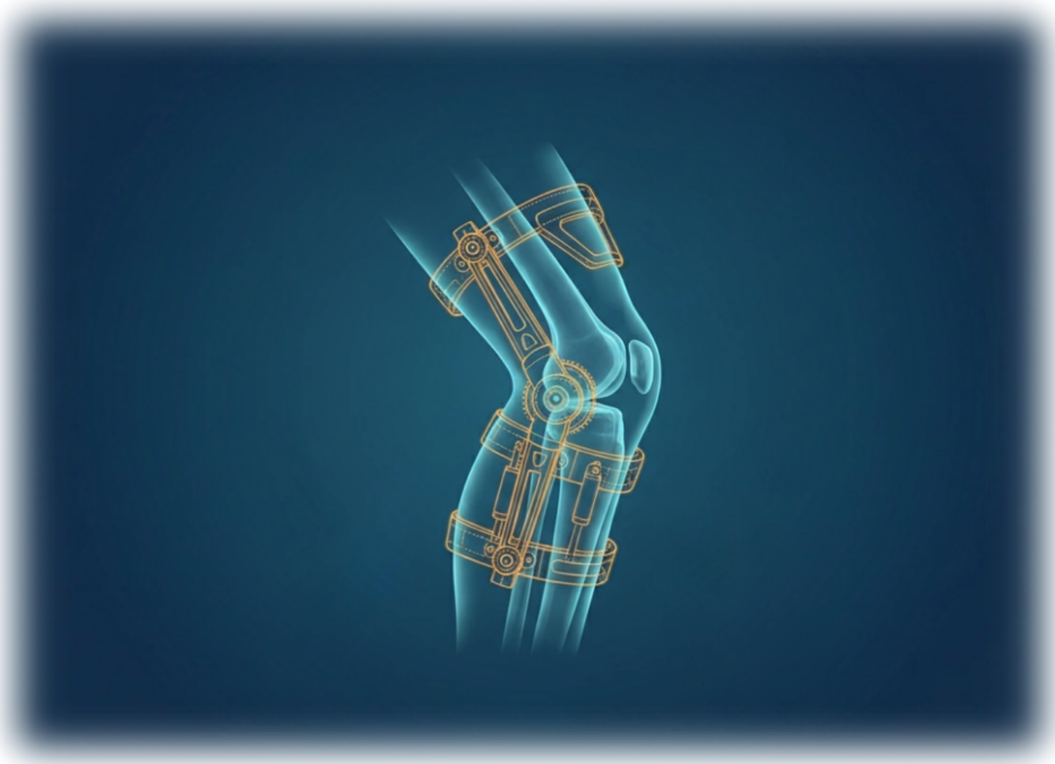

Design Features and Clinical Considerations of Orthopedic Knee Rehabilitation Exoskeletons

A Systematic Literature Review and Analysis

Master’s thesis in Systems, control and mechatronics

ZIKUN WEI

DEPARTMENT OF Electrical Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2026
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Master's thesis 2026

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Master's Thesis 2026
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Cover: AI-generated sensorized and motorized exoskeleton for knee orthopedic rehabilitation.

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Abstract

As rehabilitation robotics expands from neurorehabilitation to orthopedics, the biomechanical suitability of existing devices remains unclear. This paper systematically reviews 57 wearable knee exoskeletons (2015–2025) to evaluate their clinical compatibility. It highlights the critical design divergence between the “repurposing strategy” of neuro-derived systems and the “specialized design philosophy” of orthopedic-specific solutions.

Using a novel five-dimensional evaluation framework, this study reveals a significant design "mismatch." While systems relying on a generalist, neuro-adapted approach offer advanced control, their architectures often lack the kinematic compatibility and structural support required for vulnerable orthopedic joints. In contrast, "specialized" designs have seen explosive growth, prioritizing unilateral modularity and anatomical protection. However, a "valley of death" persists in translational research: over 60% of orthopedic-specific devices remain at Technology Readiness Level (TRL) 4, failing to reach clinical patient trials.

The study concluded that most current cases of transplanting neurological rehabilitation equipment for orthopedic use cannot address the specific needs and limitations of orthopedics. Future development should adopt an "orthopedic-first" philosophy—prioritizing multi-DOF stability, modular adaptability, and pain-aware control. These shifts are imperative to reduce adverse events and optimize treatment outcomes in orthopedic rehabilitation.

In addition, another systematic review should be conducted on mature and cutting-edge neurosurgical exoskeletons that do not claim to include orthopedic rehabilitation functions to analyze their potential to meet orthopedic rehabilitation needs.

Keywords: Orthopedic Rehabilitation, Knee Exoskeleton, Systematic Review, Mechanical Design, Clinical Compatibility.

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Special thanks to the Department of Electrical Engineering and the Department of Systems and Control at Chalmers University of Technology for the academic environment and resources provided for this research.

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Finally, I would like to thank my family for their unconditional love and support throughout my studies. This journey would not have been possible without their encouragement.

Zikun Wei, Gothenburg, January 2026

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

ACLR	Anterior Cruciate Ligament Reconstruction
BAM	Body Adduction Moment
CMPM	Coupled Movable Pulley Mechanism
DOF	Degrees of Freedom
EEG	Electroencephalography
EMG	Electromyography
FSM	Finite State Machine
GRF	Ground Reaction Force
ICR	Instantaneous Center of Rotation
IMU	Inertial Measurement Unit
KAM	Knee Adduction Moment
KOA	Knee Osteoarthritis
KOOS	Knee Injury and Osteoarthritis Outcome Score
PCL	Posterior Cruciate Ligament
PD	Proportional-Derivative
PID	Proportional-Integral-Derivative
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RCT	Randomized Controlled Trial
RQ	Research Questions
SCI	Spinal Cord Injury
SEA	Series Elastic Actuator
TKA	Total Knee Arthroplasty
TRL	Technology Readiness Level
VAS	Visual Analog Scale
WOMAC	Western Ontario and McMaster Universities Osteoarthritis Index

Nomenclature

This article is a literature review and uses Nomenclature very rarely.

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1

Introduction

1.1 Background and Motivation

Knee osteoarthritis (KOA) is one of the most common and serious challenges in modern medicine. The knee joint is a vital weight-bearing joint, and dysfunction can severely impact daily life. Knee osteoarthritis, ligament injuries (such as anterior cruciate ligament rupture), and periarticular fractures place a heavy burden on the health of people worldwide, potentially reducing their ability to work and preventing them from participating in normal outdoor activities and social interactions. With an aging population, the incidence of these diseases is rising; notably, it is estimated that by 2025, the number of people suffering from knee osteoarthritis globally will exceed 250 million.[5]

In today's clinical setting, physical therapy is the foundation of rehabilitation. However, traditional manual therapy faces numerous limitations: it is time-consuming, labor-intensive, and highly repetitive, placing a heavy burden on the therapist's physical condition and easily leading to fatigue and illness. Furthermore, it is difficult to scale. Labor shortages, rising wages in the service industry, and a growing patient population make it increasingly difficult to provide the precise, repetitive training needed for effective motor function retraining.[6]

Wearable exoskeletons are emerging as a promising solution. While they have already improved many established solutions and tools for neurological conditions, this study found that literature on knee exoskeletons specifically designed for orthopedic rehabilitation is growing at an extremely rapid pace. Our literature analysis (n=57) shows a rapid increase in the number of papers on orthopedic-specific designs, surpassing traditional neurorehabilitation research in this field, especially after 2019. This surge indicates that the engineering community recognizes orthopedic rehabilitation as a pressing and in-demand area, with an increasing number of research institutions and universities joining the effort.[7, 8]

1.2 Problem Statement

Despite the increasing number of devices under development, their quality still lags significantly behind those widely used in clinical practice. Currently, a considerable portion of the devices used in orthopedic surgery are actually "neuro-orthopedic designs." These systems were originally developed for neurorehabilitation and later reused in orthopedic surgery.

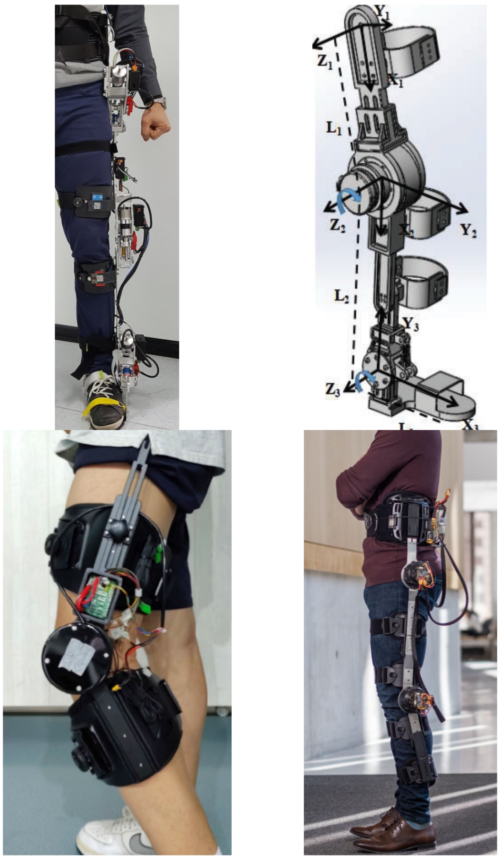

Figure 1.1: Examples of lower-limb exoskeletons with different joint coverage. Top-left: device covering the hip, knee, and ankle joints[1]; top-right: knee–ankle device[2]; bottom-right: hip–knee device[3]; bottom-left: single-joint knee exoskeleton[4].

This "transplantation" strategy introduces a fundamental mismatch between device capabilities and clinical needs:

- **Kinematic Incompatibility:** Neurological knee rehabilitation devices focus more on strength assistance, primarily helping the knee joint generate force in the sagittal plane, while paying less attention to other actual degrees of freedom such as the frontal plane and rotation. Without bilateral support, these devices may generate shear forces, potentially damaging the orthopedic joint and even requiring postoperative reconstructive surgery.
- **Clinical Impracticality:** Many Neuro-derived systems are often quite heavy, typically covering both legs and their joints to meet the needs of neurological rehabilitation. Furthermore, they often include multiple body joints to achieve more comprehensive and ideal neural reconstruction and sensory enhancement. However, such a design may be redundant for orthopedic patients, who, compared to neurological patients, usually only have one affected side or only one knee joint to focus on.

- **Lack of Clinical Readiness:** Although engineering prototypes and model simulations are emerging in large numbers, there is evidence that few systems can surpass laboratory feasibility tests to demonstrate their effectiveness in real clinical settings.

Therefore, the central problem addressed by this thesis is the lack of a systematic framework to distinguish and evaluate exoskeletons that truly meet the biomechanical demands of orthopedic rehabilitation.

1.3 Terminology and Scope

To ensure clarity, this thesis adopts the following definitions:

- **Orthopedic Knee Exoskeleton:** A wearable mechatronic device aligned with the knee joint, providing active mechanical power or controllable passive resistance through motors, pneumatic devices, etc., to assist or guide movement, complete therapeutic exercises, and achieve therapeutic goals.
- **Passive Brace with Sensing:** This study also includes devices that rely on static mechanical elements (springs, etc.) while integrating onboard sensors for kinematic monitoring, as these represent a transition to "intelligent" rehabilitation.
- **Exclusion:** This study does not include purely static braces (standard treatment protocols) that lack both sensing and actuation functions.

This dissertation focuses on wearable systems centered on the knee joint; Figure 1 illustrates examples of different lower limb joint coverage.

1.4 Research Objectives and Questions

The primary objective is to conduct an engineering and rehabilitation needs correlation analysis of state-of-the-art orthopedic knee exoskeletons. This study aims to answer the following research questions (RQs):

- **RQ1:** Can a statistically significant design paradigm be found in orthopedic rehabilitation that differentiates it from the development trajectory of general-purpose neurorehabilitation robots?
- **RQ2:** To what extent do current designs, such as mechanical degrees of freedom (DOF) and support structures, meet the biomechanical constraints specific to orthopedics, such as frontal plane stability and intra-articular rotation center (ICR) alignment?
- **RQ3:** What are the limitations of the 'repurposing strategy' when applying neuro-rehabilitation architectures to orthopedic pathology?
- **RQ4:** What are the main technical and clinical barriers preventing orthopedic-specific designs from transitioning from laboratory prototypes (TRL 4) to actual clinical validation in humans and even clinical patients (TRL 5+)?

1.5 Research Hypotheses

To guide the validation process, this paper proposes three core hypotheses:

- **Hypothesis 1 (The Trend Hypothesis):**
  Orthopedic-specific designs are experiencing rapid growth, with over half of the literature published in the past decade occurring within the last three to five years.
- **Hypothesis 2 (The Mismatch Hypothesis):**
  Neuroscience-derived designs exhibit a measurable applicability gap compared to orthopedic-specific designs, a characteristic clearly visible in the multidimensional radar chart assessment of orthopedic clinical applicability.
- **Hypothesis 3 (The Maturity Hypothesis):**
  The field remains immature in clinical application, with over half of the systems stalled in the laboratory validation phase (Technology Maturity Level 4), and less than one-tenth of the systems having completed large-scale patient trials with extended follow-up (Technology Maturity Level 6 and above).

2

Methods

This study employs a systematic literature review, supplemented by a framework that moves from descriptive analysis to quantitative assessment. To validate the hypotheses presented in the introduction, we established a rigorous and detailed classification system for equipment literature, borrowing the European Commission's Technology Readiness Level (TRL), and defined a clear and intuitive set of rules to generate a multi-dimensional radar chart of orthopedic rehabilitation suitability.

2.1 Systematic Literature Search

This study followed the PRISMA (Preferred Reporting Item for Systematic Reviews and Meta-analyses) guidelines, conducting a comprehensive and systematic search of relevant engineering studies published between 2015 and September 2025.
Note on Meta-Analysis: This review strictly adhered to the PRISMA guidelines for terminology construction, study identification, screening, and inclusion, but did not conduct a quantitative meta-analysis. This was due to the high heterogeneity of the collected data and trials (manifested in variations in clinical protocols, mechanical designs, and a lack of standardized outcome measures), and the fact that most of the literature had not yet conducted large-scale clinical rehabilitation studies. Therefore, this study combined descriptive analysis with simple and reliable statistical analysis.

2.1.1 Data Sources and Search Strategy

Four electronic databases were queried: **IEEE Xplore**, **PubMed**, **Scopus**, and **Web of Science**. The search strategy utilized a structured syntax combining three core conceptual blocks:

1. **Device Terms:** "exoskeleton", "wearable robot", "powered orthosis", "robotic brace"...
2. **Target Anatomy:** "knee", "lower limb", "knee joint"...
3. **Clinical Context:** "orthopedics", "rehabilitation", "osteoarthritis", "post-operative", "ligament injury"...

Database-specific search strategies are summarized in Appendix A.

2.1.2 Screening and Selection

The initial search yielded 5,341 records. After deduplication and a two-stage screening process (Title/Abstract and Full-Text), 57 studies were selected for final analysis.

Table 2.1: Database-specific search strategies

Database	Search field and core string[a]
IEEE Xplore	Full-text search: $(D_1) \wedge (D_2)$; English; 2015–3 Sept. 2025; magazines/news excluded.
PubMed	MeSH + Title/Abstract: device block AND orthopedics block AND design/evaluation block; humans; English; 2015–3 Sept. 2025.
Scopus	TITLE-ABS-KEY: $(D_1)\wedge(D_2)\wedge(D_3)$; English; 2015–3 Sept. 2025; articles, conference papers, reviews.
Web of Science	TS: $(D_1) \wedge (D_2) \wedge (D_3)$; English; 2015–3 Sept. 2025; articles, reviews, proceedings papers.

[a] Full keyword lists and complete search strings for D_1–D_3 are provided in Appendix A.

Inclusion Criteria:

- Devices must be wearable and align with the human knee joint.
- Devices must possess active actuation or integrated sensing capabilities (smart passive: devices with passive actuation but with sensors will be included).
- The study must clearly indicate that the designed device has a certain orthopedic rehabilitation function or specific indications (e.g., knee osteoarthritis, anterior cruciate ligament injury, fracture).

Exclusion Criteria:

- **Intra-operative Surgical Robots:** Robotic systems designed to assist in surgery (e.g., navigation and implant placement in total knee arthroplasty) were strictly excluded because the focus of this study was postoperative and other orthopedic rehabilitation.
- **Stationary Systems:** End-effectors or other devices that do not have a matching movable joint to the human knee are not included because such devices provide virtually no assistance or restraint to the knee joint and are extremely dangerous for severely ill orthopedic patients.
- **Purely Passive Braces:** Standard nursing braces that do not include sensors and actuators were also excluded.
- **Neurological-Only Devices:** Device designed solely for neurological disorders (e.g., spinal cord injury, stroke) were excluded as they do not claim orthopedic utility and thus fall outside the scope of this comparative analysis.

