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PURE-MECHANICAL ANTI-VIBRATION SYSTEMS FOR HAND TREMOR IN PARKINSON'S DISEASE: REVIEW AND BIBLIOMETRIC ANALYSIS

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Abstract - This comprehensive review and bibliometric analysis synthesize the recent literature and patent landscape regarding purely mechanical anti-vibration systems for mitigating debilitating hand tremor associated with Parkinson's disease (PD). These non-invasive devices, which utilize fundamental engineering principles such as passive damping and gyroscopic effects, offer substantial practical advantages over mechatronic or pharmacological solutions, including energy independence, inherent robustness, and operational simplicity. The analysis validates the capacity of these systems, with reported amplitude reductions of up to 93% in some controlled studies, to substantially reduce oscillation amplitude, leading to noticeable enhancement of patients' daily functioning. However, critical challenges persist. Bibliometric analysis highlights a major research gap: the imperative for extensive, rigorous clinical validation studies to prove long-term efficacy and safety in real-world settings. The primary emerging research directions are therefore focused on addressing user-centric needs through advanced design (aesthetics, comfort, and miniaturization) and fulfilling the need for robust, long-term clinical trials. Future development must prioritize advanced personalization and adaptability to account for the inherent variability of Parkinsonian tremor.

Keywords: Parkinson's disease, Tremor management, Anti-vibration systems, Pure-mechanical devices, Non-invasive therapy, Passive damping, Gyroscopic effect, Orthoses, Rehabilitation technology.

1. Introduction

Parkinson's disease (PD) is a progressive neurodegenerative disorder and the second most common neurological condition worldwide. It affects around 10 million people and is expected to become more prevalent in the coming decades as the population ages [1]. PD is characterised by the degeneration of dopaminergic neurons in the substantia nigra and manifests through four cardinal motor symptoms: bradykinesia (slowness of movement), rigidity, postural instability and tremor. Of these, tremor — especially resting tremor of the hands — is one of the most visible and disabling manifestations and has a profound impact on patients' quality of life [2]. This involuntary tremor, predominantly occurring at frequencies between 4 and 6 Hz, significantly interferes with essential daily activities, ranging from basic tasks such as eating and personal hygiene to more complex activities like writing, using a computer, or performing professional duties. The consequences extend beyond the physical realm, leading to frustration, loss of autonomy, social stigmatisation and increased dependence on caregivers [2], [3].

Current therapeutic strategies for Parkinsonian tremor include pharmacological approaches, predominantly dopaminergic (e.g. levodopa and dopaminergic agonists), and surgical interventions such as deep brain stimulation (DBS) in severe cases [3]. While these treatments can substantially alleviate motor symptoms, they have significant

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limitations. Pharmacological therapy can induce adverse side effects (e.g. dyskinesia, hallucinations and nausea) and may lose efficacy over time, necessitating complex dose adjustments. Surgical interventions are invasive and associated with perioperative and postoperative risks and prohibitive costs. They are also not suitable for all patients [3], [4]. The considerable number of patients with unmet needs or contraindications to existing therapies has stimulated the search for complementary or alternative solutions. The focus has shifted towards lower-risk, non-invasive approaches that are more accessible and aimed at directly improving tremor symptoms.

In this context, purely mechanical anti-vibration systems have emerged as a promising class of non-invasive devices, offering a distinct approach to tremor suppression based on passive or minimally active engineering principles [4]. Unlike pharmacological solutions or complex mechatronic devices, which integrate active electronics, sensors, actuators and software, purely mechanical systems rely on the inherent physical and mechanical properties to counteract the unwanted oscillatory movements of the affected limb. Examples of these innovations range from weighted utensils and simple orthoses to more sophisticated concepts that utilise vibration damping principles, such as tuned mass dampers (TMDs) or gyroscopic effects.

A central and substantial argument in favor of purely mechanical systems, compared to mechatronic ones, derives from multiple practical and usability considerations [5], [6], [7], [8], especially for a patient population that is often elderly and has potential cognitive deficits associated PD.

