with age when vision is eliminated from balance performance, underscoring the critical relationship between sensory input and postural control as people age.

Keywords: Postural Stability, Balance Training, Postural Control, Proprioception

Introduction

The ability to perceive and understand one's body position and movement is fundamental to balance throughout life [67]. These abilities enable individuals to recognize and respond to external stimuli effectively, maintaining or modifying their posture and movement. Proprioception, a sense of one's body positions in space, relies on specialized proprioceptors [26] that provide crucial information (e.g., muscle length, tendon tension, joint internal pressure, and head orientation) to the central nervous system [17]. A key aspect of proprioception is balance, defined as the capacity to keep the body's center of gravity within its base of support, which is crucial for maintaining equilibrium in both static and dynamic conditions [41]. Injuries and various orthopedic pathologies often impair proprioception and balance. These impairments may arise from damage to proprioceptors due to tissue or nerve degeneration typical of certain orthopedic conditions [9]. Consequently, proprioception and balance form an integral part of training and rehabilitation programs. Accurate balance assessment is essential for quantifying deficits and monitoring progress in rehabilitation pathways [44, 57]. Among tasks used for balance assessment, single-limb stance (SLS) is one of the most popular in both research and clinical practice [14, 16, 28, 40], since it is a challenging task that requires an efficient sensory integration of somatosensory, vestibular and visual information with the aim to provide an effective and ongoing motor response to deal with the reduced base of support. In addition, the SLS quantifies altered balance of the single limb which can be concealed during the performance of double-limb tasks. However, to the best of the authors' knowledge, past research on the SLS has been primarily focused on young, elderly or injured individuals (Chomiak et al., 2014; Ghislieri et al., 2023; Kurz et al., 2018; Labanca et al., 2021; Labanca, et al., 2021; Negahban et al., 2013) leaving a knowledge gap regarding healthy adult reference groups [43]. Thus, our main aim in this study was to assess balance during a SLS task in a cohort of healthy adults to determine whether there are differences in participants' age, dominant limb, sex, or in testing conditions. We expected these data to inform clinicians and researchers about what to expect in balance performance among healthy adults.

Method

Participants

We recruited 120 participants and categorized them into four age groups of 15 males and 15 females each, ensuring an equal gender distribution within each group of age 30-39, 40-49, 50-59, and 60-65. Recruitment was based on public notices and institutional outreach programs. Inclusion criteria were to be aged between 30 and 65 years, to have normal body weight as defined by a Body Mass Index (BMI) greater than 18.5 and less than 24.99. BMI was calculated as the body mass divided by the square of the height of each participant. Exclusion criteria were history of orthopedic or neurological pathologies that might affect postural stability, engagement in competitive sports activities that could influence baseline proprioceptive abilities, and a sedentary lifestyle as defined by the absence of regular physical activity. Additional information on participants is reported in Table 1.

Table 1. Participant Characteristics

Characteristics	Data
Sample Size	N = 120
Age: Mean (*SD*)	48.8 (10.9) years; Range: 30 to 65 years
Gender	50% Female (n = 60); 50% Male (n =60)
Dominant Leg	17.5% Left (n = 21); 82.5% Right (n = 99)
Weight: Mean (*SD*)	70 (19) kg
Height: Mean (*SD*)	170 (15) cm
BMI: Mean (*SD*)	24.2 (3.5)

Note. BMI (Body Mass Index) was calculated as the body mass divided by the square of the height of each participant.

Sample Size

We determined sample size from a past research study [47] in which the center of pressure displacement length was determined during a static postural stability task with closed eyes on a force platform, involving two groups of participants from different age groups (young and elderly). Based on these data from Seigle et al. (2009), we conducted a power analysis using GPower 3.1.9.6 (University of Kiel, Germany). We considered an independent samples t-test where the mean center of pressure displacement length was 390 (*SD* = 89) mm for young participants and 563 (*SD* = 239) mm for elderly participants, and an effect size of 0.95 (Seigle et al., 2009). With a significance level of $\alpha = 0.05$ and a power of 95%, the power analysis suggested that a minimum of 25 participants per group would be required for this study. Additionally, we planned to recruit five additional participants for each group to account for potential drop-outs or difficulties in conducting measurements.

Ethical Considerations

Our research protocol received approval from the Ethics Committee XXXXX with AVEC EC protocol code: 924/2020/Sper/IOR. We obtained written informed consent from all participants before starting any study-specific evaluation.

Balance Assessment

We assessed balance during the SLS task using the Delos Postural Proprioceptive System (Delos Srl, Turin, Italy) (see Figure 1) as in previous studies (Riva et al. 2019; Benedetti et al. 2019; Dąbrowska et al. 2020; Labanca et al., 2021; Permoda-Białozorczyk et al. 2022). This system includes a wooden platform where the participant stands on, a two-dimensional accelerometer attached to the participant's sternum, used to measure trunk inclination in the frontal and sagittal planes, and a horizontal bar instrumented with an infrared sensor, used to record the number and duration of eventual hand touch for support. The experimental set up is shown in Figure 1. During the SLS performance, participants were asked to stand barefoot for 45 seconds on the wooden platform alternately with the dominant and the non-dominant limb in both a closed and an open-eyes conditions in a random order. They were asked to stand as still as possible with the upper limbs aligned at the sides, and to hold their hands on the horizontal bar if needed. They performed three trials for each condition. A rest period of 60 seconds was allowed between trials. For each trial the variables we considered were: the Stability Index (SI) and the Autonomy Index (AU), defined as follows:

(a) **Stability Index (SI):** The SI measured the magnitude and consistency of trunk oscillations in the frontal and sagittal planes. Participants stood on a platform, and the accelerometer recorded trunk inclination during a 45-second SLS task. The SI is calculated as a percentage score from 0 to 100%, with lower oscillations indicating better stability and thus a higher SI score. This score combined total displacement and oscillation frequency, normalized against a stability threshold. The SI quantified the participant's ability to maintain balance by measuring trunk oscillations. Smaller and more consistent oscillations indicated better balance control. A higher SI score, expressed as a percentage, represented better stability, making it a direct and quantifiable measure of postural stability.

(b) **Autonomy Index (AU):** The AU measured reliance on external support. During the SLS task, participants could use a horizontal bar for support if needed. The AU was based on the number and duration of hand touches recorded by an infrared sensor. AU scores ranged from 0 to 100%, where higher scores indicated fewer touches and less reliance on external support, reflecting better balance control. The AU assessed the participant's reliance on external support, with fewer and shorter touches indicating greater autonomy. Higher AU scores, expressed as a percentage, reflected less reliance on support, providing a comprehensive measure of balance performance by complementing the SI.

We averaged the three trials to obtain values for subsequent data analysis. The dominant limb was identified by asking the participants which limb they used to kick a ball, as in previous studies (Elias & Bryden 1998; Labanca et al. 2020; Nuccio et al. 2021).

Figure 1. Delos Postural Proprioceptive System

Statistical Analyses

We calculated descriptive statistics including means, standard deviations, and frequency distributions for all quantitative and categorical variables. We assessed data normality using the Shapiro-Wilk test. We conducted a four-way analysis of variance or ANOVA (4 age groups x dominant or non dominant limb x sex x OA or CE condition) on the Stability Index (SI) and the Autonomy Index (AU), recorded during the SLS task. When the main effect was significant we used a Student's t-test with a Bonferroni correction to make pairwise comparisons. We calculated effect size as partial eta squared (ηp^2) and based interpretations of effect size as small (0.01), medium (0.06), and large (0.14) (Lakens et al., 2013). All the analysis were conducted with the Statistical Package for Social Sciences (SPSS v23).

Results

Participant Characteristics

As shown in Table 1, we included 120 participants (50% females, 50% males) in four age groups of 30 individuals each. Most participants (82.5%, n = 99) reported right leg dominance, with a smaller proportion (17.5%, n = 21) indicating left leg dominance.

Balance

Mean values (and standard deviations) related to balance performance for all participants are reported in Table 2.