The study screening flowchart conforming to the official PRISMA guidelines is shown in Figure 2.1.

2.2 Classification Framework

From a design philosophy perspective, this paper strictly categorizes devices into three types based on the descriptions provided by the authors of the collected literature. Devices without specific applications or applicable departments are excluded from core literature.

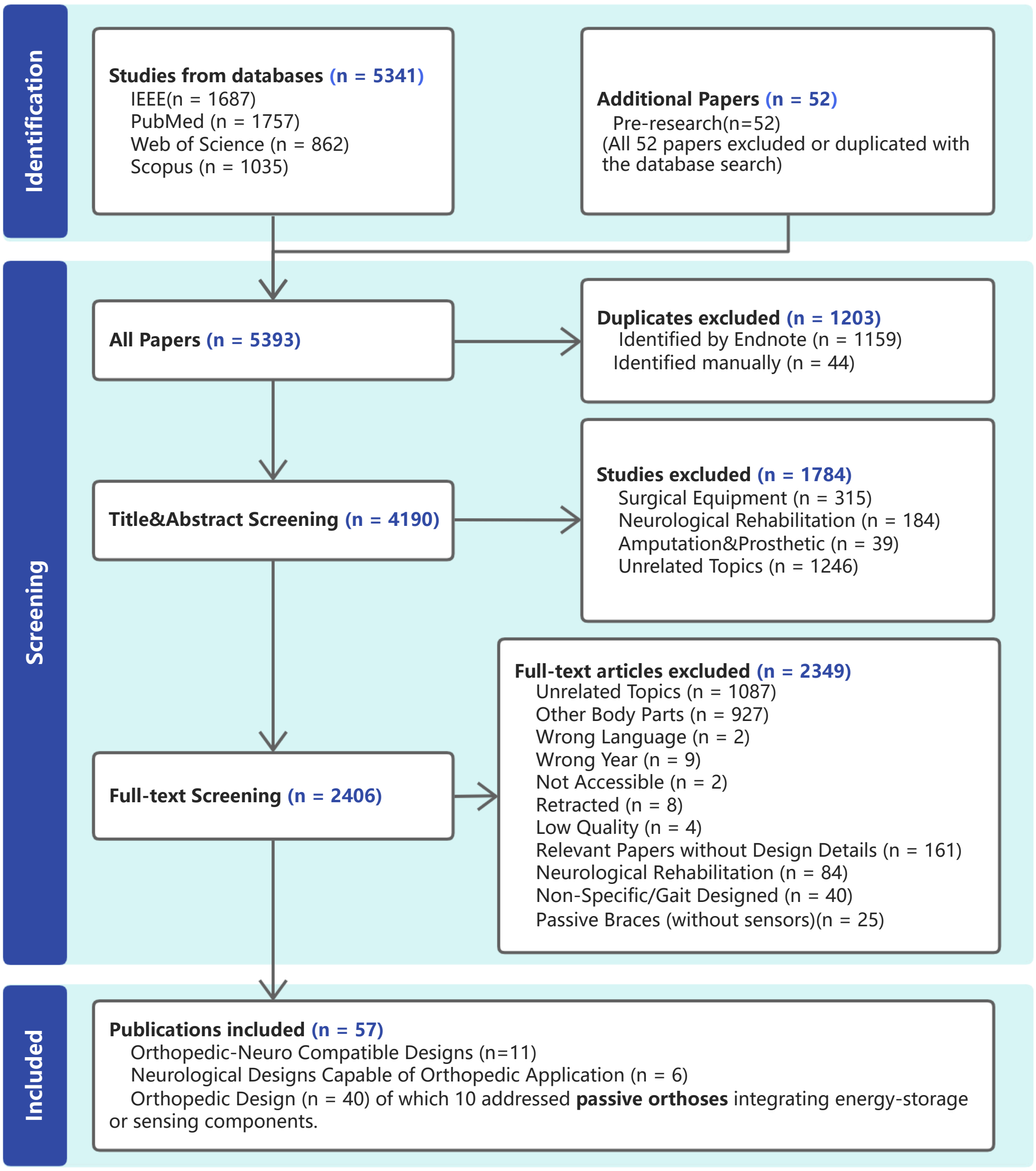

Figure 2.1: PRISMA flow diagram of the study selection process.

- **Orthopedic-Specific Designs:** Authors explicitly state that the developed device is designed for the treatment of a specific orthopedic disease or for orthopedic rehabilitation. Researchers not only possess engineering knowledge and skills but often have some understanding of orthopedic rehabilitation mechanisms and human anatomy, or have conducted research on them. Their parameters and mechanical characteristics are highly targeted towards orthopedic rehabilitation. Common advertised advantages include joint decompression, range of motion protection, and unilateral modular adjustable configuration.
- **Neuro-Derived Orthopedic Designs:** Authors state that their orthopedic

rehabilitation function development... is based on existing neurorehabilitation platforms. These studies represent the 'repurposing strategy' evaluated in this thesis.
- **Orthopedic-Neuro Compatible Designs:** Hybrid systems where authors claim that the designed device is inherently suitable for both orthopedic and neurological patients.

2.3 Assessment Framework

To quantitatively validate the hypotheses of "mismatch" (Hypothesis 2) and "maturity" (Hypothesis 3), this study adopted existing assessment frameworks and defined another specific assessment tool.

2.3.1 Technology Readiness Level (TRL) Scale

Given that this thesis was conducted within a European research context, the European Commission's (Horizon 2020) Technology Maturity Level Scale was used. This scale is specifically designed to assess the maturity of a technology toward commercialization and social application.

The following definitions apply to the field of rehabilitation technology:

- **TRL 1–3 (Lab Concept):**
  The basic principles have been observed; the technology concept has been formed; proof-of-concept experiments (benchmark testing) have been conducted in a laboratory setting.
- **TRL 4 (Lab Validation):**
  The technology has been validated in a laboratory setting. In this study, this corresponds to functional prototype testing on healthy human subjects.
- **TRL 5 (Relevant Environment):**
  The technology has been validated in a relevant environment. This corresponds to pilot testing on healthy subjects in simulated pathological conditions, or preliminary safety testing in a clinical setting.
- **TRL 6–7 (System Demonstration):**
  The technology has been demonstrated in a relevant or operational environment. This means that pilot clinical trials have been conducted on actual patients (small sample size) to demonstrate preliminary efficacy.
- **TRL 8–9 (Market Ready):**
  System complete and qualified. This corresponds to large-scale clinical validation (RCTs), regulatory approval (CE/FDA), and commercial availability.

For detailed European Commission TRL criteria, please see Appendix D.

2.3.2 Radar Chart Mapping Logic

To quantify and visualize the structural and functional differences between orthopedic-specific designs and other design systems, this paper designs a multi-dimensional radar chart using an intuitive and simple classification method. The radar chart rules allow for a five-dimensional evaluation of the collected core literature, using a scale of 1-5. Higher scores indicate a greater likelihood of meeting clinical needs in orthopedic rehabilitation. Please note that the final radar chart displays the average scores for different types of equipment. Applying this rule to a single piece of literature may result in extremely high scores in four dimensions but only a score of 1 in the fifth dimension, rendering it unsuitable for practical clinical application.

- **Clinical Indications:**
  5 = Orthopedic core + pathology specific (e.g., targeted design for ACL, TKA, or KOA, with functions such as medial unloading, extension lag correction, or callus stimulation);
  4 = Explicitly mentions the orthopedic disease and has clear rehabilitation goals;
  3 = Mentions the disease or high-end mechanical details (e.g., ICR alignment), but does not target a specific pathology;
  2 = Refers broadly to "postoperative" or combined training, not targeting a specific surgery;
  1 = Terminology is too broad (e.g., "trauma" or "lower limb dysfunction"), lacking orthopedic-specific clinical protocols.
- **Knee Joint Stability and Alignment:**
  5 = Advanced stability using multi-center instantaneous rotation center (ICR) trajectory, active alignment compensation, or a hybrid soft-hard multi-point lever design;
  4 = Passive self-alignment mechanisms (e.g., sliding grooves), reinforced lateral support, or high-tension soft active support;
  3 = Standard single-axis hinge with basic ergonomic alignment adjustment;
  1-2 = Rigid fixation structures that ignore anatomical changes, easily generating harmful shear forces.
- **Sensing and Control Design:**
  Neurological-derived devices, due to their relatively mature development, often attempt to incorporate more advanced sensing and control systems to overcome competitive bottlenecks, thus scoring higher. However, such sensing and control may not be very effective for their claimed orthopedic rehabilitation or may even become harmful redundancy.
  5 = Multimodal/intent recognition (e.g., electromyography, electroencephalography, or neural networks);
  4 = Dynamic closed loop with force/torque sensing or impedance/admittance control;
  3 = Basic feedback using encoders or inertial measurement units (IMUs) for position/angle tracking;
  2 = Basic interaction (e.g., manual buttons or limit switches);
  1 = Only active/passive functions are implemented, without sensor control design for it. (sometimes the sensor is for other data collection use)
- **Deployment Scenario & Compatibility:**
  5 = Patients can easily put on and take off their masks, supporting basic lifestyle and living radius;
  4 = Patients may need to make a significant learning effort to put on and take off their masks, limiting their activity range to home or hospital, allowing only

short-distance movement such as walking around the hospital building or their own garden;
3 = Limited to limited indoor spaces, unable to leave the hospital, clinic, or home, requiring assistance from others for deployment and use;
2 = Limited to use within a fixed room, often requiring external cameras to achieve functionality, requiring specialized assistance and guidance for use;
1 = Similar to fixed fitness equipment, putting on and taking off these devices requires significant time and effort, making them unsuitable for all-day wear and only supporting on-site rehabilitation training.

- **Wearing Burden & Social Acceptance:**
  5 = Easily concealed by everyday clothing or with minimal visual presence (single joint, unilateral, soft and lightweight support, can be worn inside clothing, etc.); weight is relatively light and distributed throughout the legs;
  4 = Lightweight and unobtrusive; although noticeable, there is no significant additional structure to attract attention; weight is noticeable to the wearer but has minimal impact on daily activities;
  3 = Similar to standard traditional braces; noticeable appearance; weight significantly impacts daily activities;
  2 = Heavy equipment with a waist belt module or external backpack, leg pack, or other additional load-bearing platform.
  1 = Requires a large external platform for power, computing, or other functions; cannot operate independently as a wearable component.

3

Results

This section presents a comprehensive technical analysis of the 57 identified systems. By applying the classification and assessment frameworks defined in Section 2, the mechanical, kinematic, and mechatronic characteristics of the devices are evaluated to test the core hypotheses of this thesis. A comprehensive extraction of all included systems and key attributes is provided in Appendix C.

3.1 Overview of Target Systems and Trends

The systematic review yielded a total of 57 distinct wearable devices specifically addressing orthopedic knee rehabilitation. Based on the classification framework, the distribution is as follows:

- **Orthopedic-Specific Designs:** 40 devices (70.2%).
- **Orthopedic-Neuro Compatible Designs:** 11 devices (19.3%).
- **Neuro-Derived Orthopedic Designs:** 6 devices (10.5%).

Validation of the "Surge" Trend (Hypothesis 1):
Analyzing the publication dates by year reveals a clear trend: the number of neurological rehabilitation robots converted to orthopedic rehabilitation applications remains stable, while exoskeletons specifically designed for orthopedic rehabilitation show explosive growth.

As shown in Figure 3.1, **32 of the 57 included studies (56.1%)** were published within the compact timeframe of **2023 to September 2025**. This includes novel designs for post-TKA rehabilitation [9, 10], fracture management [11], and ligament protection [12, 13]. This intense concentration of recent literature [14, 15, 16] statistically supports Hypothesis 1, confirming that orthopedic rehabilitation robotics is evolving into an independent research domain.

The distribution of major clinical indications is summarized in Figure 3.2. Clearly, more literature on orthopedic-specific devices describes and explains one or more specific orthopedic applications, while devices derived from neurological rehabilitation and general-purpose designs are more general or primarily target cross-conditions with less pronounced orthopedic characteristics.

3.2 Mechanical and Kinematic Analysis

The mechanical structure of rehabilitation assistive devices is a key factor determining their clinical applicability. This article focuses on the following configurations:
1. Can the knee orthopedic rehabilitation device be applied only to the knee of

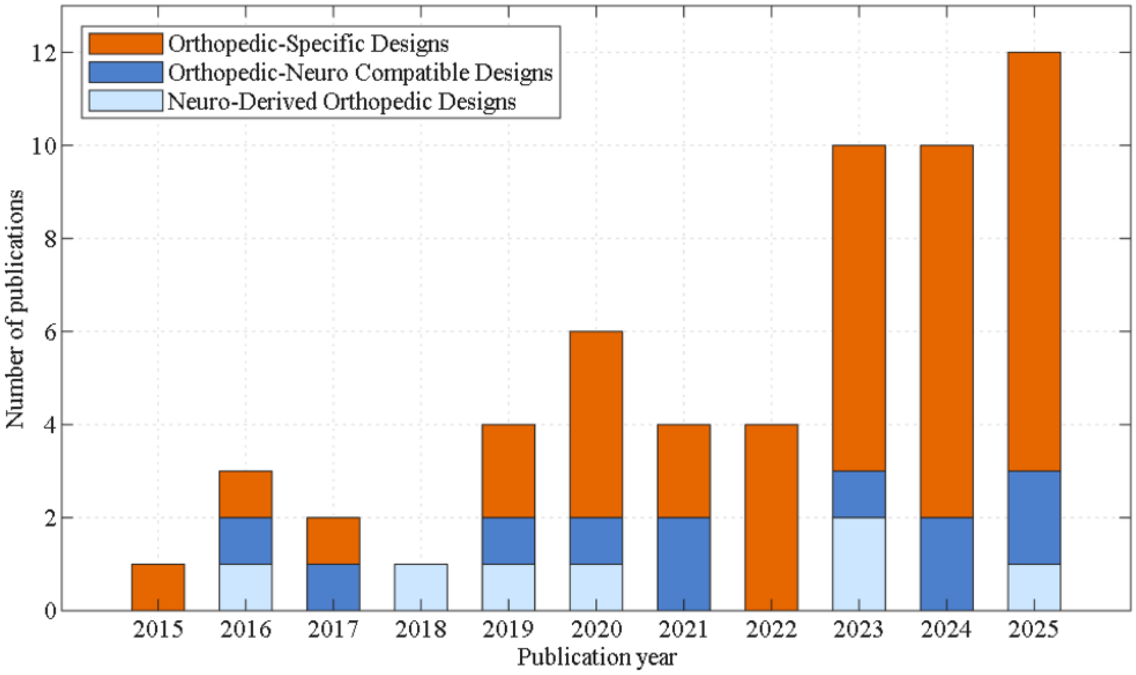

Figure 3.1: Number of publications by year and design type. Shows rapid growth in the past three years.

one leg, or must it be worn on both lower limbs simultaneously? 2. Which of the six natural degrees of freedom of the human knee joint is compatible with the knee joint's mechanical structure? 3. Does the device structure at the knee joint provide stability, and if so, through what structure?

Specifically, orthopedic diseases often involve one leg being severely affected while the other is unaffected or minimally affected, such as sports injuries. Therefore, devices that must be worn on both legs may have negative impacts such as excessive weight and deployment difficulty. Regarding the degrees of freedom of the knee joint, although the human knee joint only has three rotational degrees of freedom as its primary degrees of freedom, three translational degrees of freedom also exist through ligament and some muscle activity. If the rehabilitation device cannot track these activities, it will lead to a mismatch between the device's rotation axis and the knee joint, and in severe cases, it may even injure the patient when generating assistive forces. In addition to the two points mentioned above, knee joint stability plays a crucial role in orthopedic rehabilitation. If the knee joint is subjected to further impact during rehabilitation training or daily life, it can potentially cause problems more severe than the original injury. Currently, a common solution is to use a bilateral rigid support structure to protect the knee joint from potential impacts from all directions. Some devices are also exploring newer technologies to address this issue, such as using pneumatic artificial muscles to wrap around the knee joint, providing rapid, skin-to-skin stabilizing assistance.