First, energy independence is a major advantage and an essential simplification; the absence of the need to charge batteries eliminates a recurring cognitive and logistical burden, ensuring constant availability of the device and reducing anxiety related to energy autonomy [9]. This is important for patients with memory impairment, planning difficulties, or diminished executive functions, for whom the periodic management of a charging cycle, connecting to power outlets, or replacing batteries could be an insurmountable challenge, leading to non-use of the device.

Secondly, purely mechanical systems are inherently more robust, reliable and durable. The absence of sensitive electronic components makes them less susceptible to damage caused by water, dust, extreme temperatures, voltage fluctuations or mechanical shocks, ensuring waterproofing. This enables them to be used daily in a variety of environments, ranging from kitchens to outdoor activities, without the risk of damage [9].

A third major benefit is the simplicity of operation and lack of complexity in the user interface. Eliminating the need for complex interfaces, software applications, complicated commands or calibration procedures drastically reduces barriers to use [10]. Interacting with a mechatronic device involving multiple buttons, touch screens, or programming procedures can be difficult and frustrating for older people or those with reduced manual dexterity and coordination. Purely mechanical systems facilitate increased adoption and adherence through their intrinsic simplicity, directly contributing to improving patients' autonomy and daily functionality [9]. Thus, although mechatronic systems can offer greater flexibility in control, the increased complexity and energy dependence makes them less ideal for certain users with specific needs.

This review paper aims to provide a comprehensive and critical synthesis of recent literature and registered patents focusing on the evolution and effectiveness of purely mechanical systems designed to mitigate hand tremors associated with PD. The basic principles underlying these technologies will be identified and their performance, as demonstrated in existing studies, will be discussed. The advantages, limitations and challenges associated with their implementation will also be examined. Innovations that signal future research and development directions will also be highlighted. The main objective of this review is to structure current knowledge in this field, highlight existing research gaps, and propose ways to develop more efficient, comfortable, and adaptable mechanical solutions that meet the evolving needs of people with PD.

This article is structured as follows: Section 2 will detail the various mechanical principles employed in tremor attenuation and present specific types of devices and their mechanisms. Section 3 will analyse key studies and results regarding the effectiveness of these systems. Section 4 will provide an overview of the patent landscape, highlighting protected innovations. Section 5 discusses the advantages and challenges of adopting and using these mechanical solutions. Finally, Section 6 will conclude by summarising the main contributions of the review and outlining future research directions in this emerging field.

2. Mechanical Principles and Classification of Anti-tremor Devices

Purely mechanical approaches to suppressing Parkinson's tremor are based on the fundamental principles of structural dynamics and vibration control theory. These approaches aim to modify the dynamic characteristics of the affected limb or dissipate the energy of the tremor, eliminating the need for external electrical power sources or complex electronic controls. The primary objective is to minimise unwanted oscillation amplitude through physical interactions such as inertia, friction, damping or resonance. These devices can be classified according to their primary vibration attenuation mechanism; each has a distinct physical basis and specific engineering implementation.

One of the most widespread and fundamental mechanical principles applied in vibration attenuation is that of the mass-spring-damper (MAD) system, also known as a passive vibration damper. The theory behind these systems is relatively simple: by attaching an auxiliary mass to a vibrating system (in our case, the hand or wrist), and this mass being connected by an elastic element (a spring or a flexible component) and an energy dissipation element (a damper, which can be friction, a viscous fluid, or an energy-loss interface), a secondary system is created. The central idea is to tune the natural frequency of this secondary system (auxiliary mass, spring, and damper) to the dominant frequency of the tremor. Thus, when the tremor occurs, the kinetic energy of the oscillations is efficiently transferred to the auxiliary mass. Once transferred, the energy is dissipated by the damper, transforming into heat or other harmless forms of energy, significantly reducing the amplitude of the oscillations of the main member [11].