Table 2: Summary of Stability Index and Autonomy by Age Group, Gender for the Dominant Limb

Age Group	Gender	Dominant Limb (Right %)	Dominant Limb (Left %)	Stability Index (%) Dominant Limb OE	Stability Index (%) Dominant Limb CE	Autonomy (%) Dominant Limb OE	Autonomy (%) Dominant Limb CE
30-40	Female	85.7	14.3	90.5 (2.8)	74.2 (12.2)	97.6 (7.4)	93.4 (9.40)
30-40	Male	85.7	14.3	88.3 (4.6)	78.1 (10.7)	100 (0.0)	97.6 (4.3)
40-50	Female	90.0	10.0	87.1 (11.8)	70.1 (16.4)	97.0 (9.4)	86.7 (13.5)
40-50	Male	90.0	10.0	88.1 (7.5)	66.1 (14.5)	98.7 (4.7)	83.5 (14.0)
50-60	Female	80.0	20.0	89.3 (6.2)	66.1 (18.1)	98.4 (4.2)	80.4 (20.5)
50-60	Male	80.0	20.0	87.8 (6.8)	64.2 (17.9)	97.7 (5.3)	79.9 (21.5)
60-65	Female	75.0	25.0	86.2 (7.7)	57.3 (12.9)	97.9 (4.6)	77.1 (13.1)
60-65	Male	75.0	25.0	81.6 (12.3)	52.2 (10.4)	96.2 (9.2)	71.0 (10.7)

Legend: Autonomy (%) Left CE: Autonomy (left leg eyes closed); Autonomy (%) Left OE: Autonomy (left leg eyes open); Autonomy (%) Right CE: Autonomy (right leg eyes closed); Autonomy (%) Right OE: Autonomy (right leg eyes open); Stability Index (%) Left CE: Stability Index (left leg eyes closed); Stability Index (%) Left OE: Stability Index (left leg eyes open); Stability Index (%) Right CE: Stability Index (right leg eyes closed); Stability Index (%) Right OE: Stability Index (right leg eyes open). Note. Values in parentheses represent the standard deviation (SD).

Regarding the SI, the ANOVA showed no significant interaction effects between limb dominance and sex, $F(1, 116) = 0.008$, $p = 0.92$, $\eta p^2 = 0.01$; limb dominance and testing condition, $F(1, 116) = 0.282$, $p = 0.59$, $\eta p^2 = 0.01$; limb dominance and age, $F(3, 116) = 0.173$, $p = 0.91$, $\eta p^2 = 0.01$; sex and testing condition, $F(1, 116) = 0.047$, $p = 0.08$, $\eta p^2 = 0.01$; and sex and age, $F(1, 116) = 1.026$, $p = 0.38$, $\eta p^2 = 0.01$. However, there was a significant interaction between age and testing condition, $F(3, 116) = 11.378$, $p < 0.001$, $\eta p^2 = 0.01$. Mean values and significant differences after the post-hoc analysis are represented in Figure 2. Since no significant differences were observed between the dominant and the non-dominant limbs, F (df1) = 0.01; $p = 0.91$; ηp 2 = 0.01, and between males and females, F (df1) = 2.678; $p = 0.11$; ηp 2 = 0.01, we show only the data related to the dominant limb as a mean for each age group. We observed no significant differences between the age groups in the OE condition, but we observed a significantly lower SI ($p < 0.001$) in the CE compared to the OE condition for all the age groups. In addition, in the CE condition SI was significantly higher in the 30-39 compared to the 40-49 age group ($p < 0.001$; Cohen's $d = 0.59$), the 50-59 age group ($p < 0.001$; Cohen's $d = 0.74$) and the 60-65 age group ($p < 0.001$; Cohen's $d = 1.84$). SI was also significantly higher in the 40-49 compared to the 50-59 ($p < 0.001$; Cohen's $d = 0.17$) and the 60-65 ($p < 0.001$; Cohen's $d = 0.84$) age groups; and in the 50-59 compared to the 60-65 ($p < 0.001$; Cohen's $d = 0.69$) age group.

Regarding the AU, the ANOVA showed no significant interaction effects between limb dominance and sex, $F(1, 116) = 0.178$, $p = 0.67$, $\eta p^2 = 0.01$; limb dominance and testing condition, $F(1, 116) = 0.11$, $p = 0.92$, $\eta p^2 = 0.01$; limb dominance and age, $F(3, 116) = 0.444$, $p = 0.72$, $\eta p^2 = 0.01$; sex and testing condition, $F(1, 116) = 0.74$, $p = 0.39$, $\eta p^2 = 0.01$; sex and age, $F(3, 116) = 1.678$, $p = 0.17$, $\eta p^2 = 0.01$, but there was a significant interaction effect between age and testing condition, $F(3, 116) = 20.048$, $p < 0.001$, $\eta p^2 = 0.06$. Since no significant differences were observed between the dominant and the non-dominant limbs, F (df1) = 0.95; $p = 0.75$; ηp 2 = 0.01, and between males and females, F (df1) = 1.046; $p = 0.31$; ηp 2 = 0.01, we show only the data related to the dominant limb as a mean for each age group. While we observed no significant differences between the age groups in the OE condition, we did observe a significantly lower AU ($p < 0.001$) in the CE compared to the OE condition for all age groups, except the 30-39 group, which showed a trend but no significant differences between the OE and CE conditions ($p = 0.06$). In addition, in the CE condition, the AU was significantly higher in the 30-39 compared to the 40-49 age group ($p < 0.001$; Cohen's $d = 0.95$), the 50-59 age group ($p < 0.001$; Cohen's $d = 1.02$) and the 60-65 group ($p < 0.001$; Cohen's $d = 2.12$). AU was also significantly higher in the 40-49 compared to the 60-65 age group ($p < 0.01$; Cohen's $d = 1.01$). No significant differences were found between the 40-49 compared to the 50-59 age group ($p = 0.24$; Cohen's $d = 0.31$) and between the 50-59 and the 60-65 age group ($p = 0.19$; Cohen's $d = 0.34$).

Figure 2. Mean values (and standard deviations) of Stability Index recorded in the four age groups and in the open eyes (OE) and closed eyes (CE) conditions. Note. ***p < 0.001