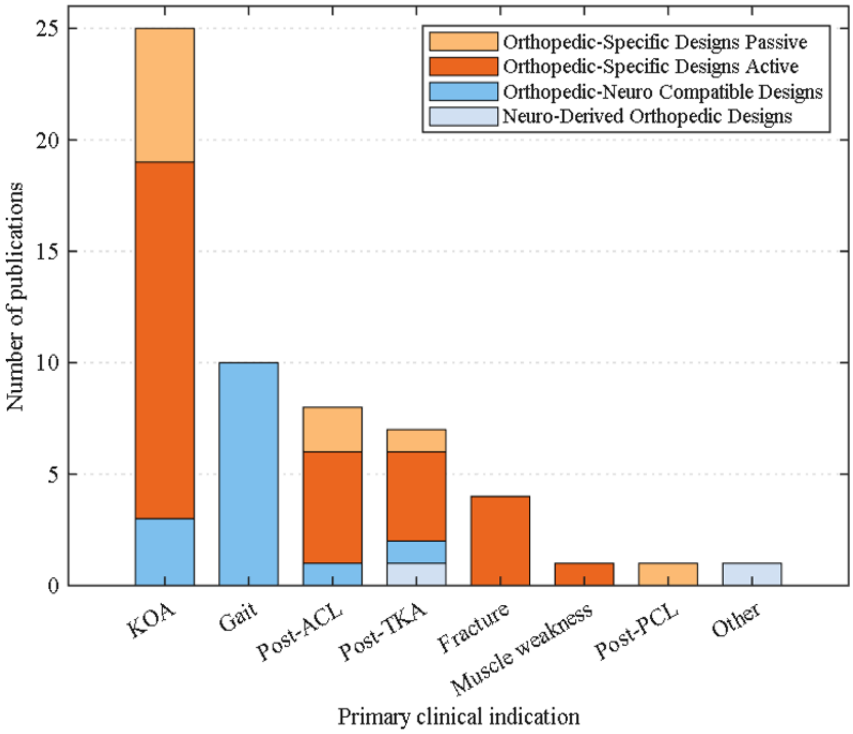

Figure 3.2: Number of publications by Clinical Indications
Orthopedic-specific designs significantly more concerned about specific orthopedic conditions

3.2.1 Configuration: Unilateral vs. Bilateral

Orthopedic diseases often involve one leg being severely affected while the other is unaffected or minimally affected, such as sports injuries. Therefore, devices that must be worn on both legs may have negative impacts such as excessive weight and deployment difficulty.

- **orthopedic-specific designs Findings:** The Figure 3.3 shows that the vast majority of Orthopedic-Specific Designs utilize a **unilateral (single-leg)** configuration. Examples include modular cable-driven systems [17, 18] and lightweight robotic braces [19, 20], which allow for donning on the affected limb without encumbering the healthy side.
- **Neuro-Derived Orthopedic Designs Findings:** In contrast, half of the neural derivative system uses a bilateral rigid frame connected to the pelvic module. [21, 22]

This structural difference highlights a key design flaw: the "neural" frame may unduly restrict the healthy anatomy of orthopedic patients.

3.2.2 Joint Kinematics and Degrees of Freedom (DOF)

Regarding knee joint degrees of freedom, although the human knee joint has only three rotational degrees of freedom as its primary degrees of freedom, three translational degrees of freedom also exist through ligaments and some muscle activity. If rehabilitation equipment cannot track these activities, it will lead to mismatch

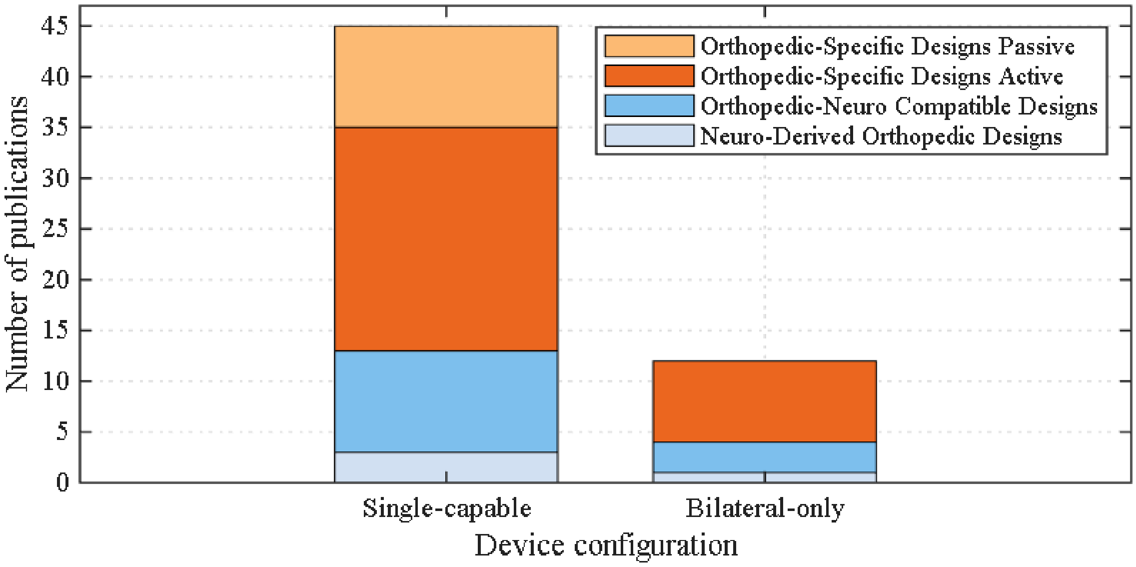

Figure 3.3: Number of publications by Single-capable and Bilateral-only. More orthopedic device options are available for use on only one leg.

between the equipment's axis of rotation and the knee joint, and in severe cases, it may even injure the patient when applying auxiliary force.

- **Sagittal Plane:** Figure 3.4 shows that among all the devices in the literature, 92% only support flexion and extension movements in the sagittal plane. Although this is the most important degree of freedom of knee joint movement, the center of rotation in the sagittal plane is actually determined by the movement between the bones in the human body. The center of rotation is not a point, but a dynamic, instantaneous center of rotation. Based on the characteristics of sagittal plane rotation of the human knee joint, this means that as the lower leg flexes and extends, the device's center of rotation may gradually lose track of the true center of rotation, causing a sudden increase in pressure or friction at the point of contact between the device and the body.
- **Horizontal/Transverse Plane:** Even without considering the potential problems with tracking sagittal plane rotation, there is another degree of freedom issue that frequently leads to adverse events: the natural lower leg rotation that accompanies flexion and extension. During full knee extension, the lower leg naturally externally rotates relative to the thigh. If the assistive rehabilitation device fails to account for this movement characteristic and completely locks the rotation in this horizontal plane, lateral shear forces are easily generated, increasing joint stress, which is a major taboo in orthopedic rehabilitation.
- **Latest solutions:** A subset of recent orthopedic-specific designs (approx. 25%) incorporate polycentric hinges or self-aligning mechanisms[23] [24] to accommodate as many of the human knee joint's motion characteristics as possible. Some studies, however, do not focus on the compatibility of the device's knee joint axis with the human body, but rather on the device's human-machine interface, attempting to avoid insufficient degree-of-freedom tracking with more flexible human-machine interface modes and fastening structures.

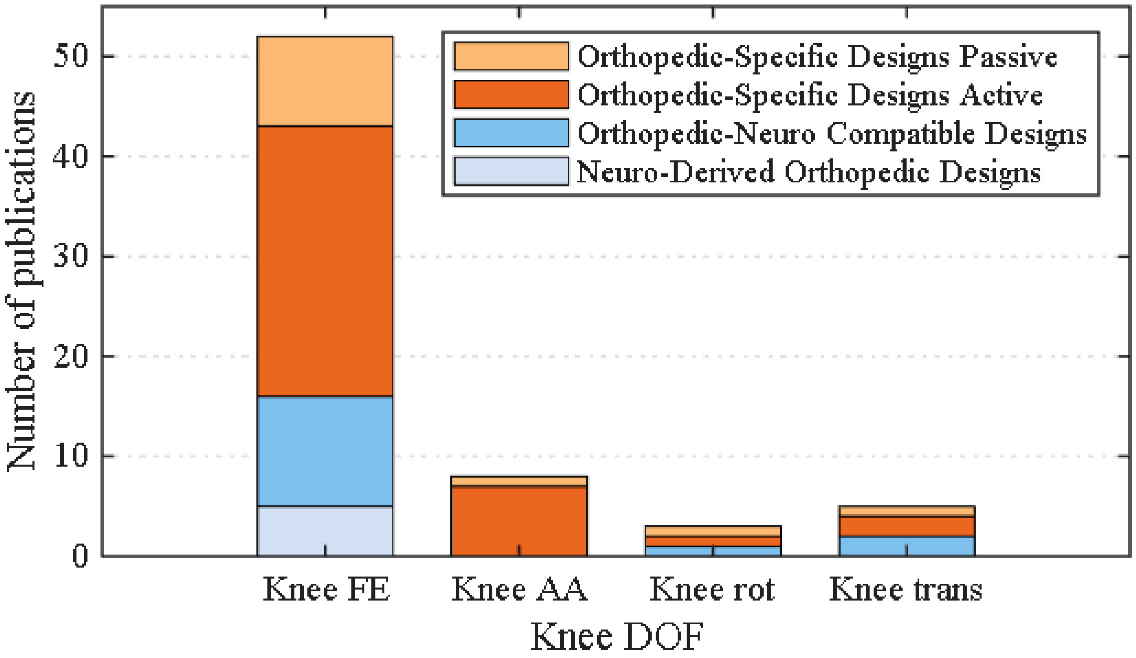

Figure 3.4: Number of publications by supported DOF on knee planes
Most devices still only support FE-surface movement of the knee joint.

However, such research is currently limited to the laboratory and has not yet passed clinical trials. Other researchers have chosen to abandon traditional brace structures in favor of artificial muscles or other novel structures; similarly, these have not yet broken through laboratory simulations and entered the clinical stage.

It can be seen that although current research and orthopedic knee joint assistive rehabilitation devices have limitations in degree-of-freedom adaptation, many researchers are attempting to address these issues from different perspectives.

3.2.3 Structures that support knee joint stability

In addition to the two points mentioned above, knee joint stability plays a crucial role in orthopedic rehabilitation. If the knee joint is subjected to further impact during rehabilitation training or daily life, it can potentially lead to consequences more severe than the original condition. A common approach to address this is to use bilateral rigid support structures to protect both sides of the knee joint and withstand impacts from all directions. Some devices are also attempting to address this issue using new technologies, such as using pneumatic unit arrays to wrap around the knee joint for rapid, skin-to-skin stabilization assistance.

- **Support structure:** As shown in Figure 5, over half of the devices still use unilateral knee support. From a design perspective, most non-orthopedic-specific devices employ unilateral knee support. Devices with both medial and lateral knee support are almost exclusively orthopedic-specific designs. From a neurological rehabilitation perspective, unilateral support is usually sufficient for support and assistive force delivery. However, in clinical orthope-

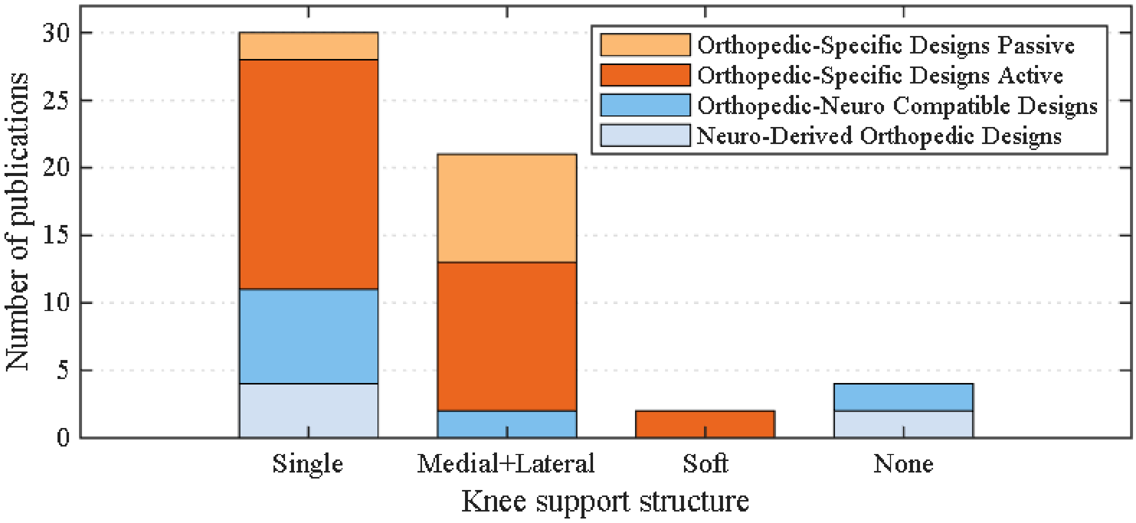

Figure 3.5: Number of publications by knee joint support structure
Devices that provide support for both the inner and outer sides of the knee are mostly designed specifically for orthopedics.

dic rehabilitation applications, greater consideration needs to be given to the vulnerability of the knee joint during disease.

- **Combining degrees of freedom** A more serious potential problem is that, during movement, devices with only unilateral support may exacerbate the issue of insufficient tracking of the human knee joint's degrees of freedom. If the torque output by the device cannot be ideally and evenly distributed across the knee through the human-machine interface, it will result in only one side (usually the outer side of the knee) receiving an auxiliary torque, while the other side undergoes passive movement. This means that unnatural varus/valgus torques are actually generated. Such torques often use the most vulnerable internal articular surfaces of orthopedic patients as leverage points, easily leading to secondary injuries.

From the above mechanical structure design of the equipment, we can see that there are many difficulties in the design of orthopedic rehabilitation equipment, which indirectly explains why the development of orthopedic equipment is later than that of neurological rehabilitation equipment.

3.3 Mechatronic Implementation: Actuation and Sensing

In H3, we argued that although knee orthopedic rehabilitation equipment is developing rapidly, its technological maturity is relatively low. A significant reason for this is that the power unit, sensors, and control strategies only meet laboratory functional requirements and are far from being truly mature for clinical use.

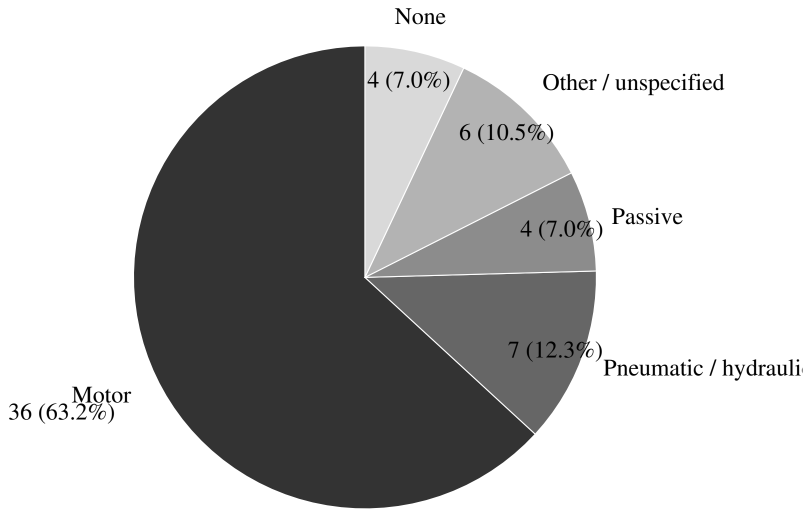

Figure 3.6: Number of publications by actuator
More than half of the equipment chooses to use electric motors

3.3.1 Actuation Modalities

The choice of actuator has a significant impact on the overall weight, power, and auxiliary force output of the equipment, often determining the system's power supply design. Some devices are not explicitly described in their literature. Figure 3.6 summarizes the statistical data on drive methods.

- **Electric Motors:** Dominant in 63% of systems. Designs range from Series Elastic Actuators (SEA) for compliant force control [25, 26] to direct-drive setups [3].
- **Soft Pneumatic/Cable Actuators:** An emerging trend is the use of soft, textile-based solutions. Examples include air microfluidic braces for OA [27] and cable-driven exosuits for gait symmetry [16, 28].
- **Variable Damping:** Some devices utilize Magnetorheological or friction-based dampers to provide resistive training without active energy injection [29, 30].

3.3.2 Sensing and Control Interfaces

To ultimately be applicable in clinical treatment and rehabilitation, devices need to meet various needs of physicians. Among these, the ability to detect the patient's movement intent and apply assistive force or resistance as needed, to determine if the patient is fatigued or experiencing adverse events and intervene accordingly, and to help patients train in a pain-tolerant manner and improve their compliance are all crucial[31, 1].