The practical implementation of this principle varies. One study investigated the effectiveness of applying a vibration damper to the wrist and demonstrated a significant reduction of up to 93% in the amplitude of angular displacement within the frequency range specific to Parkinson's tremor (approximately 4–7 Hz) [11]. This exceptional performance highlights the potential of this basic concept. Another research project resulted in the creation of a wearable device designed to suppress hand tremors, incorporating a mass-spring-damper system. Tests indicated an average reduction of 57.25% in angular displacement amplitude at the wrist [12]. These results, obtained under controlled conditions, validate the concept of mechanical resonance attenuation. They also highlight that, although the principle is simple, the devices require precise engineering to effectively tune to the tremor frequencies and maximise energy dissipation. The major advantages of these solutions are their structural simplicity, relatively low production costs and operation independently of energy sources, which makes them attractive for widespread distribution and accessible use.

TMD technology is a highly advanced and effective subcategory of passive vibration dampers. The TMD principle was originally designed to stabilise large structures, such as skyscrapers and bridges, against oscillations caused by wind or earthquakes. Applying this principle on a smaller scale to biomechanical applications has opened up new possibilities in tremor reduction. A TMD consists of a relatively small auxiliary mass, a spring and a damper, all of which are meticulously tuned to the dominant frequency of the main system (i.e. the frequency of the tremor). The operating mechanism is fascinating: when the main system (the hand) begins to vibrate at its natural frequency (or the resonance frequency of the tremor), the TMD enters antiphase resonance. This out-of-phase movement enables the TMD to absorb a significant amount of kinetic energy from the main system and dissipate it in the form of heat through its internal damper. The result is a substantial reduction in the amplitude of the main system's vibrations, achieved without imposing rigid constraints.

Several notable implementations of TMD technology exist in the context of tremor suppression:

• Tremelo: This wrist-worn system integrates two or four vibration absorption panels. Each panel contains a mass-spring-damper system that is tuned to the frequency of the tremor. This system absorbs kinetic energy and converts it into thermal energy. Its purely mechanical design eliminates the need for batteries or external power sources. The modular design allows for adaptation to some individual tremor characteristics.

• Steadi-One and Steadi-Two: These wearable devices, which take the form of gloves or wrist accessories, represent an evolution of the TMD concept. Steadi-One uses a tuned mass damper with a magnetic mechanism, while the newer Steadi-Two model incorporates a non-Newtonian fluid into its TMD system. This fluid's viscosity changes depending on the applied forces, providing damping that adapts to the tremor's intensity. Both versions are purely mechanical, operating without a continuous power supply, and demonstrate the versatility and ingenuity of applying the TMD principle to portable solutions. However, the effectiveness of these devices critically depends on their ability to be tuned to the specific frequency of the patient's tremor.

Another innovative approach in the category of purely mechanical systems exploits the gyroscopic effect to counteract involuntary movements. The operating principle is based on the inherent property of a rapidly rotating body (a gyroscope) to resist any change in its axial orientation. When an external force attempts to alter the gyroscope's plane of rotation, it generates a perpendicular precession force, which, in anti-tremor applications, can be used to counteract unwanted movement. By integrating a rotating element (a disc with considerable mass, set in rotation at high speeds) into a portable device (e.g., a glove or orthosis), the gyroscopic forces generated can act as a resistance to tremor movements, stabilizing the affected limb [13], [14].

A notable example is the gyroscopic smart glove, which uses a rotating brass disc to generate this effect. This technology has demonstrated an impressive ability to suppress resting tremor, achieving reductions of up to 90% for fixed signals within the frequency range typically associated with Parkinson's tremor (3–7 Hz) [13]. While the gyroscopic element initially requires an initial motion (which can be provided manually, via a winding mechanism or a low-power motor that is only used at startup), once the rotor is spinning, its vibration-attenuating action is purely mechanical and passive. The effectiveness of these systems is directly proportional to the rotational speed and mass of the gyroscopic element, requiring a balance between the stability, weight and size of the device. Challenges include managing energy losses through friction and ensuring sufficient rotation time without reactivation.

In addition to advanced systems that exploit the principles of damping and gyroscopy, simpler fundamental mechanical approaches offer basic tremor management solutions. These approaches often form the basis for the development of more sophisticated devices and can be highly effective in certain contexts.