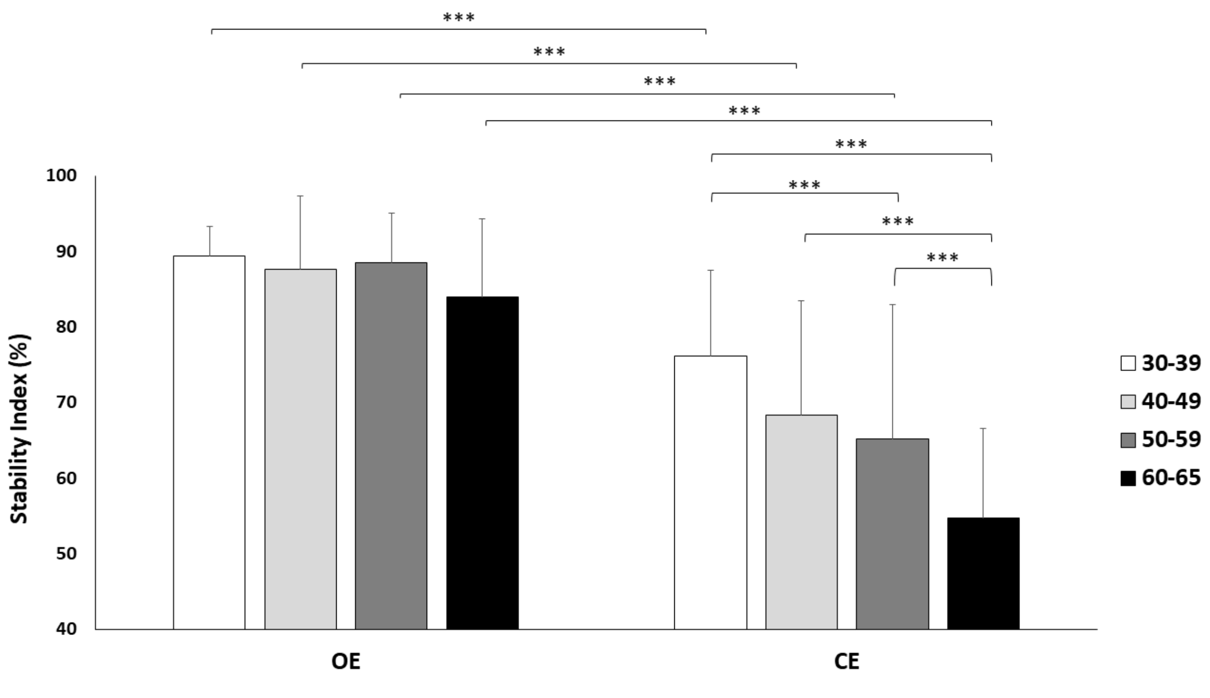
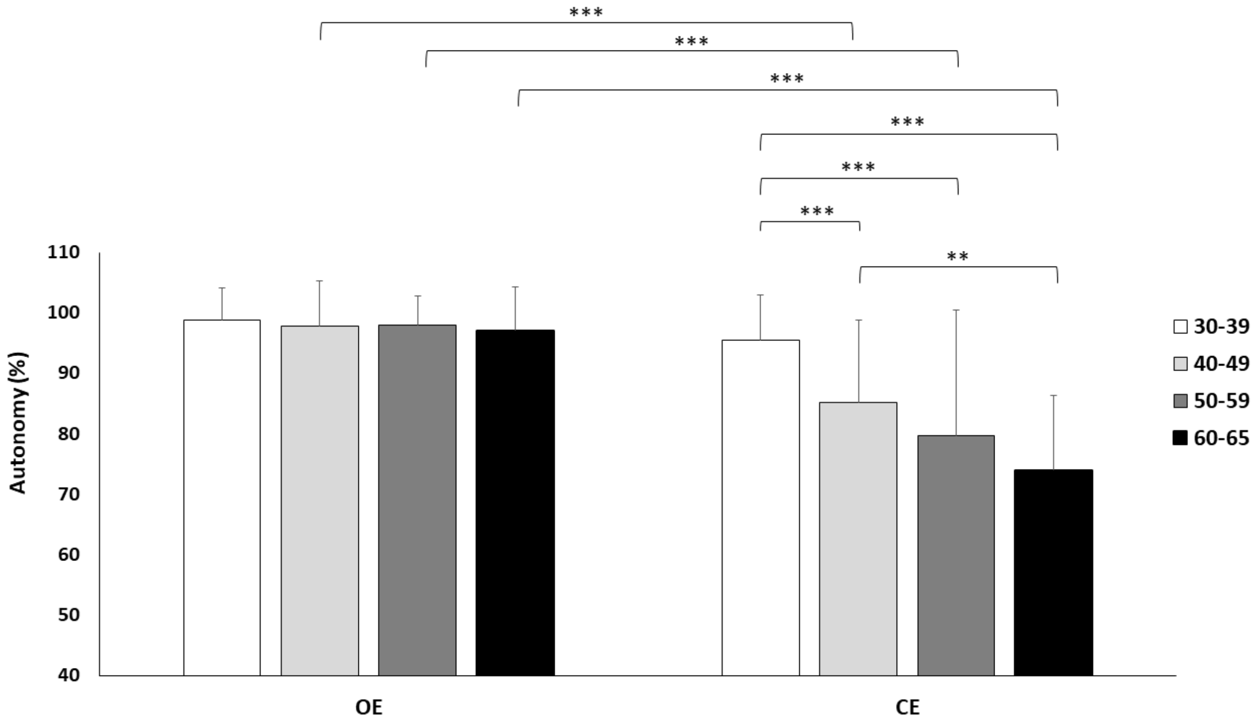


Figure 3. Means (and standard deviations) of the Autonomy Index recorded in the four age groups and in the open eyes (OE) and closed eyes (CE) conditions. Note. **p < 0.01; ***p < 0.001



Discussion

In this study, we provided data regarding balance stability in healthy adults and determined whether there were performance differences between participants of varying ages, sex, and leg dominance and whether there were differences between eyes closed and eyes open conditions during the single limb stance task. We found no significant differences in balance parameters between participants of different sexes, and there were no differences based on participants' dominant limbs; these findings are in accordance with previous literature conducted on clinical and elderly populations of other age ranges and physical activity levels [45, 46]. Thus, among healthy adults, there appears to be a homogenous neuromuscular control mechanism, irrespective of these variables. Of importance, however, we observed a significant interaction between age and sensory testing conditions (open and closed eyes) such that balance performance declined with age, but only in the closed eyes condition. This finding aligns with the theory of age-associated sensory integration decline [5, 71]. The ANOVA showed significant interaction effects between age and testing condition, $F(3, 116) = 20.048$, $p < 0.001$, $\eta p^2 = 0.06$. All age ranges in the present study showed a worse balance performance in the closed eyes compare to the open eyes condition, but the differences between the two conditions were higher as age increased. One of the key mechanisms underlying this decline is sensory reweighting. Sensory reweighting refers to the central nervous system's ability to adjust reliance on different sensory inputs (visual, vestibular, and proprioceptive) to maintain balance[29]. When visual input is limited or absent, as in the closed eyes condition, older adults may struggle to compensate due to age-related declines in proprioceptive and vestibular functions. This limitation in sensory reweighting capacity highlights the need for balance training programs that enhance proprioceptive and vestibular functions, particularly for older adults. Such programs can help mitigate the risk of falls by improving the ability to adapt to sensory changes. This is critically important, considering the roles of proprioceptive and vestibular systems in maintaining balance, especially under sensory-deprived conditions. Our results indicate a more pronounced decline in balance ability or a reduction in compensatory strategies with age that was observable when visual information was removed. This is in accordance with previous studies conducted on elderly individuals showing worse balance performance in a closed, compared to open eyes, condition [38, 50]. Interestingly, our results suggest that age also affected postural strategy used to maintain balance in the closed eyes condition. In fact, the youngest participants (age range 30-39) had a higher AU (close to 100%) in comparison with all the other age ranges in the closed eyes condition despite a worsening SI when transitioning from the open to the closed eyes condition. This result can be explained by the fact that changes in motor control and deterioration of the effectiveness of mechanisms related to balance are aspects of the ageing process [6, 31]. As a consequence of these motor control declines, there was a higher fear of falling that lead to an increase in the use of hand support only in the oldest age ranges. Beyond the fear of falling, other mechanisms explaining our results are the age-related changes in mechanisms for postural control related to the sensory system, also known as "sensory reweighting" (Peterka et al. 2018), suggesting that when a sensory system is impaired the the other available systems are increasingly used to substitute for the impaired one. In line with these mechanisms, our older participants' increased reliance on visual information for balance maintenance was probably related to the reduction in the acuity of the other sensory receptors. Our results suggest also that the decline is even more marked as age increased, but that the strategy to maintain balance seem to not change much between 40 and 65 years. Thus, it could be speculated that in the 30-39 age group, sensory acuity is still high since individuals show a worsened stability in the CE compared to the OE condition, but they are still able to control balance and do not need external support, in contrast to their oldest counterparts, who showed higher difficulties in reweighting their reliance on other senses when vision was lacking. These findings have direct implications for clinical practice, as they emphasize the necessity for tailored balance assessment and training programs across different age groups. Specifically, younger healthy adults may benefit from more challenging balance training regimes, while older individuals may need to incorporate proprioceptive exercises in their training regimens. Additionally, it is important to note that these recommendations extend to populations at risk of fracture, such as osteoporotic women, even in age groups younger than 65 years old. Balance and stability issues must be addressed comprehensively in various clinical contexts to promote better overall health and reduce the risk of falls and fractures. Furthermore, the absence of significant sex-based differences in our study highlights the need for re-evaluating gender-based assumptions in balance training and rehabilitation programs in healthy adults.