- **Basic Kinematic Sensing:** Based on the data collected on figure 3.7, 95%

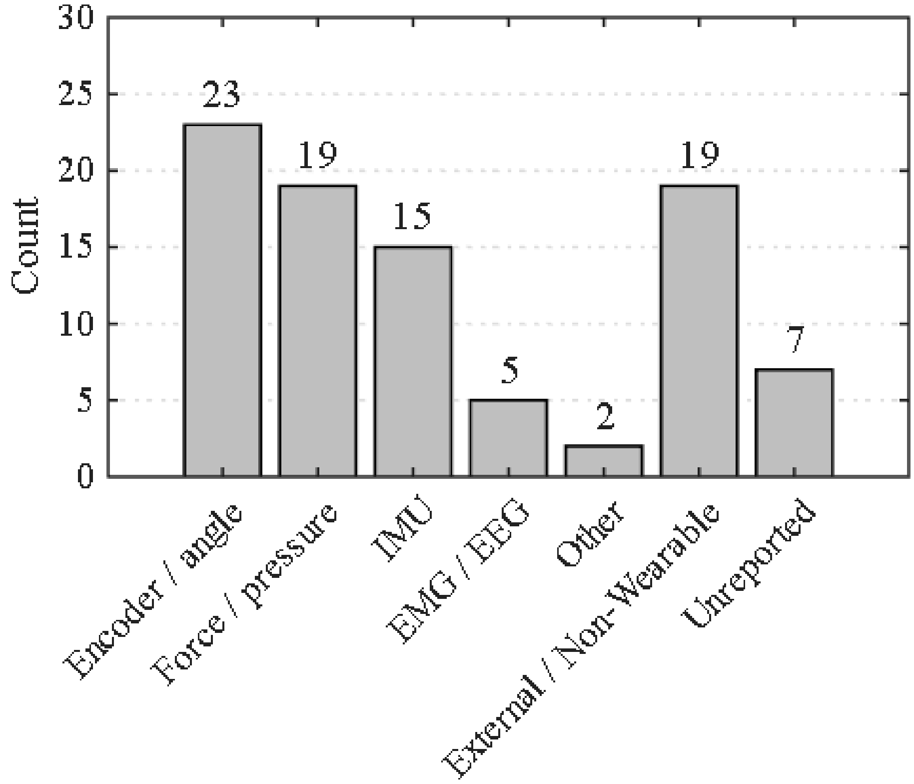

Figure 3.7: Number of publications by sensors
Encoders and angle sensors remain the most commonly used sensors.

of devices are equipped with encoders[32]. or potentiometers to measure joint angle.

- **Interaction Force:** Load cells or torque sensors are found in roughly 40% of systems, primarily for admittance control.
- **The Bio-signal Gap:** Advanced physiological sensing (EMG for muscle activity) is present in less than 15% of the reviewed studies. This indicates that most devices operate on "position control" (robot in charge) rather than "intent-based control" (patient in charge).Note that EMG and EEG are often common designs in neurological rehabilitation aimed at enhancing patient force perception and proprioception; their role in orthopedic rehabilitation may not be as significant as in neurological rehabilitation.
- **Control Strategies:** As shown in Figure 3.8, the equipment control strategies in this field have largely moved beyond mechanical and open-loop control, laying the foundation for further development of more advanced controls that better meet rehabilitation needs.

Despite some emerging technologies and designs, the field is still largely in the mature stage of mechatronics and has not yet reached the level of mass clinical rehabilitation applications. Future control and sensing systems may allow devices to attempt to align with the needs of doctors and patients from a perspective more aligned with the patient or physician, rather than from the perspective of the mechatronics system itself.

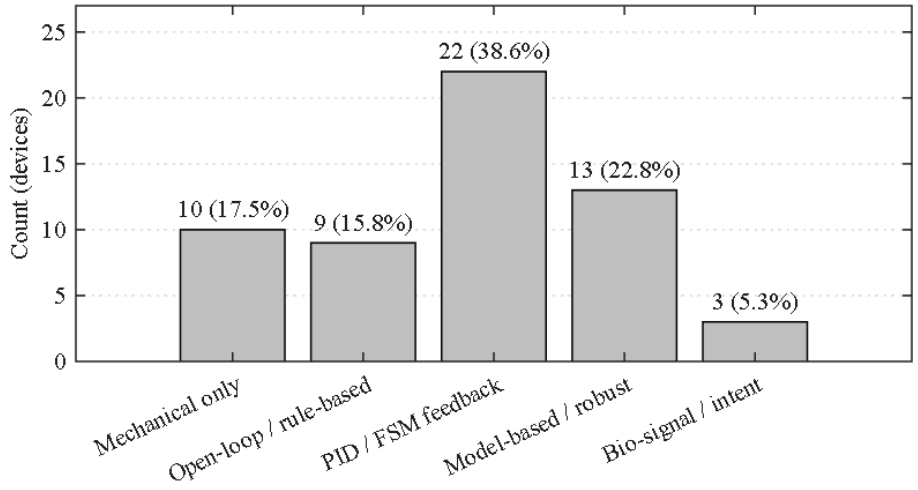

Figure 3.8: Number of publications by control strategies
PID and FSM feedback control are the most common, representing the initial maturity of engineering approaches.

3.4 Technology Readiness Level (TRL) Analysis

To validate the "maturity hypothesis" (H3), we assessed the development stage of each identified system using the European Commission's Technology Maturity Level (TRL). The distribution is shown in Figure 3.9. The TRL scoring mechanism has been described in Chapter 2, Section C. For a detailed explanation of the EU TRL classification, please see Appendix D.

3.4.1 The "Valley of Death" in Rehabilitation

The analysis reveals a skewed distribution of maturity levels across the 57 reviewed studies:

- **TRL 1–3 (Concept & Benchtop):** Approximately 25% of studies are at the conceptual stage, focusing on mechanism optimization or simulations [33, 34, 35].
- **TRL 4 (Lab Validation):** This is the most populated category (approx. 60%). Studies typically validate kinematics on healthy subjects [36, 37, 38].
- **TRL 5–7 (Clinical Validation):** Less than 15% of systems have progressed to patient testing. Notable exceptions include the HAL feasibility study for TKA [39], the decompressive device trials for OA [40, 41], and specific post-operative training evaluations [42].
- **TRL 8–9 (Market Ready):** Only a handful of systems (e.g., AlterG Bionic Leg, Keeogo) have reached commercial availability with regulatory approval, and even these often lack large-scale randomized controlled trial (RCT) data specifically for orthopedic outcomes.

Validation of H3:

The high percentage of technology maturity levels 3-4 and the extremely low percentage of those above level 6 validate Hypothesis 3. The surge in publications indicates more of a growing field than medical or commercial maturity. Devices that have

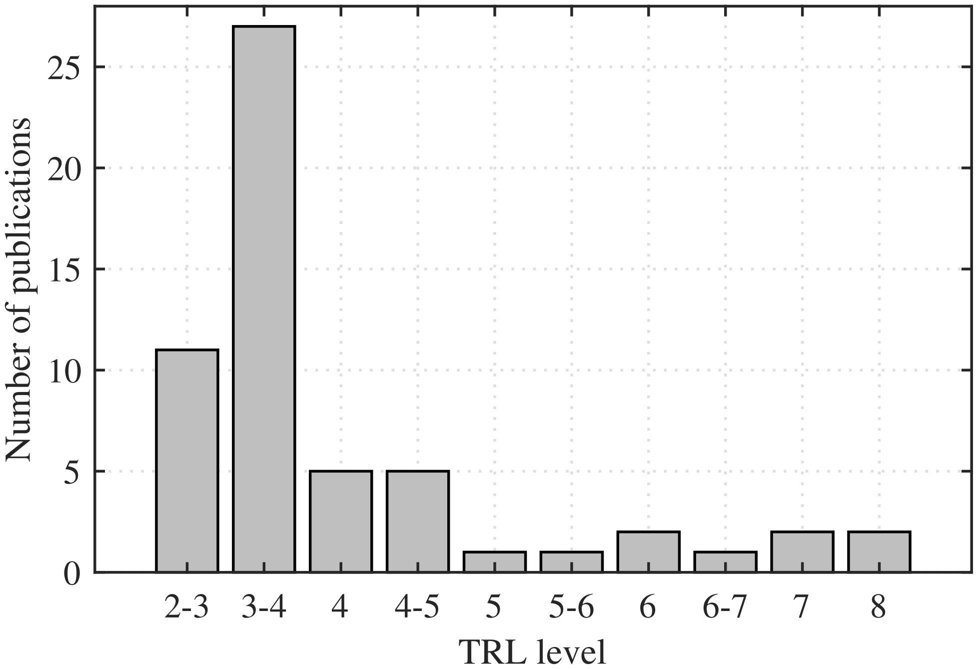

Figure 3.9: Distribution of technology readiness levels (TRL) . Most devices do not exceed TRL4, and those exceeding TRL5 are extremely rare. The devices in this field still has a significant gap to bridge before reaching medical and intelligent applications.

completed laboratory simulation testing are difficult to translate into devices that have passed clinical trials.

3.5 Comparative Analysis: Orthopedic-specific design vs. Others (Neuro-Derived orthopedic design + Orthopedic-Neuro Compatible design

To test the "mismatch hypothesis" (H2), this section uses the radar chart framework defined in the methodology to compare the orthopedic-specific design with the other two designs. Figure 13 presents the comparison results visually. The scoring criteria for each dimension of the radar chart are described in Chapter 2c.[9, 14]

3.5.1 Radar Chart Dimensions Evaluation

Through comparative analysis, we can see that the underlying design philosophy has a significant impact on the design direction and performance characteristics of the device across five important clinical applicability dimensions. The radar chart evaluation highlights the divergence between a ’Specialized Design Philosophy’ and

Table 3.1: Comparison of Mean Scores Between Orthopedic-Specific and Other Designs Across Dimensions

Evaluation Dimension	**Orthopedic-Specific**	**Others**
Clinical Indications	4.17	2.53
Knee Joint Stability and Alignment	3.80	3.24
Sensing and Control Design	3.85	4.24
Wearing Burden & Social Acceptance	3.48	2.86
Deployment Scenario & Compatibility	3.24	2.72

a ’Generalist/Repurposed Design Philosophy’, rather than a simple comparison of device origins. This validates the five-dimensional structural differences between orthopedic-specific designs and those relying on a repurposing & compatibility strategy.

- **Clinical Indications:**
  - *Orthopedic-Specific Designs (Mean Score: 4.17):* Exhibits high pathological targeting, focusing on localized joint mechanics such as medial compartment unloading for KOA, extension lag correction for post-TKA, or bone-callus stimulation during fracture healing.
  - *Others (Mean Score: 2.53):* Primarily characterized by a "repurposing mindset," these designs offer generalized gait assistance but lack specific protocols for localized tissue protection or pain-aware rehabilitation.
- **Knee Joint Stability and Alignment:**
  - *Orthopedic-Specific Designs (Mean Score: 3.80):* More often addresses ergonomic issues through multi-center hinges or active alignment compensation; some designs employ a hybrid rigid-soft structure to ensure frontal plane stability.
  - *Others (Mean Score: 3.24):* Relatively reliant on standard single-axis hinges or cantilever connections, which increases the risk of generating harmful shear forces in unstable orthopedic joints.
- **Sensing and Control Design:**
  - *Others (Mean Score: 4.24):* Scores higher due to the inheritance of mature neurological control paradigms (e.g., multi-modal intent recognition) and larger hardware capacities for complex sensor suites.
  - *Orthopedic-Specific Designs (Mean Score: 3.85):* While these systems are functionally effective for orthopedic tasks, they are often technically immature, focusing on specific biomechanical goals rather than more advanced designs such as intent detection.
- **Wearing Burden & Social Acceptance:**
  - *Orthopedic-Specific Designs (Mean Score: 3.48):* Often prioritize modular unilateral designs and lightweight, independent structures to reduce physical burden and social stigma, meeting long-term chronic rehabilitation needs.

Figure 3.10: Five Comparisons Between Orthopedic Specialty Equipment and Other Equipment
Aside from sensors and controls, orthopedic applications are superior in all other aspects, especially in terms of their specificity for orthopedic clinical indications.

  - *Others (Mean Score: 2.86):* Prefer bulky bilateral frames and pelvic-driven modules designed for patients with neuroparalysis, leading to significant social stress and unnecessary burden on healthy limbs.
- **Deployment Scenario & Compatibility:**
  - *Orthopedic-Specific Designs (Mean Score: 3.24):* Shows better practical application potential (e.g., assisting with daily living activities on stairs/ramps), focusing on removing external connection cables or power sources.
  - *Others (Mean Score: 2.72):* A significant portion remains confined to home or hospital settings, often relying on external computing, power stations, or sensors, which limits their potential for conversion into independent outpatient use in orthopedic rehabilitation clinics.

Validation of H2:

Comparative analysis confirmed the poor structural compatibility of non-orthopedic-specific devices with orthopedic clinical use.

Neurally derived systems consistently scored low on several dimensions crucial to the safety and effectiveness of orthopedic rehabilitation.

This is better understood from the perspective of the designers' own knowledge background. Compared to designers of orthopedic-specific devices, designers of neurally derived orthopedic devices pay insufficient attention to the unique needs of orthopedic patients or lack a deep understanding of orthopedic pathology and rehabilitation. This is reflected in Tables 3.3 and 3.4. This demonstrates that simply iterating or modifying neuroexoskeletons is insufficient to meet the practical applications of orthopedic rehabilitation. (Excerpts of rehabilitation needs statements from all 57 articles can be found in Appendix 5.)

3.6 Summary of Hypothesis Verification

Based on the evidence presented in Sections 3.1 through 3.5, the three core hypotheses of this thesis are resolved as follows:

- **H1 (The Trend): VALIDATED.** The explosive growth in publications related to orthopedic-specific designs (32 papers in total from 2023-2025) confirms the rise of this field.
- **H2 (The Mismatch): VALIDATED.** Structural analysis confirms that, despite low scores for orthopedic-specific designs, neurally derived devices are relatively less able to meet the specific biomechanical constraints (bilateral stability, unilateral wearability) required for orthopedic treatment.
- **H3 (The Maturity): VALIDATED.** Technology Readiness Level (TRL) analysis confirms that the field is currently flooded with TRL 4 laboratory prototypes, while clinical evidence for TRL 5 and above is severely lacking.

Table 3.2: Summary of knee joint unloading devices and key experimental results.
KCF (Knee Contact Force); KAI (Knee Adduction Impulse); %GC (Percentage of Gait Cycle)

Knee joint support structure	Equipment Abbreviation	Main DOF	Control Design	Test subject + key results
Rigid, rear support [15](2025)	Soft knee exosuit	AA (active)	Gait-event trigger; PD+ILC force tracking target KAM	$n = 6$ healthy; peak net KAM $\downarrow\approx$ 30%–40%, inner contact force peak $\downarrow\approx$ 20%.
Soft + unilateral soft airbag [33](2024)	CMPM fracture exo	FE + axial (active)	Motor-driven CMPM; force/torque closed-loop dual mode	$n = 0$, bench only; axial load and torque errors are both $< 10\%$.
Rigid, bilateral [43](2022)	Quasi-passive unloading brace	FE (quasi-passive)	Spring and motor locking pawl lock the knee extension moment at the target angle.	$n = 1$, healthy; experimental peak KCF $\downarrow$ 24%, model prediction $\downarrow\approx$ 36%.
Rigid, bilateral [34](2025)	ABLE robotic unloader brace	AA (active)	GRF+Kalman calculation of %GC; motor PID tracking of BAM trajectory	$n = 1$ healthy; BAM trajectory RMSE 0.18–0.58 Nm, system bandwidth > 10 Hz.
Soft + hard single side [41](2023)	Vibratory unloader orthosis	FE (passive)	Eversion brace + fixed-frequency local muscle vibration	KOA RCT, $n = 14$; both groups showed improvement in WOMAC, with the vibration group showing a greater decrease in KAM.
Rigid, bilateral [40](2016)	Decompressive valgus brace (Rebel Reliever)	FE (passive)	The orthotist sets a fixed eversion angle and bandage tension.	$n = 15$ KOA; 2–8 weeks KAI $\downarrow\approx$ 35%, second peak KAM $\downarrow$ 26%, pace $\uparrow$.