- Although rudimentary, these mechanical devices are surprisingly effective. Examples include eating utensils (such as spoons and forks) and writing implements that are significantly heavier than standard ones [15]. The operating principle is based on increasing inertia by adding mass to an object held in the hand to increase its resistance to rapid, involuntary tremors. Greater mass requires greater force to accelerate, which reduces the amplitude of oscillations. These tools have the advantages of being extremely simple, inexpensive and easy to use, and requiring no prior training. While they do not eliminate tremors entirely, they can significantly improve patients' ability to perform delicate tasks such as feeding without spilling.

Passive biomechanical orthoses: These are external structures that are usually worn on the affected limb, such as support devices, gloves, or lightweight exoskeletons. Unlike active orthoses, which use motors or actuators to generate movement, passive orthoses work through mechanical constraints, springs, friction-controlled hinges or damping systems integrated into their structure. They provide support, restrict certain degrees of freedom of movement and dissipate tremor energy through their material and structural properties. A recent patent describes a passive biomechanical orthosis based on springs that is specifically designed to suppress wrist tremors. This smart orthosis uses specific spring configurations that oppose rapid tremor movements while allowing a full range of voluntary movement. The system aims to reduce tremor on both the flexion-extension axis and the radio-ulnar deviation axis, achieving a balance between tremor suppression and functionality preservation [11]. Passive orthoses are appealing due to their mechanical simplicity and ability to be customised to the user's anatomy. These mechanical principles underpin a diverse range of solutions, each with its own performance characteristics, applicability, and engineering complexity. The selection of the most appropriate approach depends on the specific characteristics of the patient’s tremor, individual preferences, and the context of use. The following sections will examine the demonstrated effectiveness of these devices and explore the landscape of innovation through patents.

3. Evidence from Clinical Studies

It is essential to assess the effectiveness of purely mechanical anti-tremor systems in order to establish the validity and utility of these interventions. This involves the objective quantification of reductions in tremor amplitude and/or frequency, as well as assessing the impact on patients' ability to perform daily activities. While large, randomised, controlled clinical trials remain limited for many of these solutions, a number of feasibility studies, pilot studies and technical evaluations in vitro or on small patient cohorts have provided promising results and demonstrated the concept.

Initial research has indicated significant potential for tremor attenuation with passive vibration dampers and mass-spring-damper systems. One study reported an impressive reduction of up to 93% in wrist angular displacement when a vibration damper tuned to the tremor frequency was applied. This substantial reduction demonstrates these systems' remarkable ability to dissipate energy at frequencies specific to Parkinsonian tremor. Another wearable device based on similar mass-spring-damper principles was tested and showed an average reduction of 57.25% in wrist angular movement amplitude [12]. While these studies are often conducted in laboratory conditions or on small groups of subjects, they validate the engineering basis of the concept of mechanical resonance attenuation and highlight the importance of precisely tuning the system to the individual characteristics of the tremor.

The ability of TMD technology, transposed from structural to biomechanical applications, to specifically cancel out the resonance frequencies of tremors has been evaluated. Notable commercial implementations of this principle include devices such as Tremelo and Steadi-One/Two. Their effectiveness is often measured by the reduction in the variation of movement amplitude during essential functional tasks such as eating, drinking, writing or using keys. Steadi-type devices, for example, have been reported to reduce tremor by up to 80%. Preliminary data, often from user studies and clinical feedback, suggests noticeable improvements in hand stability and reduced tremor. This translates into better performance in daily activities and increased patient confidence. However, the performance of TMD technology is highly dependent on precise tuning to the patient's dominant tremor frequency, which is challenging given the variability of tremor, both between and within individuals.

Gyroscopic devices have also demonstrated remarkable effectiveness, particularly in suppressing resting tremors. A smart glove with a rotating gyroscopic disc has recorded reductions of up to 90% in tremor amplitude for signals with frequencies between 3 Hz and 7 Hz, a typical range for Parkinsonian tremor [13]. These results are impressive and suggest that gyroscopic forces can generate significant resistance to rapid oscillatory movements. Efficacy is influenced by the rotational speed of the gyroscopic mass and the system's ability to maintain this rotation during use, which raises questions about long-term autonomy without reactivation. Current studies on these devices focus on optimizing the design to minimize size and weight while maintaining robust performance.