Limitations and Directions for Further Research

Limitations of our study include the homogeneity of our sample in terms of health and physical activity levels, potentially limiting the generalizability of our findings to a broader population that might include active healthy adults. Future investigators should aim to include these specific populations, including individuals with varying levels of physical activity and health status, to comprehensively understand balance control mechanisms across different demographics. While our study begins to fill a critical gap in the literature by providing data on postural stability in a non-clinical, healthy adult population, there is a need to gather and report these data on a large number of adults and to determine how it may be affected by high levels of physical activity and/or sport involvement. Meanwhile, our data underscore the importance of age and sensory testing conditions in balance control, suggesting avenues for targeted interventions and further research in this field.

Conclusions

Data from this study provide preliminary normative data on SLS balance control in healthy sedentary adults and reveal that that age and sensory conditions significantly influence postural stability in this population, while limb dominance and sex do not. These findings highlight the need for age-specific approaches to balance training and assessment, and they suggest that there may be a uniform balance control mechanism across different genders and limbs in healthy adults.

Chapter 6

Discussion

The results of this research contribute significantly to the fields of musculoskeletal disorders, neurological rehabilitation, and pain management, presenting innovative strategies and methodologies to address the complex needs of patients suffering from chronic pain and functional impairments. Through a combination of clinical trials, cross-sectional studies, and collaborative efforts with leading institutions, this body of work has examined both traditional and emerging approaches to rehabilitation, emphasizing the importance of an integrated, patient-centered approach to care. The studies presented highlight the efficacy of tele-rehabilitation for musculoskeletal conditions, the crucial role of balance and proprioception in functional recovery, and the need for advanced pain management techniques that incorporate both pharmacological and non-pharmacological interventions.

A key focus of this research was the exploration of tele-rehabilitation as an alternative to conventional therapy for patients with chronic musculoskeletal disorders, particularly knee osteoarthritis (OA)[8]. Osteoarthritis, one of the most prevalent causes of pain and disability among older adults, poses significant challenges in rehabilitation due to its progressive nature and the multifaceted impact it has on mobility, pain, and quality of life. The randomized controlled trial conducted in this research demonstrated that tele-rehabilitation (TR) is as effective as conventional therapy (CT) in reducing pain and improving physical function. This finding is particularly relevant in the current healthcare landscape, where remote healthcare delivery has become increasingly necessary due to logistical constraints and the growing demand for accessible rehabilitation services.

The trial revealed that both TR and CT significantly reduced pain, as measured by the Numeric Pain Rating Scale (NPRS), and improved functional outcomes, as evidenced by the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC). Importantly, the study showed that the benefits of tele-rehabilitation were sustained over time, with patients maintaining improvements in pain and function at a three-month follow-up. This suggests that tele-rehabilitation offers a viable, long-term solution for managing chronic conditions like knee osteoarthritis, providing patients with an accessible, flexible, and effective means of engaging in therapeutic exercises from their homes. Furthermore, the findings reinforce the notion that digital healthcare interventions can be just as impactful as traditional, in-person therapies when properly structured and supervised.

The efficacy of tele-rehabilitation likely stems from several critical factors. First, the structured exercise programs used in TR mirror those traditionally offered in clinical settings, ensuring that patients receive evidence-based, therapeutic interventions regardless of the delivery method. Second, the real-time supervision provided by physiotherapists via video calls helps to maintain patient adherence and ensures proper execution of the exercises, which is crucial for preventing injury and optimizing therapeutic outcomes. Additionally, the remote nature of TR allows for more individualized care, enabling patients to participate in rehabilitation at times and locations that are most convenient for them. This flexibility likely contributes to higher adherence rates and improved patient satisfaction, particularly among individuals who may face challenges accessing traditional outpatient facilities due to mobility issues or geographic barriers[39, 66].

These findings have broader implications for the field of rehabilitation, suggesting that tele-rehabilitation could be effectively applied to other musculoskeletal conditions beyond knee osteoarthritis. Chronic low back pain, hip osteoarthritis, and post-surgical recovery are just a few examples of conditions where tele-rehabilitation could be implemented to extend the reach of rehabilitation services and improve patient outcomes. Additionally, as healthcare technology continues to advance, the integration of wearable devices and mobile health applications could further enhance the effectiveness of tele-rehabilitation by providing real-time feedback on patients' movements and progress, allowing for more personalized and data-driven interventions[33, 60].

The importance of proprioception and balance in functional recovery is another key finding of this research. Balance impairments are common in both aging populations and individuals with musculoskeletal conditions, yet they are often under-addressed in traditional rehabilitation programs. The cross-sectional study on balance assessment using a single-limb stance task provided critical insights into how proprioception declines with age, particularly under challenging conditions that remove visual input. This decline in balance performance, measured using the Stability Index (SI) and Autonomy Index (AU), underscores the essential role that proprioception and sensory feedback play in maintaining postural control and preventing falls.

The deterioration of proprioceptive abilities with age highlights the need for targeted interventions that address both sensory and motor deficits in rehabilitation programs. The results suggest that balance training, which specifically challenges proprioceptive systems, should be a core component of rehabilitation for older adults and patients with musculoskeletal conditions, such as knee osteoarthritis. By incorporating exercises that improve balance and proprioception, clinicians can help mitigate the age-related decline in postural stability and reduce the risk of falls, which is a leading cause of injury and disability in the elderly population.

Incorporating balance training into tele-rehabilitation programs could further enhance the outcomes for patients with musculoskeletal disorders. Proprioceptive exercises, particularly those that challenge patients to maintain balance in conditions with reduced sensory input (such as eyes closed or unstable surfaces), could be easily integrated into remote rehabilitation sessions. This would offer a more holistic approach to rehabilitation, addressing not only pain and physical function but also the sensory and motor aspects that are critical for maintaining independence and mobility in daily life.

The role of advanced pain management strategies was another focal point of this research, with a particular emphasis on integrating both pharmacological and non-pharmacological interventions. Pain, especially chronic pain, is a complex phenomenon that involves not only physical discomfort but also emotional and psychological distress. The neurophysiological mechanisms underlying pain, including nociception and central sensitization, necessitate a multifaceted approach to pain management that goes beyond simple analgesics. The research explored various innovative approaches to managing pain in rehabilitation, including physical therapies, cognitive-behavioral strategies, and neuromodulation techniques.

One of the key findings in this area was the effectiveness of integrating techniques like transcranial direct current stimulation (tDCS) and transcutaneous electrical nerve stimulation (TENS) into rehabilitation programs[37]. These non-invasive neuromodulation techniques have shown promise in reducing pain intensity and improving functional outcomes, particularly in conditions like chronic musculoskeletal pain and neuropathic pain. The research also highlighted the potential of psychological interventions, such as cognitive-behavioral therapy (CBT) and relaxation techniques, in addressing the emotional and cognitive dimensions of chronic pain. These methods not only help patients manage the psychological impact of chronic pain but also improve adherence to rehabilitation protocols, enhancing overall outcomes.

Additionally, the exploration of the placebo and nocebo effects in pain management, particularly in relation to digital interventions, provided important insights into how patient expectations can influence therapeutic outcomes. The concept of the Drucebo effect — where positive expectations are enhanced through digital and remote interactions — represents a novel approach to optimizing patient outcomes without relying solely on pharmacological interventions. This highlights the importance of the therapeutic context and patient-provider interactions in pain management, suggesting that clinicians should actively engage with patients to foster positive expectations and enhance the overall effectiveness of rehabilitation.

This research provides substantial evidence supporting the use of tele-rehabilitation as a viable and effective alternative to conventional therapy for managing musculoskeletal conditions like knee osteoarthritis. The findings emphasize the importance of incorporating balance and proprioceptive training into rehabilitation programs, particularly for older adults and individuals with sensory impairments. Moreover, the integration of advanced pain management strategies, including neuromodulation and psychological interventions, offers a comprehensive approach to addressing the complex nature of chronic pain in rehabilitation. These insights have far-reaching implications for clinical practice, advocating for a more personalized, patient-centered approach to rehabilitation that leverages technology and innovative therapeutic strategies to improve outcomes and enhance the quality of life for individuals with chronic musculoskeletal and neurological conditions.