Table 3.3: **Contrast of Orthopedic Insight Across Robot Categories (Selected Representative Works)Part 1.**

Category	**Article Source**	**Key Quote (Condensed)**	**Clinical Insight Analysis**
Neuro-Derived Designs	*Design and Analysis... (Li et al.)[18]*	"Existing robots typically assist both limbs simultaneously... **not suitable for unilateral** impairments caused by trauma."	**Ignores Asymmetry:** Orthopedic trauma is rarely bilateral; neuro-symmetry fails here.
	Design... Knee... (Aubeeluck)[32]	"Active exoskeletons (HAL)... Joint Type: **single-pivot**. [We devised] a mechanism which closer resembles the ligaments."	**Oversimplified Anatomy:** Critiques simple hinges used in neuro-rehab.
	Feasibility... (Kotani et al.)[39]	"Excluded because of severe coordination problem... **pain** made HAL-supported exercise impossible."	**Pain Interference:** EMG control fails when pain causes muscle co-contraction.
	Exoskeleton Suit... (Reanaree)[44]	"Unexpected issues involved **squeezing** of the skin... Making sure that the device does not touch any bones."	**Safety Blind-spot:** Lacks awareness of bone pressure points/-soft tissue.
Compatible Designs	*Design and control... (Du et al.)[3]*	"Knee has flexion, rotation... [but] **Fixed-axis** is considered to ensure simplicity and compactness."	**Conscious Simplification:** Sacrifices 6-DOF anatomy for engineering simplicity.
	Design of Biomimetic... (Liu et al.)[24]	"Utilizing a cam-based mechanism to achieve sagittal motion while **disregarding** movements in other planes."	**Planar Restriction:** Adopts a 'planar model', ignoring coronal stability.
	iT-Knee... (Saccares et al.)[37]	"Assists flexion/extension, while all other knee DoFs are **accommodated** [passively]."	**Passive Tolerance:** Treats non-sagittal movements as interferences to allow.

Table 3.4: Contrast of Orthopedic Insight Across Robot Categories (Selected Representative Works)Part 2.

Category	Article Source	Key Quote (Condensed)	Clinical Insight Analysis
Passive Ortho	*Biomechanical... PCL (Heinrichs)[13]*	"**Gravity**... provoke posterior tibial translation (PTT)... brace allows adjustable anteriorly directed force."	**Anti-Gravity:** Addresses invisible static forces affecting ligament healing.
	A Distraction Brace... (Boillereaux)[14]	"Conforms to the **nonlinear behavior** of the tibiofemoral contact force during squat motions."	**Nonlinear Mechanics:** Matches nonlinear cartilage pressure curves.
Active Ortho	*Conceptual Design... (Ji et al.)[33]*	"Exerts controlled axial load... to provide tunable mechanical stimulation [**Wolff's Law**]."	**Bone Physiology:** Stimulates bone growth (callus) via axial loading.
	Automatic rehab... (Makino)[45]	"Patients with **Extension Lag** cannot extend knee straightly... rehabilitation is hard work for PTs."	**Pathology Specificity:** Targets 'Extension Lag' (quadriceps inhibition).
	Task-Agnostic... (Divekar)[46]	"High knee extension torques... increased **patellofemoral compression**, which aggravates pain."	**PF Joint Mechanics:** Targets 'high torque' compression causing pain.
	Soft Knee Exosuit... (Han et al.)[15]	"Directly provides abduction moment... aiming to reduce the **KAM** (Knee Adduction Moment)."	**Kinetic Intervention:** Actively modifies KAM, the root cause of OA.
	Exosuit for ACL... (Li et al.)[12]	"AAOS Guidelines do **not recommend** functional brace... [developed] Exosuit to improve comfort."	**Guideline Compliance:** Respects guidelines avoiding rigid braces (atrophy).
	Robotic Unloader... (Reinsdorf)[47]	"Intelligently modulates BAM in **real time**... to better protect the knee joint, improve pain relief."	**Dynamic Pain Mgmt:** Synchronizes unloading with gait phases.
	Switchable Robot... (Makino)[10]	"Asymmetrical gear corresponding with **roll-back** motion... bilateral asymmetrical gear."	**Micro-Kinematics:** Replicates femoral condyle 'roll-back'.
	Knee Brace control... (Javanfar)[48]	"Calculates **cartilage penetration depth**... as surrogate parameter for determining pain."	**Micro-Pathology:** Uses cartilage depth as control variable.

4

Discussion

4.1 Divergence in Clinical Insight: A Qualitative Analysis

To validate H2 from multiple perspectives, this paper will meticulously analyze the design and analytical statements described by developers of devices with different design purposes. The study found that researchers specializing in orthopedic designs have a significantly deeper and broader understanding of orthopedic rehabilitation needs than researchers of other types of devices.

As shown in Tables 3.3 and 3.4, it is evident that designers and developers of orthopedic devices tend to define design requirements based on the constraints of human tissue (e.g., ligament shear force, cartilage contact pressure) analyzing the needs of a specific condition. In contrast, designers and developers of devices derived from neurological rehabilitation equipment often describe problems using more vague or higher-level kinematic terms (e.g., trajectory tracking, gravity compensation). Some researchers even choose to trust existing neurological rehabilitation devices and claim their suitability for orthopedic applications with minimal modifications. They may provide various experimental simulations and graphs, but due to the unique complexity of knee orthopedic rehabilitation, even with superior performance in some areas, it is often impossible to simultaneously meet all performance requirements.

A systematic analysis of 57 devices confirms that while the field of orthopedic knee exoskeletons is experiencing a surge in publications (validating Hypothesis 1), it faces significant structural challenges (Hypothesis 2) and remains in the early stages of technology maturity (Hypothesis 3). This section synthesizes these findings, proposes design considerations, and discusses the limitations of current research.

4.2 Summary of Findings

This review identified significant differences in development trajectories:

- **Neuro-Derived Limitations:** These systems typically have a relatively high Technology Readiness Level (TRL), characterized by bilateral frames and rigid kinematics, retaining an architecture designed specifically for neurological patients. Due to this design philosophy, such designs often struggle to meet the multifaceted needs of orthopedic rehabilitation through simple optimization; for example, insufficient knee support structures may require a complete redesign to address and provide multidimensional stability.

- **Orthopedic-Specific Potential:** Of the 40 identified orthopedic-specific design systems, the vast majority prioritize anatomical protection of the knee joint compared to other designs. However, most remain in the prototype stage (TRL 3-4), lacking sufficient population and duration of clinical testing, and often lacking the advanced sensor integration required for complex clinical interactions.

To ensure the discussion aligns with specific biomechanical results, Table 3.2 summarizes all experimental devices involving healthy individuals/patients and their reported results, totaling only 6.

4.3 Design Considerations for the "Orthopedic-First" Paradigm

Based on mismatch analysis, this paper outlines key design considerations for future development. These are not rigid rules, but evidence-based guidelines designed to improve clinical compatibility.

4.3.1 Kinematic Requirement: Stability and Bio-Fidelity

The knee joint is a complex joint whose instantaneous center of rotation (ICR) changes.

- **Guideline:** While multi-center mechanisms theoretically offer biofidelity, relatively mature bilateral uniaxial hinges may still remain a viable and robust solution, provided they are integrated with flexible interfaces (e.g., adaptive bracing systems) to accommodate changes in the ICR.
- **Crucial Design Feature:** A key finding of this study is the importance of bilateral (medial-lateral) support in the knee joint. Devices relying on unilateral support struts (cantilever designs) are more prone to generating misalignment torque. Ideally, the design should support both sides of the knee joint (or have other similar structures) to ensure frontal plane stability and prevent harmful shear forces.

4.3.2 Structural Requirement: Modular Versatility

Orthopedic diseases are primarily unilateral, thus requiring devices that do not burden the healthy limb.

- **Guideline:** Systems should prioritize modular configurations capable of independent single-leg manipulation. This flexibility allows for treatment of unilateral conditions without the need for pelvic-driven bilateral braces. Furthermore, modularity is crucial for improving device adaptability to patients with diverse characteristics.
- **Usability Factors:** To ensure clinical acceptability, the design should be as lightweight and structurally flexible as possible. Specifically, the frame structure should account for postoperative swelling and employ an open structure to avoid contact with potential surgical incision sites.

4.3.3 Control Requirement: Transparency and Pain Awareness

Unlike neurorehabilitation, where motor nerves can be restored through high-stiffness "forced" movement, orthopedic rehabilitation is often limited by severe pain and the constraints of a tight rehabilitation training window.[49, 47, 43, 50]

- **Clinical Principles:** Pain management must be a crucial consideration. Failed pain management reduces patient compliance, preventing the completion of required training. Devices that effectively allow patients to adapt and train at an acceptable level of pain during orthopedic rehabilitation will be highly valued by both therapists and patients.
- **Guideline:** Therefore, control strategies must prioritize "mechanical transparency" during voluntary movement to avoid hindering natural kinematics. Furthermore, speed control and stability should be maintained throughout movement. Additionally, the control logic should assess patient pain levels from some perspective, allowing for the design of safety mechanisms to prevent excessive pain.

4.4 Perspectives on Clinical Translation

The concentration of devices at Technology Readiness Level 4 (TRL 4) indicates a need to bridge the gap between engineering and clinical validation. Future R&D efforts may benefit from the following key shifts:

- **Testing Environments:** While testing on healthy subjects is standard practice, we encourage exploring pathological simulation models (e.g., simulating gait deviations) where feasible to better predict device behavior under irregular loading conditions prior to patient trials.
- **Multi-Objective Optimization:** Design is a compromise. Future iterations should balance factors such as drive and stability, ease of use and weight, including single-person wearability and multi-scenario deployment compatibility—key determinants of clinical application.
- **Outcome Metrics:** In this area, designers should draw on relevant experience from other rehabilitation programs, selecting effective and as homogeneous clinical trial outcome metrics as possible (e.g., VAS pain score, KOOS) and combining them with engineering metrics to progressively achieve evidence-based validation.

4.5 Research Limitations

This review's methodology has some inherent limitations:

- **No Pure Neurological Purpose Devices:**Without comparisons to "state-of-the-art purely neurological equipment," the conclusions are limited to those devices that "attempt to cross boundaries" and do not represent the highest level of neurorehabilitation engineering.

- **No Meta-Analysis:** As discussed in the methodology section, the high heterogeneity of mechanical designs and the lack of standardized clinical reporting protocols prevented quantitative meta-analysis. Therefore, the results are primarily descriptive and qualitative.
- **Language Bias:** The search scope was limited to English publications, which may have missed relevant developments in non-English speaking regions.
- **Publication Bias:** The analysis relied on published academic literature, which may lag behind commercial developments or miss the negative consequences of prototype failures.

5

Conclusion

This paper collected, screened, and analyzed 57 articles on wearable knee orthopedic rehabilitation exoskeletons, conducting a systematic review and quantitative analysis. It distinguished between orthopedic-specific designs, neurorehabilitation-derived orthopedic rehabilitation designs, and neuro-orthopedic compatible rehabilitation designs, comparing the adaptability potential of different designs in different dimensions of orthopedic rehabilitation. This paper emphasizes the differences in mechanical structural characteristics caused by divergent design philosophies, employing methods specifically designed for these purposes for analysis, and drawing the important conclusion that orthopedic-specific designs are the main development direction.

Regarding the research questions raised in the introduction:

- **RQ1 (Trend):** The field of knee orthopedic rehabilitation exoskeletons has experienced a clear trend change. Analysis shows an explosive growth in literature on orthopedic-specific devices, with over 56% of relevant research occurring between September 2023 and 2025, verifying the gradual rise and dominance of orthopedic-specific designs in this field, indicating increasing industry interest in this area.
- **RQ2 (Mechanical Suitability):** Due to the high complexity of the human knee joint and the objectively existing extreme sensitivity to stress in orthopedic rehabilitation, current support structures and degrees of freedom designs are insufficient to fully meet rehabilitation needs. Although the vast majority of devices still focus solely on sagittal rotational assistance, a growing number of researchers and designers are recognizing this issue and have begun to develop emerging orthopedic-specific designs to bridge this gap.
- **RQ3 (Mismatch & Risks):** A fundamental design mismatch exists when employing a repurposing strategy on neurological rehabilitation equipment and neuro-orthopedic compatible rehabilitation devices. Multiple dimensions indicate that designs based on a generalist philosophy, or those attempting to simultaneously accommodate multiple design purposes, are currently more challenging in meeting the unique rehabilitation needs of orthopedics (e.g., knee joint support stability and modular unilateral limb application).
- **RQ4 (Maturity):** Despite a booming research literature and innovative designs, this field remains in a 'valley of death' in terms of technology maturity. The vast majority of device systems remain at a technology maturity level of 4 or below, and very few have even completed trials on healthy individuals. This means that designs in this field are currently only relatively mature in laboratory electromechanical system simulation testing, and in a relatively short

development history, it is difficult to meet the multi-objective design optimization challenges of the complex needs of orthopedic rehabilitation. Specifically, achieving a balance and meeting requirements in areas such as motion stability, peak assist force, deployment environment compatibility, patient training or daily living posture compatibility, disease compatibility, pain management, and economic and human resource costs remains extremely difficult. It is expected that researchers specializing in orthopedic designs can gradually supplement and optimize designs through greater specificity and design freedom.

Final Verdict:

In the field of knee joint orthopedic rehabilitation exoskeletons, future researchers should fully understand the mechanisms of orthopedic rehabilitation and human anatomy, make full use of the development experience and systems of neurological rehabilitation devices, design devices with orthopedic-specific rehabilitation or rehabilitation for specific orthopedic diseases as the design purpose, overcome effectiveness barriers with a smaller range of indications, and select the correct outcome indicators for further development through mature clinical trials to achieve technological maturity and accumulate reliable experience in the design of orthopedic-specific rehabilitation devices.

Based on current mainstream design experience, devices that can be deployed on one affected limb, are highly modular, have dual rigid structure support on the medial and lateral sides of the knee joint, include control functions such as pain management and emergency stop, and are not limited by non-wearable components in deployment scenarios are likely the ideal design in a universal sense, and are closest to meeting the ultimate goal of clinical needs.

Bibliography

[1] T. Bacek *et al.*, “Biomot exoskeleton — towards a smart wearable robot for symbiotic human-robot interaction,” in *2017 International Conference on Rehabilitation Robotics (ICORR)*, 2017, pp. 1666–1671.

[2] Y. Shen, Y. Tian, and H. Wang, “Structural design and intelligent control of lower limb knee rehabilitation exoskeleton based on motion intention estimation method,” in *1st International Conference on Mechanical System Dynamics (ICMSD 2022)*, 2022, pp. 677–683.

[3] K. Du, Y. Yu, and L. Dong, “Design and control of a novel powered wearable knee exoskeleton for lower limb rehabilitation,” in *2024 WRC Symposium on Advanced Robotics and Automation (WRC SARA)*, 2024, pp. 274–279.

[4] A. Sanchez, T. Rossos, A. Mihailidis, and B. Laschowski, “Preliminary development of a robotic hip-knee exoskeleton with 3d-printed backdrivable actuators,” in *ASME 2023 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference (IDETC-CIE2023)*, 2023.

[5] Global Burden of Disease Study Collaborators, “Global, regional, and national burden of osteoarthritis from 1990 to 2021 and projections to 2035: A cross-sectional study,” *PLOS One*, 2025.

[6] Z. Patrick, R. Clark, and A. David, “Current and projected future supply and demand for physical therapists from 2022 to 2037: A new approach using microsimulation,” *Physical Therapy & Rehabilitation Journal*, 2025.

[7] N. Hogan and H. I. Krebs, “The history of robotics in medicine,” *Proceedings of the IEEE*, vol. 94, no. 9, pp. 1656–1662, 2006.

[8] L. Wang, Y. Zhang, and X. Chen, “Characteristics and emerging trends in research on rehabilitation robots from 2001 to 2020: Bibliometric study,” *Journal of Medical Internet Research*, vol. 25, p. e45678, 2023.

[9] Y. Qu, X. Wang, J. Zhao, G. Zhang, D. Huo, and Y. Hao, “Design and experimental study of a wearable passive rehabilitation exoskeleton for post-tka patients,” in *Journal of Physics: Conference Series*, vol. 3043, no. 1, 2025.

[10] K. Makino, T. Ogura, M. Nakamura, and H. Terada, “Development of a switchable wearable robot for rehabilitation after surgery of knee,” in *CISM International Centre for Mechanical Sciences, Courses and Lectures.* Springer, 2021, vol. 601, pp. 60–67.

[11] X. Kong, M. Li, Z. Yang, D. He, and Y. Zheng, “A multimodal knee exoskeleton for fracture rehabilitation,” in *17th International Convention on Rehabilitation Engineering and Assistive Technology*, 2024, pp. 385–390.

[12] J. S. Li *et al.*, “Development of an exosuit knee brace for anterior cruciate ligament injury,” *IEEE Transactions on Medical Robotics and Bionics*, 2025.