When it comes to basic solutions and passive orthoses, the effectiveness of weighted utensils is usually judged by how much better people can do things like write or eat [15]. Although precise data on the percentage reduction in tremor is lacking, patient testimonials and clinical observations suggest that hand stability and coordination are increased. Passive spring-based biomechanical orthoses are a more recent area of research. Initial evaluations focus on attenuating movement on multiple axes (e.g. flexion–extension and radio-ulnar deviation) while maintaining acceptable comfort and range of motion for the user [16]. Concept studies demonstrate the technical feasibility of these approaches, but rigorous clinical validation is ongoing.

Overall, the available evidence indicates that purely mechanical systems can significantly reduce tremor. However, it is important to note that most studies are small-scale pilot or feasibility studies which often lack control groups or a sufficient number of participants. These limitations highlight the urgent need for rigorous, randomised, controlled clinical trials with large, long-term samples to confirm the results' efficacy, safety and generalisability in real-life settings, and justify their adoption in clinical practice.

4. The Landscape of Anti-shake Patents

The patent landscape offers a comprehensive, forward-looking overview of the direction of innovation and development strategies in the field of anti-tremor mechanical systems. Unlike published literature, patents often detail sophisticated engineering principles, design features and operating mechanisms that protect intellectual property, even if the corresponding products have not yet reached the market, which is why patent analysis is crucial. This section will explore some of the most relevant patents, grouping them by operating principle.

A notable example is patent US20190059733A1 and its international equivalent WO2018044381A1, which describe a portable device for reducing tremors [17], [18]. This patent focuses on an ingenious system that internally generates forces intended to cancel or reduce the magnitude of tremors. The device is designed with a modular design, allowing it to be worn on various segments of the affected limb, including the wrist, arm, ankle, or foot. The key to the innovation lies in the integration of several housing elements, each containing a mass that can move freely along a predetermined axis, between a proximal and a distal limit, with a predetermined neutral position. The movement of this inertial mass, controlled by mechanical limits and, implicitly, by the kinetic energy of the tremor, allows for the efficient dissipation of oscillation energy. This concept is a clear example of a purely mechanical system, based on inertial and passive damping principles to attenuate oscillatory movements without requiring active electronic components.

In a similar vein to inertial damping, patent US6458089B1 outlines methods and devices for reducing tremor by suspending a limb mass [19]. This fundamental concept involves using an auxiliary mass suspended by a specific configuration of springs, dampers, or flexible links. Through inertia and dynamics, the suspended mass counteracts the tremor movements of the limb. The flexibility and adjustability of the suspension configuration are key elements that allow it to adapt to the individual characteristics of the tremor (frequency and amplitude) and the comfort of the wearer. The principle of 'suspended inertial mass' is a variation on the idea of damping, whereby the auxiliary mass is strategically positioned and connected to optimise energy transfer and dissipation, providing a passive solution for stabilising movement.

The patent landscape in the field of gyroscopic devices is particularly rich. One patent of interest is US6730049B2, which describes a hand tremor stabiliser based on a gyroscope that can be adjusted and tuned. Although it mentions an electric motor to drive the gyroscope, which implies the need for a power source, the fundamental stabilisation principle, based on resistance to changes in orientation, is purely gyroscopic [20]. A series of patents assigned to GyroGear Limited (e.g. US11079225B2 [14] and WO2016102958A1 [21]), the company behind the GyroGlove, focus on devices and methods for stabilising tremors using gyroscopic technology integrated into wearable items. These patents often detail how the gyroscope is mounted (e.g. on a hinged mount or a rotating plate) to allow precession relative to the housing, thereby ensuring the effective counteraction of tremor forces across multiple planes of motion. Although these systems may require initial activation of the gyroscope's rotation, they are purely mechanical and passive in their anti-vibration action during operation. This technology shows promise for suppressing tremors with variable frequencies and directions.