Practical implications for clinical practice

The findings of this research have significant and practical implications for clinical practice, particularly in the fields of musculoskeletal rehabilitation, pain management, and the use of innovative technologies in healthcare. The results underscore the necessity of integrating advanced therapeutic approaches, such as tele-rehabilitation, proprioceptive training, and multimodal pain management, into routine clinical protocols to enhance patient outcomes, improve access to care, and optimize resource utilization. These implications are directly applicable to clinicians who aim to provide evidence-based, personalized care for patients with chronic musculoskeletal and neurological conditions.

One of the most important implications for clinical practice is the demonstrated efficacy of tele-rehabilitation (TR) as a viable alternative to conventional in-person therapy. The results of this study indicate that TR is not only as effective as traditional rehabilitation methods in managing conditions such as knee osteoarthritis (OA), but it also offers significant advantages in terms of accessibility and flexibility for patients. Given the increasing demand for remote healthcare solutions, particularly in the wake of the COVID-19 pandemic, integrating tele-rehabilitation into routine clinical practice could vastly improve access to therapeutic interventions for patients in remote or underserved areas, as well as for those with mobility limitations.

In practical terms, this means that clinicians can use digital platforms to deliver supervised rehabilitation sessions, ensuring patients perform exercises correctly and adhere to their prescribed treatment plans. By incorporating tele-rehabilitation into standard care, healthcare providers can reduce the need for frequent in-person visits, lower healthcare costs, and still maintain high-quality therapeutic outcomes. Moreover, tele-rehabilitation allows for more individualized treatment regimens, as it enables real-time monitoring and feedback, which can be tailored to each patient's specific needs and progress. This personalized approach enhances patient engagement and compliance, which are critical for long-term success in rehabilitation.

Another key implication for clinical practice is the importance of integrating proprioceptive and balance training into rehabilitation programs, particularly for older adults and individuals with musculoskeletal disorders. The findings from the study on balance assessments indicate that proprioception deteriorates with age, especially under challenging conditions such as visual deprivation. This decline in postural stability increases the risk of falls, which can lead to further injuries and complications, especially in the elderly. As such, clinicians should prioritize the inclusion of proprioceptive exercises in rehabilitation protocols to improve sensory feedback and postural control[25, 46].

In clinical settings, this can be achieved through the use of balance boards, unstable surfaces, and exercises that challenge the sensory-motor system, such as single-leg stances and tasks performed with closed eyes. These exercises should be incorporated not only in the rehabilitation of conditions like osteoarthritis but also in the management of patients recovering from surgeries or other musculoskeletal injuries. Regular assessment of proprioception and balance is crucial, as it allows clinicians to monitor progress and adjust rehabilitation programs accordingly. By addressing proprioceptive deficits, healthcare providers can help reduce the risk of falls, improve functional mobility, and enhance patients' overall quality of life.

The findings on multimodal pain management also have significant clinical implications, particularly for the treatment of chronic pain in musculoskeletal and neurological conditions. The research emphasizes the importance of combining pharmacological and non-pharmacological interventions to achieve optimal pain control. Techniques such as transcutaneous electrical nerve stimulation (TENS) and transcranial magnetic stimulation (TMS) have been shown to modulate neural activity and reduce pain perception, offering a valuable tool for clinicians managing chronic pain that is resistant to conventional treatments.

Incorporating these neuromodulation techniques into routine practice allows clinicians to provide patients with non-invasive, low-risk options for pain management, which can be particularly beneficial for those seeking to minimize reliance on medications such as opioids. Additionally, combining these techniques with other non-pharmacological strategies, such as cognitive-behavioral therapy (CBT) and relaxation techniques, can enhance patient outcomes by addressing both the physical and psychological components of chronic pain. This integrative approach helps patients develop better coping mechanisms, improve their mental well-being, and increase adherence to rehabilitation programs, ultimately leading to more sustainable pain relief and functional improvements[2, 23].

Furthermore, the exploration of the placebo and nocebo effects in pain management highlights the critical role that patient expectations and therapeutic interactions play in the overall success of rehabilitation. The concept of the Drucebo effect, which amplifies positive outcomes through the use of digital interactions and therapeutic suggestions, underscores the importance of optimizing the patient-provider relationship in clinical practice. Clinicians should aim to foster positive patient expectations by using encouraging language, establishing strong therapeutic rapport, and creating a supportive treatment environment that enhances patients' belief in the efficacy of their care. This can be especially effective in tele-rehabilitation settings, where digital platforms can be leveraged to reinforce positive therapeutic experiences and boost treatment outcomes.

Finally, one of the most practical implications of this research is the need for a data-driven, personalized approach to rehabilitation. The use of wearable devices, mobile health applications, and other digital tools allows clinicians to gather continuous, real-time data on patients' performance, which can inform treatment adjustments and ensure that interventions are tailored to individual needs[18]. By adopting these technologies, clinicians can shift from episodic assessments to ongoing monitoring, enabling them to detect subtle changes in a patient's condition and respond proactively. This approach not only improves clinical outcomes but also empowers patients to take a more active role in their own recovery by providing them with insights into their progress and encouraging greater engagement with their treatment plan.

The practical implications of this research for clinical practice are clear: integrating tele-rehabilitation, proprioceptive training, multimodal pain management, and personalized, data-driven care into standard rehabilitation protocols can significantly enhance patient outcomes. These strategies provide clinicians with the tools to offer more accessible, flexible, and effective care for patients with chronic musculoskeletal and neurological conditions, ultimately improving both the quality of life for patients and the efficiency of healthcare delivery systems[24]. As healthcare continues to evolve, these innovations will be critical in meeting the diverse and growing needs of patients in rehabilitation.

Future investigation

The research presented in this thesis opens several promising avenues for future investigations that could significantly impact the fields of rehabilitation, pain management, and proprioceptive training. The integration of digital technologies, personalized medicine, and innovative therapeutic strategies has the potential to transform clinical practices, and further research is necessary to expand on these findings to optimize patient outcomes.

One of the most pressing areas for future exploration is the long-term efficacy of tele-rehabilitation in managing musculoskeletal disorders. While the present research demonstrated its effectiveness in treating knee osteoarthritis in the short to medium term, it is crucial to assess whether these benefits are sustained over a more extended period. Future studies should investigate whether tele-rehabilitation can maintain pain reduction, physical function, and quality of life improvements over several years. Additionally, expanding research to other patient populations, such as those suffering from chronic low back pain, hip osteoarthritis, or post-operative recovery, could provide valuable insights into the broader applicability of this intervention. Furthermore, understanding how tele-rehabilitation impacts patients with comorbidities, such as cardiovascular diseases or diabetes, would enhance its use in more diverse and complex cases.

In addition to studying long-term outcomes, the integration of emerging technologies into tele-rehabilitation platforms offers exciting research prospects. Wearable devices, sensors, and mobile health applications could provide real-time data on patients' biomechanics, movement quality, and adherence to prescribed exercises. Future studies should explore the potential of these technologies to monitor and optimize patient performance during tele-rehabilitation sessions, allowing for more precise feedback and personalized treatment adjustments. Furthermore, the incorporation of virtual reality (VR) and augmented reality (AR) into rehabilitation could offer immersive, interactive environments that improve patient engagement and motivation. Research comparing traditional tele-rehabilitation methods with these advanced technologies would help to determine their effectiveness in enhancing adherence and long-term functional outcomes.

Proprioceptive training represents another critical area for future research, particularly for aging populations and individuals with neurological conditions. This research has shown that proprioception declines with age, particularly when visual input is limited, leading to an increased risk of falls and reduced mobility. Future studies should focus on developing targeted proprioceptive interventions to prevent balance impairments in older adults. Additionally, these interventions could be adapted for patients with neurological disorders such as Parkinson's disease, stroke, or multiple sclerosis, to prevent further deterioration of balance and motor function. Investigating the neuroplasticity mechanisms underlying proprioceptive improvements following training would offer valuable insights into the brain's adaptability and could inform the development of more effective, evidence-based rehabilitation strategies. Using neuroimaging techniques, such as functional MRI, to track neuroplastic changes would further our understanding of how proprioceptive exercises influence sensory-motor integration and recovery.