[13] C. H. Heinrichs, W. Schmoelz, R. Mayr, A. Keiler, P. B. Schottle, and R. Attal, “Biomechanical evaluation of a novel dynamic posterior cruciate ligament brace,” *Clinical Biomechanics*, vol. 33, pp. 20–25, 2016.

[14] L. Boillereaux, S. L. Floc’h, F. Jourdan, G. Camp, A. Tanguy, and A. Kheddar, “A distraction knee-brace and a robotic testbed for tibiofemoral load reduction during squatting,” *IEEE Transactions on Medical Robotics and Bionics*, vol. 7, no. 2, pp. 621–632, 2025.

[15] Y. Han, D. Shi, Y. Shao, Y. Feng, X. Ding, and W. Zhang, “Design and evaluation of a soft knee exosuit for reducing knee medial compartment load during walking,” *IEEE Transactions on Biomedical Engineering*, vol. 72, no. 5, pp. 1740–1749, 2025.

[16] X. Wu, A. Zhu, X. s. Wang, X. Ma, H. Mao, and J. Song, “Real-time gait symmetry enhancement in people with unilateral knee injuries using deep learning for modulation of knee exoskeleton,” in *2023 International Conference on Design Science (ICDS)*, 2023, pp. 1–7.

[17] L. Zhang *et al.*, “Mechanism design of cable-driven multi-functional knee osteoarthritis rehabilitation robot,” in *2024 International Conference on Mechatronics and Machine Vision in Practice (M2VIP)*, 2024.

[18] A. Li, F. Luan, F. Zhang, S. Lu, G. Gao, and M. Liu, “Design and analysis of a single lower limb rehabilitation exoskeleton robot,” in *2023 International Annual Conference on Complex Systems and Intelligent Science (CSIS-IAC)*, 2023, pp. 390–395.

[19] N. Siddique *et al.*, “Prototype development of an assistive lower limb exoskeleton,” in *2019 International Conference on Robotics and Automation in Industry (ICRAI)*, 2019, pp. 1–6.

[20] V. M. Hema *et al.*, “Upper and lower limb interchangeable exoskeleton-robot for post stroke rehabilitation,” in *2021 9th RSI International Conference on Robotics and Mechatronics (ICRoM)*, 2021, pp. 7–12.

[21] D. Pisla *et al.*, “Dimensional and workspace analysis of raise rehabilitation robot,” in *Mechanisms and Machine Science*, 2020, vol. 89, pp. 155–165.

[22] G. Li, J. Xu, Z. Li, R. Song, and Y. Kang, “Dynamic locomotion synchronization and fuzzy control of a lower limb exoskeleton with body weight support for active following human operator,” *IEEE Transactions on Cybernetics*, vol. 55, no. 6, pp. 2792–2805, 2025.

[23] T. Kikuchi, T. Nishimura, T. Fukuoka, T. Todaka, and I. Abe, “Design of polycentric assistive device for knee joint,” in *2021 30th IEEE International Conference on Robot & Human Interactive Communication (RO-MAN)*, 2021, pp. 546–550.

[24] K. Liu and J. He, “Design of a biomimetic knee joint orthosis for motion rehabilitation assistance,” *IEEE/ASME Transactions on Mechatronics*, pp. 1–9, 2025.

[25] B. Freitas *et al.*, “Design, modelling and control of an active weight-bearing knee exoskeleton with a series elastic actuator,” in *2019 IEEE 6th Portuguese Meeting on Bioengineering (ENBENG)*, 2019, pp. 1–4.

[26] B. Chen, B. Wang, C. Zheng, and B. Zi, "Design and simulation of a robotic knee exoskeleton with a variable stiffness actuator for gait rehabilitation," in *2021 27th International Conference on Mechatronics and Machine Vision in Practice (M2VIP)*, 2021, pp. 24–29.

[27] R. Z. Gao, K. Marriott, C. R. Dickerson, M. R. Maly, and C. L. Ren, "Design and preliminary implementation of an air microfluidics enabled soft robotic knee brace towards the management of osteoarthritis," in *Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, 2020, pp. 4502–4505.

[28] Y. Yang, J. Guo, Y. Yao, and H. Yin, "Development of a compliant lower-limb rehabilitation robot using underactuated mechanism," *Electronics*, vol. 12, no. 16, p. 3436, 2023.

[29] J. E. Rocchi, L. Labanca, V. Luongo, and L. Rum, "Innovative rehabilitative bracing with applied resistance improves walking pattern recovery in the early stages of rehabilitation after acl reconstruction: a preliminary investigation," *BMC Musculoskeletal Disorders*, vol. 21, no. 1, p. 644, 2020.

[30] S. R. Brown, E. P. Washabaugh, A. Dutt-Mazumder, E. M. Wojtys, R. M. Palmieri-Smith, and C. Krishnan, "Functional resistance training to improve knee strength and function after acute anterior cruciate ligament reconstruction: A case study," *Sports Health*, vol. 13, no. 2, pp. 136–144, 2021.

[31] P. Harish, P. Harish, K. K. Raj, P. Prakash, and P. Jisha, "Emg and eeg sensor-based exoskeleton for knee injury rehabilitation," in *International Conference on Trends in Engineering Systems and Technologies (ICTEST)*, 2025.

[32] C. Y. Aubeeluck, S. Kolbl, D. Dobriborsci, and W. Aumer, "Design and development of a knee rehabilitation exoskeleton with four-bar linkage actuation," in *2023 9th International Conference on Control, Decision and Information Technologies (CoDIT)*, 2023, pp. 1618–1623.

[33] Y. Ji, X. Lang, B. Wu, Y. Fan, Q. Zheng, and X. Yang, "Conceptual design and preliminary experiment of an orthopedic rehabilitation exoskeleton based on the coupled movable pulley mechanism (cmpm)," in *2024 International Convention on Rehabilitation Engineering and Assistive Technology and World Rehabilitation Robot Convention (WRRC)*, 2024.

[34] Z. Tu, J. Xu, Z. Dong, S. Zhang, and J. Tan, "Load-bearing optimization for customized exoskeleton design based on kinematic gait reconstruction," *Medical & Biological Engineering & Computing*, vol. 63, no. 3, pp. 807–822, 2025.

[35] H. Sun *et al.*, "Mechanical structure design and motion simulation analysis of a lower limb exoskeleton rehabilitation robot based on human–machine integration," *Sensors*, vol. 25, no. 5, p. 1611, 2025.

[36] A. Jamali, A. A. Labadin, and M. S. Jamaludin, "Investigation of hybrid mechanism for knee exoskeleton rehabilitation device," in *2024 IEEE International Conference on Smart Instrumentation, Measurement and Applications (ICSIMA)*, 2024, pp. 109–113.

[37] L. Saccares, I. Sarakoglou, and N. G. Tsagarakis, "it-knee: An exoskeleton with ideal torque transmission interface for ergonomic power augmentation," in *2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2016, pp. 780–786.

[38] J. Zhang *et al.*, “Bionic design and optimization of a rigid-soft hybrid knee exoskeleton,” in *2023 International Conference on Design Science (ICDS)*, 2023.

[39] N. Kotani *et al.*, “Feasibility of supplemental robot-assisted knee flexion exercise following total knee arthroplasty,” *Journal of Back and Musculoskeletal Rehabilitation*, vol. 33, no. 3, pp. 413–421, 2020.

[40] E. M. Lamberg, R. Streb, M. Werner, I. Kremenic, and J. Penna, “The 2- and 8-week effects of decompressive brace use in people with medial compartment knee osteoarthritis,” *Prosthetics and Orthotics International*, vol. 40, no. 4, pp. 447–453, 2016.

[41] K. Barati, M. Kamyab, I. E. Takamjani, S. Bidari, and M. Parnianpour, “Effect of equipping an unloader knee orthosis with vibrators on pain, function, stiffness, and knee adduction moment in people with knee osteoarthritis: A pilot randomized trial,” *Gait & Posture*, vol. 99, pp. 83–89, 2023.

[42] X. Wang, W. Lin, J. Zhao, and Y. Wei, “Design of wearable koa postoperative rehabilitation training equipment,” in *Mechanisms and Machine Science.* Springer, 2024, vol. 155, pp. 469–483.

[43] J. S. Stoltze *et al.*, “Development and functional testing of an unloading concept for knee osteoarthritis patients: A pilot study,” *Journal of Biomechanical Engineering*, vol. 144, no. 1, p. 011007, 2022.

[44] P. Reanaree and C. Pintavirooj, “Exoskeleton suit supports the movement,” in *2018 11th Biomedical Engineering International Conference (BMEiCON)*, 2018, pp. 1–4.

[45] K. Makino *et al.*, “Automatic rehabilitation of the extension lag using the developed knee assistive instrument,” in *2016 9th International Conference on Human System Interactions (HSI)*, 2016, pp. 386–392.

[46] N. V. Divekar, E. H. Hinojosa, J. Zhang, and R. D. Gregg, “A task-agnostic knee exoskeleton for reducing osteoarthritis pain across activities of daily life: A pilot study,” in *IEEE International Conference on Rehabilitation Robotics (ICORR)*, 2025, pp. 1437–1443.

[47] D. S. Reinsdorf, C. A. Richburg, J. M. Czerniecki, and P. M. Aubin, “Development of a robotic unloader brace for investigation of conservative treatment of medial knee osteoarthritis,” in *2019 IEEE International Conference on Rehabilitation Robotics (ICORR)*, 2019, pp. 931–937.

[48] A. Javanfar and M. Bamdad, “Knee brace control for reduction of medial compartment load,” in *2022 10th RSI International Conference on Robotics and Mechatronics (ICRoM)*, 2022, pp. 533–538.

[49] A. R. Budarick, B. E. MacKeil, S. Fitzgerald, and C. D. Cowper-Smith, “Design evaluation of a novel multicompartment unloader knee brace,” *Journal of Biomechanical Engineering*, vol. 142, no. 1, 2020.

[50] M. Bamdad and A. Javanfar, “Computational control strategy for reducing medial compartment load in knee bracing with embedded actuator,” *Actuators*, vol. 12, no. 6, p. 256, 2023.

[51] A. Elias-Neto, A. C. Villa-Parra, T. Botelho, A. Frizera-Neto, and T. Bastos-Filho, “A robotic lower-limb exoskeleton for rehabilitation,” in *IFMBE Proceedings*, vol. 75, 2020, pp. 1130–1136.

[52] J. C. Yepes, J. M. Saldarriaga, J. M. Velez, V. Z. Perez, and M. J. Betancur, “A hardware-in-the-loop simulation study of a mechatronic system for anterior cruciate ligament injuries rehabilitation,” in *10th International Conference on Biomedical Electronics and Devices (BIODEVICES)*, 2017, pp. 69–80.

[53] Q. Sun, W. Feng, H. Chen, Z. Wang, L. Cui, and W. Ren, “Design and performance evaluation of a knee assist exoskeleton based on bowden cables transmission,” in *2025 9th International Conference on Robotics, Control and Automation (ICRCA)*, 2025, pp. 11–17.

[54] R. A. M. Alalwani and A. S. Ghafari, “Design and prototyping of an robotic exoskeleton for rehabilitation after total knee arthroplasty,” in *3rd International Conference on Automation, Robotics and Computer Engineering (ICARCE)*, 2024, pp. 55–59.

[55] X. Wu *et al.*, “Design and validation of an underactuated modular exoskeleton with multijoint coupling assistance for enhancing human locomotion with reduced hip impact,” *IEEE/ASME Transactions on Mechatronics*, pp. 1–12, 2025.

[56] E. A. A. Salcido, D. Centeno-Barreda, Y. Rosales, R. Lopez-Gutierrez, S. Salazar, and R. Lozano, “Design of a lower limb exoskeleton: Robust control, simulation and experimental results,” *Algorithms*, vol. 16, no. 9, p. 449, 2023.

[57] Y. Li, Y. Wang, S. Yuan, and Y. Fei, “Design, modeling, and control of a novel soft-rigid knee joint robot for assisting motion,” *Robotica*, vol. 42, no. 3, pp. 817–832, 2024.

[58] P. Kabir, M. Zareinejad, H. A. Talebi, M. Soleimanifar, M. Mavajian, and M. Ashoori, “Development and evaluation of a soft wearable knee rehabilitation apparatus,” in *2022 10th RSI International Conference on Robotics and Mechatronics (ICRoM)*, 2022, pp. 159–164.

[59] K. Nandhini, V. Nivetha, R. Sabari, M. G. Sumithra, and S. Velmurugan, “Exoskeleton knee extension assist suspension brace for reducing joint pain in elderly aged population,” in *2023 7th International Conference on Intelligent Computing and Control Systems (ICICCS)*, 2023, pp. 1206–1210.

[60] S. D. Viswam, S. Mohan, and S. S. Suneesh, “Next-gen robotic knee rehabilitation exoskeleton technology,” in *2024 IEEE Students Conference on Engineering and Systems (SCES)*, 2024.

[61] Z. Su, W. Gao, and Y. Gao, “Research and design of a lower limb rehabilitation exoskeleton robot driven by cables,” in *2024 IEEE International Conference on Signal, Information and Data Processing (ICSIDP)*, 2024.

[62] S. Aghajani-Fesharaki, F. Farahmand, H. Saeedi, and E. Abdollahy, “Design, implementation and testing of a novel prototype orthotic knee joint with two degrees of freedom in a patient with medial knee osteoarthritis,” *Sultan Qaboos University Medical Journal*, vol. 18, no. 4, pp. e524–e528, 2018.

A

Appendix - All search terms

D_1 (device / exoskeleton terms):
"exoskeleton" OR "rehabilitation robot" OR "wearable robot" OR "assistive robot" OR "powered orthosis" OR "robotic orthosis" OR "exosuit" OR ("rehabilitation" AND "exosuit") OR "robot-assisted therapy" OR "robot-aided" OR "wearable assistive device"

D_2 (orthopedic and rehabilitation terms):
"joint degeneration" OR "gait dysfunction" OR "mobility restoration" OR "orthopedic rehabilitation" OR "bone fracture" OR "joint injury" OR "osteoarthritis" OR "knee osteoarthritis" OR "postoperative recovery" OR "postoperative rehabilitation" OR "knee surgery" OR "knee arthroplasty" OR "total knee replacement" OR "ACL" OR "anterior cruciate ligament" OR "meniscus injury" OR "meniscal tear" OR "ligament injury" OR "knee dysfunction" OR "knee effusion"

In PubMed, D_2 was further expanded with the following MeSH terms:
"Orthopedic Procedures"[MeSH] OR "Osteoarthritis, Knee"[MeSH] OR "Fractures, Bone"[MeSH] OR "Anterior Cruciate Ligament Reconstruction"[MeSH] OR "Knee Prosthesis"[MeSH] OR "Meniscus, Knee"[MeSH] OR "Neurologic Rehabilitation"[MeSH] OR "Stroke Rehabilitation"[MeSH] OR "Parkinson Disease"[MeSH].

D_3 (design / control / evaluation terms):
"design" OR "prototype" OR "development" OR "control" OR "evaluation" OR "validation"

B

Appendix - Other results in bar charts

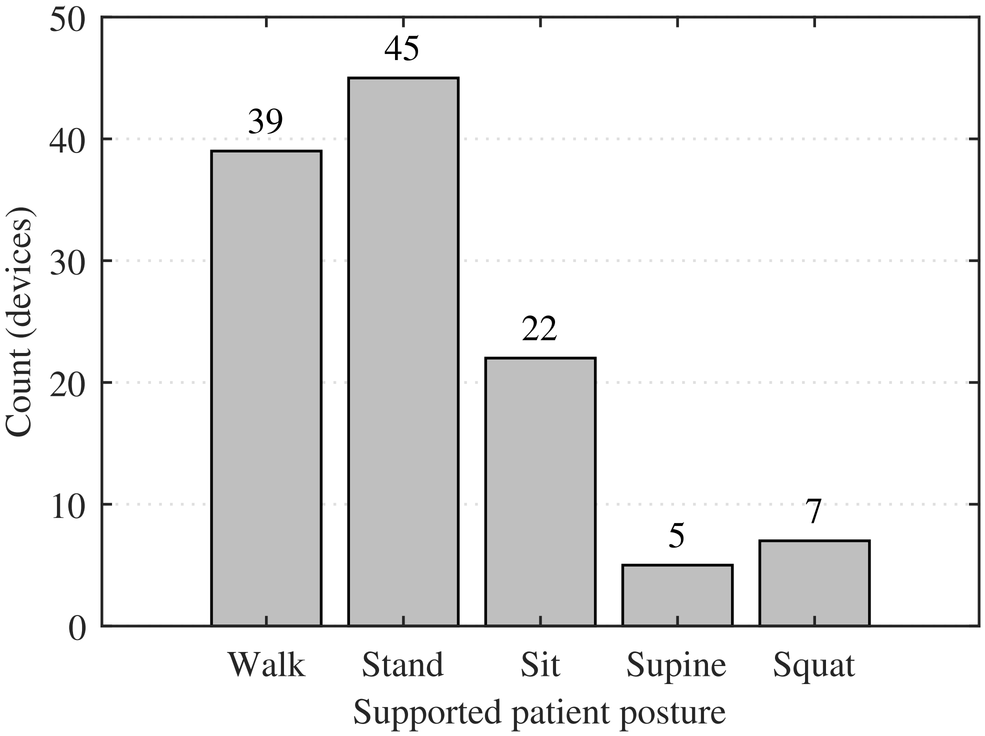

Figure B.1: Number of publications by Supported Postures
Although the patient posture supported by the device is not directly related to the quality of the device, this article also presents it as a possible reference.