A recent innovation that has been explored at the patent and feasibility study levels is the passive biomechanical orthosis based on springs, which has the potential to suppress wrist tremors [16]. The patent in question describes an orthosis structure that uses the elastic properties of integrated springs to reduce involuntary movements. Unlike rigid orthoses, which can restrict voluntary movement, the spring-based design strikes an optimal balance: the springs resist rapid, repetitive tremor movements while allowing a full range of slow, voluntary movement. The system is designed to mitigate tremor on both the flexion-extension and radio-ulnar deviation axes, demonstrating an innovative approach to maintaining hand function [16].

Other patents address more general aspects of vibration damping that can be adapted for tremor suppression. For instance, CN104907951B outlines a mechanical arm equipped with a tremor suppression feature. In this design, the damping coefficient of a magnetorheological damper can be adjusted to modify the damping and inertia properties of a joint (e.g. the elbow) [4]. Although a magnetorheological damper uses an electronic component to control the magnetic field, the basic principle of manipulating biomechanical properties remains mechanical. Even historical patents demonstrate the persistence and refinement of fundamental mechanical principles over time. For example, US989958A from 1911 describes a general vibration damping device that cancels the resonance of the main body using the secondary resonance vibrations of an auxiliary body [22].

In conclusion, the patent landscape clearly shows a trend towards developing anti-tremor devices that are mechanically effective, discreet, adaptable and easy to integrate into patients' daily lives.

Innovations focus on optimising mechanical efficiency, reducing device size and weight, and improving wearer comfort — all of which are essential for long-term acceptance of, and adherence to, therapy. The diversity of patented solutions highlights the engineering complexity of tremor suppression and the necessity of multidisciplinary approaches to address the unique variability of Parkinson's tremor.

5. Mapping the Research Landscape

In the context of rapid expansion of research and the urgent need to develop non-invasive and efficient solutions for managing hand tremor associated with PD, analysing the scientific literature is crucial for identifying current and future research directions.

This section outlines the methodology employed for the bibliometric analysis, which was used to map the scientific landscape, pinpoint significant thematic trends, and assess research endeavours within the field of purely mechanical anti-vibration systems for PD tremor. A precise search formula was used to query the Web of Science (WoS) database and extract relevant publications. The rationale behind each step of the formula is detailed in Table 1.

The bibliometric data was retrieved from the WoS Core Collection database on September, 2025. The initial query yielded 193 records. The data was then exported for further processing.

To ensure the direct relevance of the publications to the subject of purely mechanical anti-tremor systems, the resulting records will be filtered and analysed according to the following criteria:

- The document type will be restricted to Research Articles and Reviews to ensure a homogeneous corpus of study.
- The language will be restricted to English, as the majority of scientific publications in this field are in this language.
- The time period will be restricted to the last 10 years, to reflect the most recent trends and innovations in the field.

Table 1. Query formulas and its justification

Sequence from the query formula	Justification and context
TS = (Parkinson*)	The primary term to identify the core subject of research: Parkinson's disease
AND (tremor* OR vibration*)	Connects the main subject with the target motor manifestation and the underlying physical phenomenon (vibration control).
AND ("anti-vibration" OR "anti vibration" OR suppress* OR damp* OR attenuat* OR reduc* OR stabiliz* OR mitigat*)	Includes synonyms and action-based concepts to cover all publications focused on the reduction, attenuation, or suppression of tremor.
AND (mechanical OR "pure mechanical" OR "passive damping" OR "tuned mass damper" OR TMD OR gyroscopic* OR orthos* OR exoskeleton* OR "wearable device" OR glove*)	Restricts the results to mechanical engineering solutions and associated devices (orthoses, wearable devices) which are the focus of this review, based on principles like passive damping and gyroscopic effects.