The multimodal management of pain is also a promising area for future research, particularly the development of personalized pain therapies. Combining pharmacological and non-pharmacological interventions, such as neuromodulation techniques like transcutaneous electrical nerve stimulation (TENS) and transcranial magnetic stimulation

(TMS), with psychological approaches like cognitive-behavioral therapy (CBT) has proven effective in managing chronic pain. Future research should explore how these strategies can be optimized and individualized based on patients' genetic, neurophysiological, and psychological profiles. This would allow for a more targeted approach to pain management, improving outcomes while minimizing adverse effects associated with pharmacological treatments. Furthermore, investigating the potential of digital health platforms to enhance the placebo effect, as seen with the Drucebo effect, could offer new, low-cost interventions for managing chronic pain. Studies that focus on understanding the psychological and neurobiological mechanisms of the placebo effect within digital interventions could lead to the refinement of these techniques and maximize their therapeutic benefits.

Neuroplasticity, the brain's ability to reorganize itself in response to injury or training, is a cornerstone of rehabilitation, particularly in the context of neurological disorders. Future research should investigate how various rehabilitation interventions, including tele-rehabilitation, proprioceptive training, and pain management techniques, stimulate neuroplasticity. Understanding the neural pathways involved in recovery from injury, pain modulation, and balance improvement could inform the design of more effective rehabilitation protocols. Longitudinal studies using advanced neuroimaging methods to observe neuroplastic changes over time would provide deeper insights into the brain's adaptability and how rehabilitation exercises should be structured in terms of frequency and intensity to maximize neural recovery[3, 22, 42].

The economic viability and scalability of tele-rehabilitation present additional opportunities for research. Future studies should evaluate the cost-effectiveness of tele-rehabilitation compared to conventional methods, considering both direct healthcare costs and indirect factors such as patient time and travel expenses. Research on the long-term financial implications of integrating tele-rehabilitation into healthcare systems would be particularly valuable in informing policy decisions, especially in resource-limited settings where access to rehabilitation services is limited. A comprehensive understanding of the cost-benefit balance could facilitate wider implementation of tele-rehabilitation platforms and potentially reduce the strain on healthcare systems by minimizing the need for in-person visits[1, 66].

Finally, the application of artificial intelligence (AI) and machine learning to rehabilitation offers a transformative potential that warrants further exploration. AI could be used to analyze large datasets collected from wearable devices, patient-reported outcomes, and clinical assessments to predict rehabilitation outcomes and tailor interventions to individual patient needs. Machine learning models could identify patterns in patient progress, enabling clinicians to adjust rehabilitation programs dynamically in response to real-time data. This approach could lead to more personalized and effective rehabilitation strategies, improving both patient outcomes and resource efficiency in clinical settings[27].

The future research directions arising from this thesis are vast and diverse. Investigating the long-term efficacy of tele-rehabilitation, integrating advanced technologies, developing personalized pain management strategies, and exploring neuroplasticity in rehabilitation are all areas ripe for further investigation. Additionally, exploring the scalability and cost-effectiveness of tele-rehabilitation, along with the application of AI and machine learning, has the potential to revolutionize the field of rehabilitation. These future studies will not only enhance the scientific understanding of rehabilitation but also provide the tools and strategies necessary to improve the quality of care for patients suffering from musculoskeletal and neurological conditions, ultimately leading to better clinical outcomes and greater accessibility to rehabilitation services globally[4, 49].

Overall, the research presented in this thesis demonstrates the efficacy of an integrated approach to pain management and rehabilitation, combining traditional techniques with digital and psychological interventions. The importance of personalized therapies has emerged as a key factor in maximizing treatment outcomes. The various strategies analyzed throughout the thesis complement and reinforce each other, creating a multidisciplinary rehabilitation model that can be tailored to the specific needs of each patient.

Conclusion

This thesis highlights the effectiveness of tele-rehabilitation as a viable and accessible alternative to traditional rehabilitation methods, particularly in managing knee osteoarthritis. The research also underscores the importance of incorporating proprioceptive training into rehabilitation programs, especially for older adults and individuals with musculoskeletal or neurological impairments. The integration of multimodal pain management strategies, combining pharmacological, non-pharmacological, and psychological interventions, is crucial for optimizing patient outcomes. Future research should focus on long-term efficacy, advanced technological integration, and personalized approaches to rehabilitation to further enhance patient care and outcomes in clinical practice. These findings provide a foundation for more accessible, flexible, and effective rehabilitation models, ultimately improving the quality of life for patients.

References

1. Abbafati C, Rosano A (2024) Work-related socioeconomic determinants of health: evidence from educational mismatch in Italy. Front Public Health 12:1388093. https://doi.org/10.3389/fpubh.2024.1388093

2. Akgül A, Aktekin LA, Eskioğlu E (2024) Neuromuscular Dysfunction and Electrophysiological Findings in Patients With Hypothyroidism and Hyperthyroidism: Electrophysiological Findings in Thyroid Disease. Journal of European Internal Medicine Professionals. https://doi.org/10.5281/zenodo.10635564

3. Al B, Mg B, Pm N (2006) Neuroplasticity after spinal cord injury and training: an emerging paradigm shift in rehabilitation and walking recovery. Physical therapy. https://doi.org/10.2522/ptj.20050212

4. AlGhaithi A, Maskari SA (2021) Artificial intelligence application in bone fracture detection. J Musculoskelet Surg Res 5:4. https://doi.org/10.4103/jmsr.jmsr_132_20

5. Andrade HB, Costa SM, Pirôpo US et al (2017) Lower limb strength, but not sensorial integration, explains the age-associated postural control impairment. Muscles Ligaments Tendons J 7:598–602. https://doi.org/10.11138/mltj/2017.7.4.598

6. Anson E, Bigelow RT, Studenski S et al (2019) Failure on the Foam Eyes Closed Test of Standing Balance Associated With Reduced Semicircular Canal Function in Healthy Older Adults. Ear Hear 40:340–344. https://doi.org/10.1097/AUD.0000000000000619

7. Apolone G, Mosconi P (1998) The Italian SF-36 Health Survey: translation, validation and norming. J Clin Epidemiol 51:1025–1036. https://doi.org/10.1016/s0895-4356(98)00094-8

8. Bargeri S, Castellini G, Vitale JA et al (2024) Effectiveness of Telemedicine for Musculoskeletal Disorders: Umbrella Review. J Med Internet Res 26:e50090. https://doi.org/10.2196/50090

9. Benedetti MG, Coli M, Campanacci L, Manfrini M (2019) Postural control skills, proprioception, and risk of fall in long-term survivor patients treated with knee rotationplasty. Int J Rehabil Res 42:68–73. https://doi.org/10.1097/MRR.0000000000000331

10. Bennell K, Nelligan RK, Schwartz S et al (2020) Behavior Change Text Messages for Home Exercise Adherence in Knee Osteoarthritis: Randomized Trial. J Med Internet Res 22:e21749. https://doi.org/10.2196/21749

11. Boccolari P, Lando M, Zingarello L et al (2024) Treatment of wrist stiffness through posture orthosis and active exercise: A case report. Trauma Case Reports. https://doi.org/10.1016/j.tcr.2024.101068

12. Bunevicius A (2017) Reliability and validity of the SF-36 Health Survey Questionnaire in patients with brain tumors: a cross-sectional study. Health Qual Life Outcomes 15:92. https://doi.org/10.1186/s12955-017-0665-1

13. Catellani I, Arcuri P, Vita F et al (2024) An overview of rehabilitation approaches for focal hand dystonia in musicians: A scoping review. Clin Rehabil:2692155231225705. https://doi.org/10.1177/02692155231225705