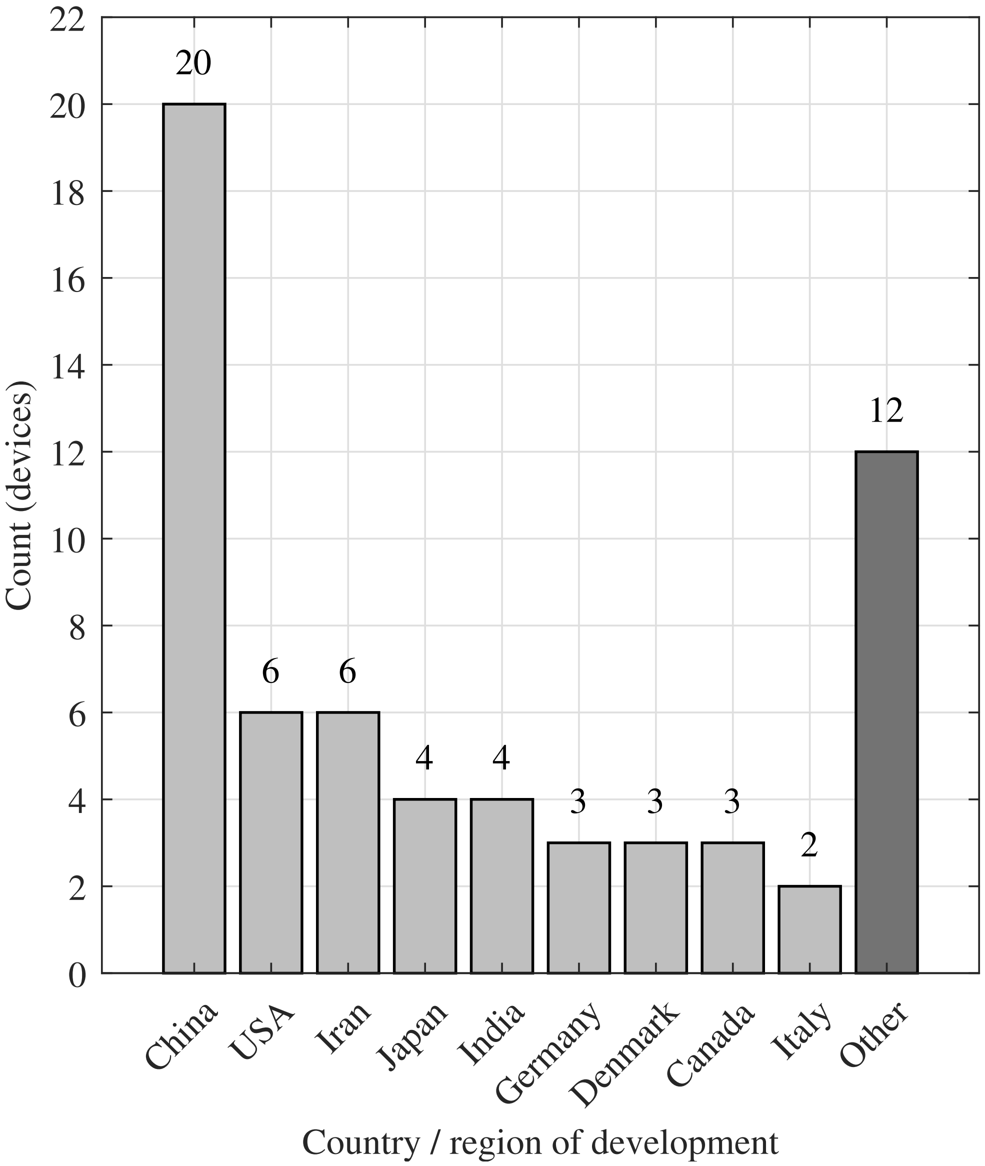

Figure B.2: Number of publications by country.
Chinese researchers has been most sensitive to and made the greatest contribution to the explosive development in this field in recent years.

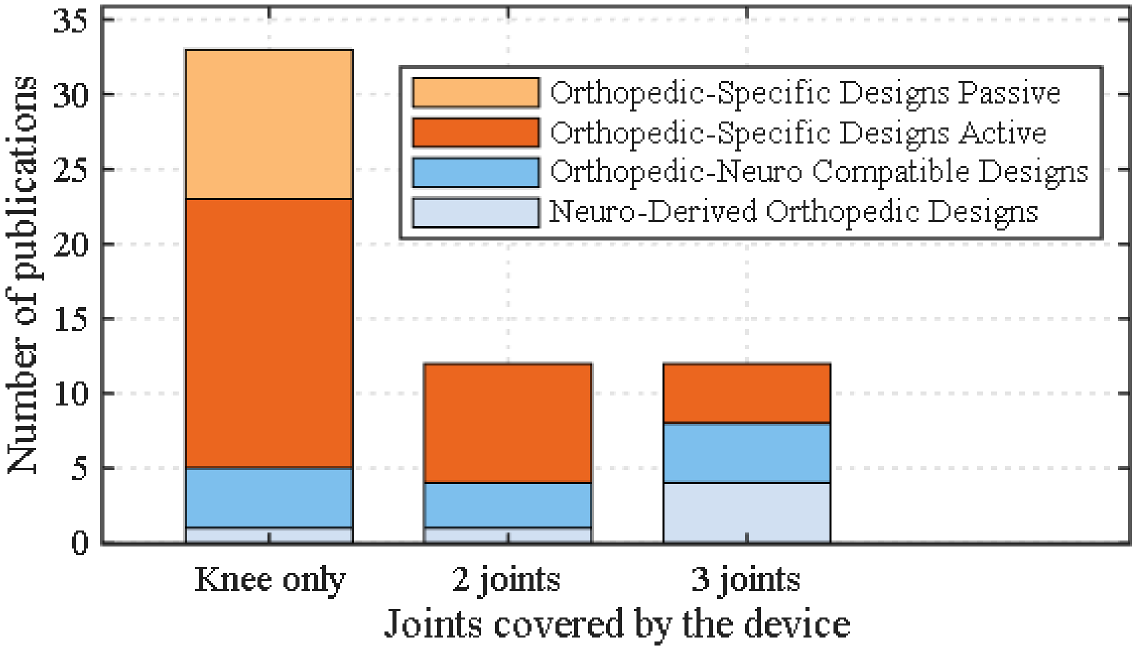

Figure B.3: Shows how many joints in the hip, knee, and ankle are included in the device.

Non-orthopedic-specific devices tend to be larger in terms of the number of joints. Since multi-joint coordination therapy is not the subject of this study, this plot is for possible reference only.

C

Appendix - Main Data Extraction

Table C.1: Comprehensive Summary of Included Orthopedic Knee Exoskeletons (n=57).

Columns: 1-ID, 2-Title, 3-Device Type, 4-Refence, 5-Single or Both Legs Device, 6-Knee Support Structure, 7-TRL, 8-Actuation.
OSD = Orthopedic-Specific Designs; ONCD = Orthopedic-Neuro Compatible Designs; NDOD = Neuro-Derived Orthopedic Designs.
Unilateral = single leg; Bilateral = both two legs, Lat = Lateral; Med = Medial

No.	**Title**	**Type**	**Ref**	**Legs config**	**Support**	**TRL**	**Drive**
1	Design and Analysis of a Single Leg	NDOD	[18]	Unilateral	Lat Rigid	TRL 2–3	motor
2	Design and Development of a knee	NDOD	[32]	Bilateral	Lat Rigid	TRL 3–4	motor
3	Dimensional and Workspace Analysis	NDOD	[21]	Unilateral	None	TRL 3–4	motor
4	Dynamic Locomotion Synchronization	NDOD	[22]	Bilateral	Lat Rigid	TRL 4–5	motor
5	Exoskeleton Suit Supports the user	NDOD	[44]	Bilateral	Lat Rigid	TRL 3	motor
6	Feasibility of supplemental robotics	NDOD	[39]	Unilateral	None	TRL 7	motor
7	A Robotic Lower-Limb Exoskeleton	ONCD	[51]	Unilateral	Med-Lat Rigid	TRL 3–4	motor
8	BioMot exoskeleton — Towards a	ONCD	[1]	Bilateral	Lat Rigid	TRL 3–4	motor
9	Design and control of a novel device	ONCD	[3]	Unilateral	Lat Rigid	TRL 3–4	motor
10	Design and Simulation of a Robot	ONCD	[26]	Unilateral	Lat Rigid	TRL 3–4	motor
11	Design of a Biomimetic Knee Joint	ONCD	[24]	Unilateral	Med-Lat Rigid	TRL 4–5	motor
12	Design, Modeling and Control of	ONCD	[25]	Unilateral	Lat Rigid	TRL 2–3	motor
13	Development of a Compliant Lower	ONCD	[28]	Unilateral	None	TRL 3–4	motor
14	Investigation of Hybrid Mechanisms	ONCD	[36]	Unilateral	None	TRL 3–4	motor
15	iT-Knee: An Exoskeleton with Int	ONCD	[37]	Unilateral	Lat Rigid	TRL 3–4	other
16	Prototype Development of an Assist	ONCD	[19]	Unilateral	Lat Rigid	TRL 3–4	motor
17	Upper and Lower limb interchange	ONCD	[20]	Unilateral	Lat Rigid	TRL 2–3	motor
18	A Hardware-in-the-loop Simulation	ActiveOSD	[52]	Bilateral	Lat Rigid	TRL 2–3	motor
19	A Multimodal Knee Exoskeleton	ActiveOSD	[11]	Unilateral	Med-Lat Rigid	TRL 3–4	motor
20	A Task-Agnostic Knee Exoskeleton	ActiveOSD	[46]	Bilateral	Lat Rigid	TRL 5	other

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Table C.1 – *Continued from previous page*

No.	**Title**	**Type**	**Ref**	**Legs**	**Support**	**TRL**	**Drive**
21	Automatic rehabilitation of the	ActiveOSD	[45]	Unilateral	Lat Rigid	TRL 5–6	motor
22	Bionic Design and Optimization	ActiveOSD	[38]	Unilateral	Med-Lat Rigid	TRL 2–3	motor
23	Computational Control Strategy	ActiveOSD	[50]	Unilateral	Med-Lat Rigid	TRL 2–3	motor
24	Conceptual Design and Preliminary	ActiveOSD	[33]	Unilateral	Med-Lat Rigid	TRL 3–4	other
25	Design and Evaluation of a Soft	ActiveOSD	[15]	Unilateral	Rear Rigid	TRL 4	motor
26	Design and Performance Evaluation	ActiveOSD	[53]	Bilateral	Lat Rigid	TRL 4	motor
27	Design and Preliminary Implement	ActiveOSD	[27]	Unilateral	Med-Lat Soft	TRL 3–4	motor
28	Design and Prototyping of an R	ActiveOSD	[54]	Unilateral	Lat Rigid	TRL 6–7	Pneumatic
29	Design and Validation of an Un	ActiveOSD	[55]	Bilateral	Lat Rigid	TRL 4	motor
30	Design of a Lower Limb Exoskel	ActiveOSD	[56]	Bilateral	Lat Rigid	TRL 3–4	motor
31	Design, modeling, and control	ActiveOSD	[57]	Unilateral	Med-Lat Mixed	TRL 3–4	motor
32	Development and Evaluation of	ActiveOSD	[58]	Unilateral	Soft+Lat Rigid	TRL 3–4	Pneumatic
33	Development and Functional Test	ActiveOSD	[43]	Unilateral	Med-Lat Rigid	TRL 3–4	Pneumatic
34	Development of a Robotic Unload	ActiveOSD	[47]	Unilateral	Med-Lat Rigid	TRL 3–4	motor
35	Development of a Switchable Wear	ActiveOSD	[10]	Unilateral	Lat Rigid	TRL 4–5	motor
36	Development of an Exosuit Knee	ActiveOSD	[12]	Unilateral	Soft	TRL 4	motor
37	Effect of equipping an unloaded	ActiveOSD	[41]	Unilateral	Soft+Lat Rigid	TRL 6	motor
38	EMG and EEG Sensor-Based Exoskel	ActiveOSD	[31]	Unilateral	Lat Rigid	TRL 3–4	motor
39	Exoskeleton Knee Extension Assist	ActiveOSD	[59]	Unilateral	Med-Lat Rigid	TRL 3–4	motor
40	Knee Brace control for Reduction	ActiveOSD	[48]	Unilateral	Med-Lat Rigid	TRL 2–3	motor
41	Load-bearing optimization for	ActiveOSD	[34]	Bilateral	Lat Rigid	TRL 2–3	other
42	Mechanism Design of Cable-driven	ActiveOSD	[17]	Unilateral	Med-Lat Rigid	TRL 2–3	motor
43	Next-Gen Robotic Knee Rehab	ActiveOSD	[60]	Unilateral	Med-Lat Rigid	TRL 2–3	motor
44	Preliminary Development of a Rob	ActiveOSD	[4]	Bilateral	Med-Lat Rigid	TRL 3–4	motor
45	Real-Time Gait Symmetry Enhance	ActiveOSD	[16]	Unilateral	Lat Rigid	TRL 4	motor
46	Research and Design of a Lower	ActiveOSD	[61]	Unilateral	Lat Rigid	TRL 3–4	motor
47	Structural design and intelligent	ActiveOSD	[2]	Bilateral	Lat Rigid	TRL 2–3	motor
48	Distraction Knee-Brace and a Rob	PassiveOSD	[14]	Unilateral	Med-Lat Rigid	TRL 3–4	Pneumatic
49	Biomechanical evaluation of a	PassiveOSD	[13]	Unilateral	Med-Lat Rigid	TRL 6	Passive
50	Design and experimental study	PassiveOSD	[9]	Unilateral	Lat Rigid	TRL 3–4	Passive
51	Design Evaluation of a Novel Mec	PassiveOSD	[49]	Unilateral	Med-Lat Rigid	TRL 8	Passive
52	Design of Polycentric Assistive	PassiveOSD	[23]	Unilateral	Med-Lat Rigid	TRL 3–4	Passive
53	Design of Wearable KOA Postop	PassiveOSD	[42]	Unilateral	Lat Rigid	TRL 3–4	other
54	Design, Implementation and Test	PassiveOSD	[62]	Unilateral	Med-Lat Rigid	TRL 4–5	Passive
55	Functional Resistance Training	PassiveOSD	[30]	Unilateral	Med-Lat Rigid	TRL 4–5	Passive
56	Innovative rehabilitative brace	PassiveOSD	[29]	Unilateral	Med-Lat Rigid	TRL 7	Passive
57	The 2- and 8-week effects of dev	PassiveOSD	[40]	Unilateral	Med-Lat Rigid	TRL 8	Passive

D

Appendix - TRL of European Commission

Table D.1: TRL Example from hardware and system technologies

TRL	**Definition Summary**	**Example from hardware and system technologies**
TRL 1	Define basic properties	Scientific research that is translated into applied activity, having paper studies of basic properties.
TRL 2	Analytical study	The resulted applications are mainly speculative, with no proof of concepts to support assumptions. At this level, technology is limited to analytical studies.
TRL 3	Proof of concept	Active R&D activities, including analytical and laboratory studies to physically validate the previous analytical predictions and assumptions. The first proof of concept.
TRL 4	Pre-prototype	The resulting system integrates basic technological components that work together in a low fidelity compared with the eventual system. This “ugly prototype” or “pre-prototype” includes integration of ad hoc hardware in the laboratory environment.
TRL 5	Pre-prototype tested in lab	Integration of components with reasonable and realistic supporting elements for testing in a simulated environment. High fidelity is achieved in laboratory.