14. Chomiak T, Pereira FV, Hu B (2014) The Single-Leg-Stance Test in Parkinson's Disease. J Clin Med Res 7:182–185. https://doi.org/10.14740/jocmr.v7i3.1878

15. Das G, Sharma K, Das S et al (2023) Platelet-rich Plasma in Patients with Symptomatic Osteoarthritis Knee: An Evidence- and Consensus-based 2023 International Society for Musculoskeletal Ultrasound in Pain Medicine Guidelines. Journal on Recent Advances in Pain. https://doi.org/10.4103/jmupm.jmupm_3_23

16. De Carli P, Patrizi M, Pepe L et al (2010) Postural control and risk of falling in bipodalic and monopodalic stabilometric tests of healthy subjects before, after visuo-proprioceptive vestibulo-postural rehabilitation and at 3 months thereafter: role of the proprioceptive system. Acta Otorhinolaryngol Ital 30:182–189

17. Dean JC (2013) Proprioceptive Feedback and Preferred Patterns of Human Movement. Exerc Sport Sci Rev 41:36–43. https://doi.org/10.1097/JES.0b013e3182724bb0

18. Deora H (2019) Neuro-rehabilitation-a multidisciplinary approach. Neurology India 67:343–345. https://doi.org/10.4103/0028-3886.253611

19. Donati D, Aroni S, Tedeschi R et al (2024) Exploring the impact of rehabilitation on post-surgical recovery in elbow fracture patients: a cohort study. Musculoskeletal Surgery. https://doi.org/10.1007/s12306-024-00848-8

20. Donati D, Tedeschi R, Spinnato P et al (2024) Ultrasoundhydrodistention in adhesivecapsulitis: Hospital versus home-based rehabilitation. Egyptian Rheumatologist 46:166–170. https://doi.org/10.1016/j.ejr.2024.06.003

21. Fabbri I, Betti F, Tedeschi R (2023) Gait quality after robot therapy compared with physiotherapy in the patient with incomplete spinal cord injured: A systematic review. eNeurologicalSci. https://doi.org/10.1016/j.ensci.2023.100467

22. Farias J (2012) Entrenamiento y neuroplasticidad.: Rehabilitación de distonias, un nuevo enfoque. Galene editions

23. Fregni F, El-Hagrassy MM, Pacheco-Barrios K et al (2021) Evidence-Based Guidelines and Secondary Meta-Analysis for the Use of Transcranial Direct Current Stimulation in Neurological and Psychiatric Disorders. Int J Neuropsychopharmacol 24:256–313. https://doi.org/10.1093/ijnp/pyaa051

24. Fritz JM, Kongsted A (2023) A new paradigm for musculoskeletal pain care: moving beyond structural impairments. Conclusion of a chiropractic and manual therapies thematic series. Chiropr Man Therap 31:15. https://doi.org/10.1186/s12998-023-00484-2

25. Ghislieri M, Labanca L, Mosca M et al (2023) Balance and Muscle Synergies During a Single-Limb Stance Task in Individuals With Chronic Ankle Instability. IEEE Trans Neural Syst Rehabil Eng 31:4367–4375. https://doi.org/10.1109/TNSRE.2023.3328933

26. Hillier S, Immink M, Thewlis D (2015) Assessing Proprioception: A Systematic Review of Possibilities. Neurorehabil Neural Repair 29:933–949. https://doi.org/10.1177/1545968315573055

27. Hong R, Li B, Bao Y et al Therapeutic robots for post-stroke rehabilitation. Med Rev (2021) 4:55–67. https://doi.org/10.1515/mr-2023-0054

28. Ivanenko Y, Gurfinkel VS (2018) Human Postural Control. Front Neurosci 12:171. https://doi.org/10.3389/fnins.2018.00171

29. Kabbaligere R, Lee B-C, Layne CS (2017) Balancing sensory inputs: Sensory reweighting of ankle proprioception and vision during a bipedal posture task. Gait Posture 52:244–250. https://doi.org/10.1016/j.gaitpost.2016.12.009

30. Kolasinski SL, Neogi T, Hochberg MC et al (2020) 2019 American College of Rheumatology/Arthritis Foundation Guideline for the Management of Osteoarthritis of the Hand, Hip, and Knee. Arthritis Rheumatol 72:220–233. https://doi.org/10.1002/art.41142

31. Kurz E, Faude O, Roth R et al (2018) Ankle muscle activity modulation during single-leg stance differs between children, young adults and seniors. Eur J Appl Physiol 118:239–247. https://doi.org/10.1007/s00421-017-3764-0

32. Labanca L, Barone G, Zaffagnini S et al (2021) Postural Stability and Proprioception Abnormalities in Patients with Knee Osteoarthritis. Applied Sciences 11:1469. https://doi.org/10.3390/app11041469

33. Labanca L, Berti L, Tedeschi R et al (2024) Effects of MLS Laser on pain, function, and disability in chronic non-specific low back pain: A double-blind placebo randomized-controlled trial. J Back Musculoskelet Rehabil. https://doi.org/10.3233/BMR-230383

34. Labanca L, Ghislieri M, Knaflitz M et al (2021) Muscle synergies for the control of single-limb stance with and without visual information in young individuals. BMC Sports Science, Medicine and Rehabilitation 13:163. https://doi.org/10.1186/s13102-021-00392-z

35. Labanca L, Tedeschi R, Mosca M, Benedetti MG (2024) Individuals With Chronic Ankle Instability Show Abnormalities in Maximal and Submaximal Isometric Strength of the Knee Extensor and Flexor Muscles. Am J Sports Med:3635465241232090. https://doi.org/10.1177/03635465241232090

36. Latif-Zade T, Tucci B, Verbovetskaya D et al (2021) Systematic Review Shows Tele-Rehabilitation Might Achieve Comparable Results to Office-Based Rehabilitation for Decreasing Pain in Patients with Knee Osteoarthritis. Medicina (Kaunas) 57:764. https://doi.org/10.3390/medicina57080764

37. Lefaucheur J-P, Antal A, Ayache SS et al (2017) Evidence-based guidelines on the therapeutic use of transcranial direct current stimulation (tDCS). Clin Neurophysiol 128:56–92. https://doi.org/10.1016/j.clinph.2016.10.087

38. Lord SR, Menz HB (2000) Visual contributions to postural stability in older adults. Gerontology 46:306–310. https://doi.org/10.1159/000022182

39. Ma C, Oa G, Sp O et al (2017) Real-time telerehabilitation for the treatment of musculoskeletal conditions is effective and comparable to standard practice: a systematic review and meta-analysis. Clinical rehabilitation. https://doi.org/10.1177/0269215516645148

40. Negahban H, Ahmadi P, Salehi R et al (2013) Attentional demands of postural control during single leg stance in patients with anterior cruciate ligament reconstruction. Neuroscience Letters 556:118–123. https://doi.org/10.1016/j.neulet.2013.10.022

41. Proske U, Gandevia SC (2018) Kinesthetic Senses. Compr Physiol 8:1157–1183. https://doi.org/10.1002/cphy.c170036

42. Puderbaugh M, Emmady PD (2024) Neuroplasticity. StatPearls

43. Riva D, Fani M, Benedetti MG et al (2019) Effects of High-Frequency Proprioceptive Training on Single Stance Stability in Older Adults: Implications for Fall Prevention. Biomed Res Int 2019:2382747. https://doi.org/10.1155/2019/2382747

44. Röijezon U, Clark NC, Treleaven J (2015) Proprioception in musculoskeletal rehabilitation. Part 1: Basic science and principles of assessment and clinical interventions. Man Ther 20:368–377. https://doi.org/10.1016/j.math.2015.01.008

45. Schedler S, Kiss R, Muehlbauer T (2019) Age and sex differences in human balance performance from 6-18 years of age: A systematic review and meta-analysis. PLoS One 14:e0214434. https://doi.org/10.1371/journal.pone.0214434

46. Schorderet C, Hilfiker R, Allet L (2021) The role of the dominant leg while assessing balance performance. A systematic review and meta-analysis. Gait Posture 84:66–78. https://doi.org/10.1016/j.gaitpost.2020.11.008

47. Seigle B, Ramdani S, Bernard PL (2009) Dynamical structure of center of pressure fluctuations in elderly people. Gait Posture 30:223–226. https://doi.org/10.1016/j.gaitpost.2009.05.005

48. Sgarbossa A, Giotto P, Alghisi E, Tedeschi R (2024) A case series analysis: rehabilitation pathway for patients with postsurgical Stener lesions treated with a functional thermoplastic splint and early physiotherapy. Manuelle Medizin. https://doi.org/10.1007/s00337-024-01087-5

49. Singh A, Das S, Mishra RK, Agrawal A (2023) Artificial intelligence and machine learning in healthcare: Scope and opportunities to use ChatGPT. J Neurosci Rural Pract 14:391–392. https://doi.org/10.25259/JNRP_391_2023

50. Tavares JT, Biasotto-Gonzalez DA, Boa Sorte Silva NC et al (2019) Age-Related Changes in Postural Control in Physically Inactive Older Women. J Geriatr Phys Ther 42:E81–E86. https://doi.org/10.1519/JPT.0000000000000169

51. Tedeschi R (2023) Assessment of Postural Control and Proprioception Using the Delos Postural Proprioceptive System. Reabilitacijos Mokslai: Slauga, Kineziterapija, Ergoterapija 2:93–109. https://doi.org/10.33607/rmske.v2i29.1428

52. Tedeschi R (2023) Automated mechanical peripheral stimulation for gait rehabilitation in Parkinson’s disease: A comprehensive review. Clin Park Relat Disord 9:100219. https://doi.org/10.1016/j.prdoa.2023.100219

53. Tedeschi R (2023) Kinematic and plantar pressure analysis in Strumpell-Lorrain disease: A case report. Brain Disorders. https://doi.org/10.1016/j.dscb.2023.100097

54. Tedeschi R (2023) Can beneficial frequencies in physiotherapy help treatment? Scoping Review. Rwanda Medical Journal 80:88–94. https://doi.org/10.4314/rmj.v80i2.8

55. Tedeschi R (2023) Case report: Integrating aerobic activity in post-surgical management of plurifragmentary distal clavicle fractures - A holistic approach to pain modulation and recovery. Int J Surg Case Rep 113:109024. https://doi.org/10.1016/j.ijscr.2023.109024

56. Tedeschi R (2023) Unveiling the Potential of Trigger Point Therapy: Exploring its Efficacy in Managing Muscular Spasticity - A Scoping Review. Muscles, Ligaments and Tendons Journal 13:564–573. https://doi.org/10.32098/mltj.04.2023.07

57. Tedeschi R (2023) Assessment of Postural Control and Proprioception Using the Delos Postural Proprioceptive System. Reabilitacijos mokslai: slauga, kineziterapija, ergoterapija 2:96–112. https://doi.org/10.33607/rmske.v2i29.1428

58. Tedeschi R (2024) Adapting RegentK principles for nonsurgical meniscal tear management: an innovative case report. Manuelle Medizin. https://doi.org/10.1007/s00337-024-01062-0

59. Tedeschi R (2024) An overview and critical analysis of the Graston technique for foot-related conditions: a scoping review. Manuelle Medizin 62:22–28. https://doi.org/10.1007/s00337-023-01018-w

60. Tedeschi R (2024) Mindful Breathing as an Adjunctive Approach to Chronic Low Back Pain Management: A Scoping Review. Pain Manag Nurs:S1524-9042(24)00152–8. https://doi.org/10.1016/j.pmn.2024.04.011

61. Tedeschi R (2024) Unlocking the power of motor imagery: a comprehensive review on its application in alleviating foot pain. Acta Neurologica Belgica. https://doi.org/10.1007/s13760-024-02492-2

62. Tedeschi R (2024) "Transcranial direct current stimulation for chronic foot pain: A comprehensive review". eNeurologicalSci. https://doi.org/10.1016/j.ensci.2024.100498

63. Tedeschi R, Amoruso V, Boetto V et al (2024) COVID-19-Associated Cerebellitis: A Case Report and Rehabilitation Outcome. Cerebellum. https://doi.org/10.1007/s12311-024-01721-x

64. Tedeschi R, Berti L, Platano D (2024) "Transcranial Direct Current Stimulation (tDCS) in managing pain and recovery: A clinical case of radial capitellum fracture". International Journal of Surgery Case Reports. https://doi.org/10.1016/j.ijscr.2023.109120

65. Tedeschi R, Pillastrini P, Pierangeli G et al (2024) Is physiotherapy in migraines known to sufferers? A cross-sectional study. Neurol Sci 45:1669–1674. https://doi.org/10.1007/s10072-023-07195-9

66. Tousignant M, Moffet H, Nadeau S et al (2015) Is telerehabilitation an adequate economic alternative to conventional rehabilitation? Physiotherapy 101:e1528. https://doi.org/10.1016/j.physio.2015.03.1516

67. Valdes K, LaStayo P (2013) The value of provocative tests for the wrist and elbow: a literature review. J Hand Ther 26:32–42; quiz 43. https://doi.org/10.1016/j.jht.2012.08.005

68. Vita F, Davoli F, Stefano G et al (2024) Surgical resolution of chronic thoracic pain stemming from a rare osteo-muscular conflict: A case report. International Journal of Surgery Case Reports. https://doi.org/10.1016/j.ijscr.2024.109589

69. Vita F, Origlio F, Pederiva D et al (2024) Efficacy of Ultrasound-Guided Hydrodissection for Treating De Quervain's Tenosynovitis. JPRAS Open 41:148–158. https://doi.org/10.1016/j.jpra.2024.06.002

70. Vita F, Pederiva D, Tedeschi R et al (2024) Adhesive capsulitis: the importance of early diagnosis and treatment. J Ultrasound. https://doi.org/10.1007/s40477-024-00891-y

71. Wingert JR, Welder C, Foo P (2014) Age-related hip proprioception declines: effects on postural sway and dynamic balance. Arch Phys Med Rehabil 95:253–261. https://doi.org/10.1016/j.apmr.2013.08.012

ABBREVIATIONS

- **ADL** - Activities of Daily Living
- **AMPS** - Automated Mechanical Peripheral Stimulation
- **AO** - Action Observation
- **AROM** - Active Range of Motion
- **BDNF** - Brain-Derived Neurotrophic Factor
- **BMI** - Body Mass Index
- **CAI** - Chronic Ankle Instability
- **CBT** - Cognitive-Behavioral Therapy
- **CT** - Computed Tomography
- **DPPS** - Delos Postural Proprioceptive System
- **EMG** - Electromyography
- **FFI** - Foot Function Index
- **FOG** - Freezing of Gait
- **FRP** - Flexion-Relaxation Phenomenon
- **FRR** - Flexion Relaxation Ratio
- **HPT** - High-Frequency Proprioceptive Training
- **IASP** - International Association for the Study of Pain
- **LD** - Longissimus Dorsi
- **MF** - Multifidus
- **MIDAS** - Migraine Disability Assessment Score
- **MLS** - Multiwave Locked System
- **MRI** - Magnetic Resonance Imaging

- **ODI** - Oswestry Disability Index
- **PCC** - Population Concept and Context
- **PRISMA** - Preferred Reporting Items for Systematic Reviews and Meta-Analyses
- **PRISMA-ScR** - Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews
- **RAGT** - Robot-Assisted Gait Training
- **ROM** - Range of Motion
- **SCS** - Spinal Cord Stimulation
- **SF-36** - Short Form Health Survey
- **TCA** - Tissue Composition Analysis
- **TENS** - Transcutaneous Electrical Nerve Stimulation
- **tDCS** - Transcranial Direct Current Stimulation
- **TMS** - Transcranial Magnetic Stimulation
- **TUG** - Timed Up and Go
- **VAS** - Visual Analogue Scale
- **WOMAC** - Western Ontario and McMaster Universities Osteoarthritis Index

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