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TRL	**Definition Summary**	**Example from hardware and system technologies**
TRL 6	Prototype tested in relevant environment	The technology is tested in a relevant environment. It starts to be considered as a representative prototype to be tested in a high-fidelity laboratory environment or in a simulated operational environment.
TRL 7	Approved prototype	Testing is moved to operational environments such as a vehicle or machines. This is the first fully approved prototype.
TRL 8	Pre-serial manufacturing	Technology is proven to work in its final form and under expected operational conditions. Tests and evaluation of the system are made in its intended or pre-production configuration. Design specifications, including quality and safety conditions along with operational suitability are evaluated. At this stage pre-serial manufacturing is intended to overcome any future mass production issues.
TRL 9	Product on market	Technology is shaped in its actual application, meeting production configuration and under real conditions such as those identified during operational tests and evaluation.

E

Appendix - Excerpts of Rehabilitation Needs - 57 Articles

Table E.1: Overview of Rehabilitation Needs Understanding in Reviewed Literature

ID	Document Name	Key Sentence on Rehabilitation Needs Understanding
Neuro-Derived Orthopedic Design		
1	Design and Analysis of a Single Lower Limb Rehabilitation Exoskeleton Robot [18]	The essential requirement of human motor ability rehabilitation is to be close to the original motor function and physical state.
2	Design and Development of a Knee Rehabilitation Exoskeleton with Four-Bar Linkage Actuation [32]	Active exoskeletons provide the additional required force for motion and gait correction, especially for patients who have suffered from limb impairment.
3	Dimensional and Workspace Analysis of RAISE Rehabilitation Robot [21]	The major benefit of using robotic technologies in post stroke rehabilitation process is the ability to deliver high intensity customized training which improves motor and locomotor function.
4	Dynamic Locomotion Synchronization and Fuzzy Control of a Lower Limb Exoskeleton [22]	Research has shown that body physical characteristics or pathological limb disorders vary among different individuals, making it necessary to conduct targeted gait training or personalized movement assistance.

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Table E.1 – continued from previous page

ID	Document Name	Key Sentence on Rehabilitation Needs Understanding
5	Exoskeleton Suit Supports the Movement [44]	The focus has been drawn to standing and walking, which will result in a better functioning of the patient's body.
6	Feasibility of supplemental robot-assisted knee flexion exercise following total knee arthroplasty [39]	However, active exercise can be disadvantageous, as it often causes pain and makes completion of the exercise difficult. Therefore, a method by which active exercise can be performed without pain is needed.
Orthopedic-Neurological Compatible Design		
7	BioMot exoskeleton — Towards a smart wearable robot for symbiotic human-robot interaction [1]	By employing a simple torque control strategy, the exoskeleton can be used to deliver user-specific assistance, both in gait rehabilitation and in assisting people suffering musculoskeletal impairments.
8	Design and control of a novel powered wearable knee exoskeleton for lower limb rehabilitation [3]	Lower limb rehabilitation is a critical aspect of recovery following a wide range of injuries and musculoskeletal disorders, including stroke, ligament tears, and osteoarthritis.
9	Design and Simulation of a Robotic Knee Exoskeleton with a Variable Stiffness Actuator for Gait Rehabilitation [26]	Patients with knee impairments caused by neurological or orthopedic diseases such as a stroke, spinal cord injury, or physical injury are at a high risk of secondary complications, which include muscular dystrophy and hemiplegia.
10	Design of a Biomimetic Knee Joint Orthosis for Motion Rehabilitation Assistance [24]	Bionic knee orthotic robots can meet clinical needs that traditional passive orthoses currently fail to address, such as correcting abnormal gaits in cerebral palsy patients or supporting post-surgery recovery.
11	Design, Modelling and Control of an Active Weight-Bearing Knee Exoskeleton with a Series Elastic Actuator [25]	Lower Limb disorders may be caused by excessive sports' practice, diseases such as stroke, spinal cord injury and other deteriorating conditions due to aging.
12	Development of a Compliant Lower-Limb Rehabilitation Robot Using Underactuated Mechanism [28]	Thus, it is still a challenge to design a portable and compliant LLRR with multiple exercises for patients after orthopedic surgery or stroke, especially in outpatient and home settings.

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Table E.1 – continued from previous page

ID	Document Name	Key Sentence on Rehabilitation Needs Understanding
13	Investigation of Hybrid Mechanism for Knee Exoskeleton Rehabilitation Device [36]	Rehabilitation is essential for knee injuries, which can occur at any age due to accidents, sports activities, strokes, osteoarthritis, or the natural process of degeneration.
14	iT-Knee An exoskeleton with ideal torque transmission interface for ergonomic power augmentation [37]	Rehabilitation exoskeletons aim at recovering the neuro-musculoskeletal function of stroke or post-surgical patients.
15	Prototype Development of an Assistive Lower Limb Exoskeleton [19]	The objective of the current study is, therefore, to design and develop a lower-limb exoskeleton to assist the patients with SCI, Osteoarthritis, Polio patients and patients with other neurological disorders.
16	Upper and Lower limb interchangeable Exoskeleton-robot for post stroke rehabilitation [20]	The recent progress in a powered exoskeleton has been focused on many regions within the medical sectors, including the purpose of load augmentation for assisting trauma patients, paraplegic patients, hemiplegic patients, spinal cord injured patients and rehabilitation purposes.
17	A Robotic Lower-Limb Exoskeleton for Rehabilitation [51]	The proposed protocol is progressive and explores the different control strategies implemented in ALLOR: passive, mobilization, assisted, active and resisted, which are suitable for individual's rehabilitation in three scenarios addressed in this work: stroke, total knee arthroplasty, and anterior cruciate ligament reconstruction.
Orthopedic Specific Design (No Active Function)		
18	A Distraction Knee-Brace and a Robotic Testbed for Tibiofemoral Load Reduction During Squatting [14]	Indeed, the development of advanced treatment modalities that focus on tissue regeneration highlights the need to reduce the load on the joint in order to create a conducive environment for cartilage healing and repair.
19	Biomechanical evaluation of a novel dynamic posterior cruciate ligament brace [13]	To prevent the loss of knee joint function and muscle activity often associated with this, a flexible knee brace has been developed that allows an adjustable anteriorly directed force to be applied to the calf in order to prevent posterior tibial translation.
20	Design and experimental study of a wearable passive rehabilitation exoskeleton for post-TKA patients [9]	In recent years, studies in rehabilitation medicine have shown that post-surgical rehabilitation training should begin as early as possible, transitioning from passive training to semi-active and eventually fully active training.

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ID	Document Name	Key Sentence on Rehabilitation Needs Understanding
21	Design Evaluation of a Novel Multicompartment Unloader Knee Brace [49]	Unfortunately, because a low percentage (4%) of patients have unicompartmental TFOA, traditional unloader braces are not indicated for most patients with knee OA who are likely to have patellofemoral or multicompartmental disease.
22	Design of Polycentric Assistive Device for Knee Joint [23]	It is difficult to adequately fit the natural motion of human knee joint only using a mechanical joint with a single axis.
23	Design of Wearable KOA Postoperative Rehabilitation Training Equipment [42]	Moreover, KOA patients have different rehabilitation needs during the recovery period, requiring both assistance in lifting the leg and resistance training.
24	Design, Implementation and Testing of a Novel Prototype Orthotic Knee Joint [62]	This mismatch can result in the pistoning of the brace components over the lower limb, constraining the wearer's normal range of motion... and potentially leading to misalignment... and uncomfortable pressure on the skin.
25	Functional Resistance Training to Improve Knee Strength [30]	A key reason for incomplete recovery could be that interventions addressing strength and activation deficits are typically performed in a "nonfunctional" manner (eg, exercises performed in seated position), which is less than optimal for inducing transfer of benefits to functional activities such as walking because of practice specificity.
26	Innovative rehabilitative bracing with applied resistance [29]	This brace... is equipped with a polycentric junction spring system that creates a 2.5 kg resistance to knee flexion, thus promoting the activity of flexor muscles during the gait cycle with a complete range of motion.
27	The 2- and 8-week effects of decompressive brace use in people with medial compartment knee osteoarthritis [40]	It is believed that as the KAM [Knee Adduction Moment] increases, so does the compressive load between the femur and tibia within the medial compartment which can be theorized as contributing to increased pain and symptoms, decreased activity, and limited participation.
Orthopedic Specific Design (Active Function)		
28	Bionic Design and Optimization of a Rigid-Soft Hybrid Knee Exoskeleton [38]	Traditional single-axis rigid exoskeletons suffer from issues such as large joint volume, high inertia, and joint misalignment, significantly reducing wearer comfort.

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ID	**Document Name**	**Key Sentence on Rehabilitation Needs Understanding**
29	Computational Control Strategy for Reducing Medial Compartment Load in Knee Bracing with Embedded Actuator [50]	However, conventional valgus unloader braces, while reducing load on the medial compartment, inadvertently increase load on the lateral compartment due to the constant abduction moment applied throughout the gait cycle.
30	Conceptual Design and Preliminary Experiment of an Orthopedic Rehabilitation Exoskeleton Based on the Coupled Movable Pulley Mechanism (CMPM) [33]	During the bone tissue proliferative phase following fracture surgery, axial mechanical stimulation has been shown to facilitate bone healing.
31	Design and Evaluation of a Soft Knee Exosuit for Reducing Knee Medial Compartment Load During Walking [15]	The knee joint experiences substantial moment in the frontal plane during walking, with the medial compartment bearing a greater load, potentially contributing to the development of knee osteoarthritis.
32	Design and Performance Evaluation of a Knee Assist Exoskeleton Based on Bowden Cables Transmission [53]	In response to the problem that previous rope driven exoskeletons could not achieve bidirectional assistance using only a single Bowden cable... ultimately achieving bidirectional assistance function for the knee joint.
33	Design and Preliminary Implementation of an Air Microfluidics Enabled Soft Robotic Knee Brace Towards the Management of Osteoarthritis [27]	The unloader knee brace provides dynamic response during the gait cycle, where a three-point leverage torque is provided only during the stance phase to contribute to joint stability when required and enhance comfort and compliance.
34	A Hardware-in-the-loop Simulation Study of a Mechatronic System for Anterior Cruciate Ligament Injuries Rehabilitation [52]	One of the main ligaments of the knee is the Anterior Cruciate Ligament (ACL), which is critical to maintain stability and regular gait patterns.
35	A Multimodal Knee Exoskeleton for Fracture Rehabilitation [11]	The system aims to alleviate the adhesion and stiffness of knee joint, improving the range of motion and restoring lower limb mobility.

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ID	Document Name	Key Sentence on Rehabilitation Needs Understanding
36	A Task-Agnostic Knee Exoskeleton for Reducing Osteoarthritis Pain Across Activities of Daily Life [46]	These movements require high knee extension torques, leading to increased quadriceps activation and patellofemoral joint compression, which aggravates pain.
37	Automatic rehabilitation of the Extension Lag using the developed knee assistive instrument [45]	Patients with Extension Lag cannot extend their knee straightly single-handedly... However, they can extend their knee without pain, if the other (a physical therapist (PT)) stretch the knee.
38	Design of a Lower Limb Exoskeleton Robust Control, Simulation and Experimental Results [56]	The goal of the control law is to follow the trajectory of a straight leg extension routine in a sitting position... This routine is commonly used to rehabilitate an injury on an Anterior Cruciate Ligament (ACL) and it is applied to the knee and ankle joints.
39	Design, modeling, and control of a novel soft-rigid knee joint robot for assisting motion [57]	Wearing on the outer side of the joint or inner side of the joint cannot align the robot's rotation axis with the human joints, so this may generate shear force on the human joints during the assisting process, affecting the safety and wearing comfort of the robot.
40	Development and Evaluation of a Soft Wearable Knee Rehabilitation Apparatus [58]	Furthermore, there is a misalignment between the knee joint and the CPM joint... and the flexing knee generates a migrating medial-lateral axis of rotation... Therefore, there is a need for a lightweight, easy-to-fit device that is compliant with the human lower limb and does not have a fixed center of rotation.
41	Development and Functional Testing of an Unloading Concept for Knee Osteoarthritis Patients A Pilot Study [43]	This paper presents a brace concept that aims to reduce the first peak total KCF [Knee Compressive Force] during gait through muscle compensation by applying an external knee extension moment.
42	Development of a Robotic Unloader Brace for Investigation of Conservative Treatment of Medial Knee Osteoarthritis [47]	We propose that brace utilization and effectiveness could be improved with a robotic device that intelligently modulates brace abduction moment in real time over the course of a step, day, and year to better protect the knee joint, improve pain relief, and increase comfort.
43	Development of a Switchable Wearable Robot for Rehabilitation After Surgery of Knee [10]	The motion of the knee joint is not simple rotation type, and it consists of rotation and slide motion... We developed the asymmetrical gear corresponding with roll-back motion.

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44	Development of an Exosuit Knee Brace for Anterior Cruciate Ligament Injury [12]	For example, simply reducing brace applied forces to near zero during the swing phase would reduce the brace pressure-impulse... and allow for better deep tissue oxygenation... [and] lower the pistoning forces that cause migration.
45	Effect of equipping an unloader knee orthosis [41]	However, despite its benefits, using knee orthoses can reduce knee muscle activity... which may result in muscular atrophy in the long term... Muscular atrophy has been shown to boost knee osteoarthritis development and progression rate.
46	Design and Prototyping of an Robotic Exoskeleton for Rehabilitation after Total Knee Arthroplasty [54]	In fact, the flexion/extension of the knee joint is always linked to the anterior/posterior movement of the knee joint, allowing for both sliding and rotation between the femur and tibia.
47	Design and Validation of an Underactuated Modular Exoskeleton [55]	This type of untethered exoskeleton presents certain issues; the additional weight increases the distal inertia of the body, which may lead to compensatory behaviors in other joints [like the hip].
48	EMG and EEG Sensor-Based Exoskeleton for Knee Injury Rehabilitation [31]	Feedback is applied for tailoring rehabilitation activities for each patient, taking into account individual's physical condition in a way that will ensure more successful and individual recovery process.
49	Exoskeleton Knee Extension Assist Suspension Brace for Reducing Joint Pain in Elderly Aged Population [59]	This compression between the bones can be reduced by extending the knee joint which can provide pain relief.
50	Knee Brace control for Reduction of Medial Compartment Load [48]	Therefore, the new unloader brace corrects the abduction angle via the embedded mechanism and applies unloader force along with attention to the contact point and cartilage penetration depth.
51	Load-bearing optimization for customized exoskeleton design based on kinematic gait reconstruction [34]	For people with acute joint injury, it is no longer probable to obtain the movement gait via computer vision... the 3D reconstruction can be executed from the CT... in order to generate micro-morphology of the joint occlusion.
52	Mechanism Design of Cable-driven Multi-functional Knee Osteoarthritis Rehabilitation Robot [17]	For patients with knee osteoarthritis with varus and valgus malformations, varus and valgus will change the force distribution within the knee joint and aggravate the symptoms of knee osteoarthritis.

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ID	Document Name	Key Sentence on Rehabilitation Needs Understanding
53	Next-Gen Robotic Knee Rehabilitation Exoskeleton Technology [60]	This work introduces a Cable-Controlled exoskeleton technology... adaptable to patients who are recovering from knee surgery and having weak muscles, and engineered to facilitate targeted support during knee rehabilitation exercises in a sitting posture.
54	Preliminary Development of a Robotic Hip-Knee Exoskeleton with 3D-Printed Backdrivable Actuators [4]	There is a large and growing population of persons who could benefit from partial locomotor assistance, such as older adults and/or persons with physical disabilities due to musculoskeletal conditions (e.g., osteoarthritis).
55	Real-Time Gait Symmetry Enhancement in People with Unilateral Knee Injuries Using Deep Learning for Modulation of Knee Exoskeleton [16]	Due to knee pain and muscle weakness, patients undergoing total knee replacement (TKR) often exhibit significant claudication... and significant gait asymmetry.
56	Research and Design of a Lower Limb Rehabilitation Exoskeleton Robot Driven by Cables [61]	During the healing process of bone tissue after surgery, in the callus formation period... the application of mechanical stimulation at this time can significantly promote the healing effect compared to no stimulation.
57	Structural design and intelligent control of lower limb knee rehabilitation exoskeleton based on motion intention estimation method [2]	Due to the complexity and differences in physiological structure, there are often alignment errors between the center of the rehabilitation exoskeleton joints and the actual human joints, thus reducing the impact of such errors through compliant joint design.

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