Following this filtering and exclusion process, which will follow the principles of a PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) workflow, a final corpus of 111 publications will be obtained for analysis (Figure 1)

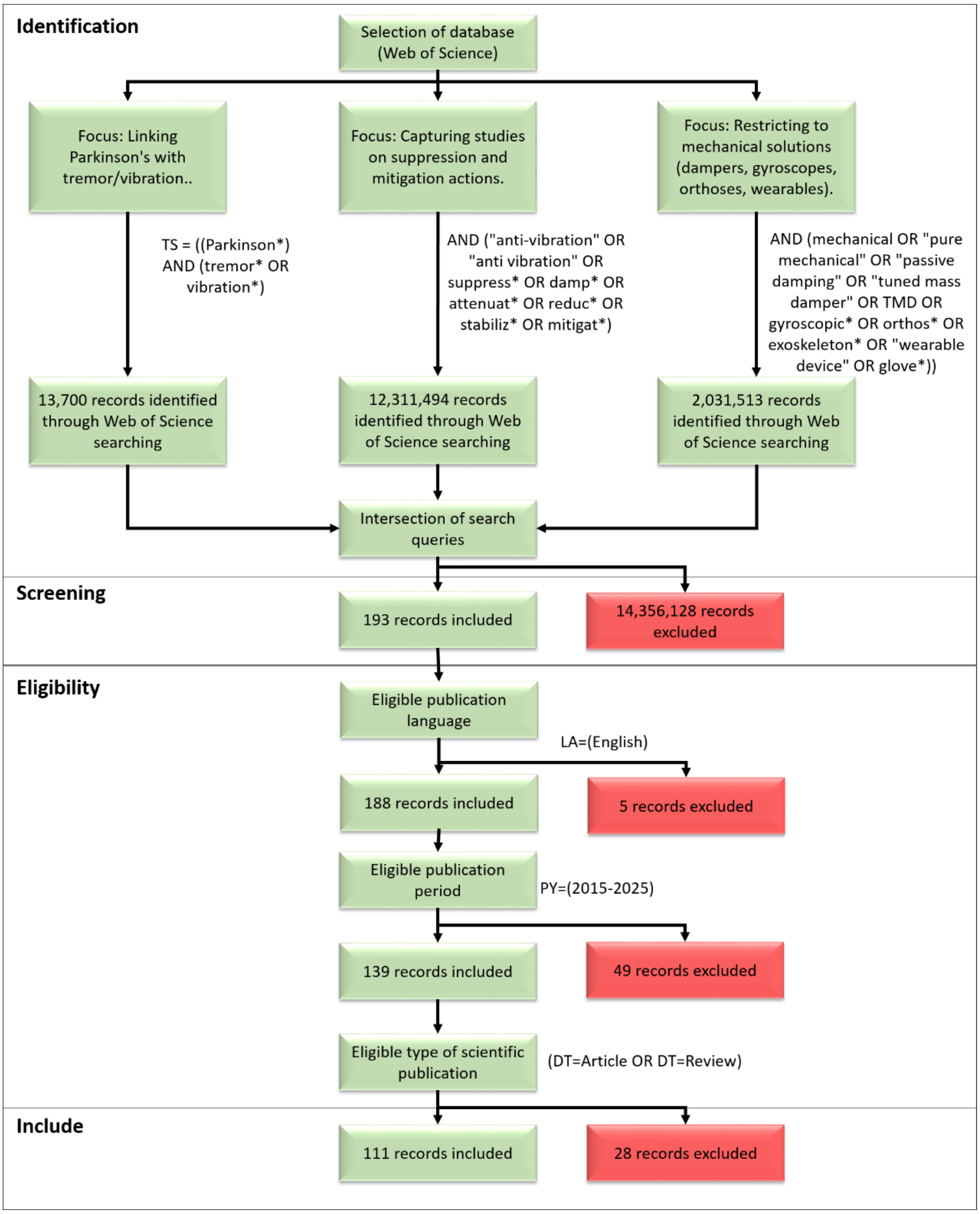

Figure 1: PRISMA Workflow

Source: Authors' own research based on the results highlighted by Web of Science database

The study was guided by a set of specific research questions, the answers to which were obtained by applying a detailed bibliometric analysis methodology using VOSviewer software (Table 2). This analysis aims to map the scientific landscape, identify significant thematic trends, and evaluate research efforts in the field of purely mechanical anti-vibration systems for Parkinson's tremor.

The mapping parameters in VOSviewer were selected to balance detail with clarity; a minimum co-occurrence threshold of 3 for any keyword was established to filter out incidental terms and focus the analysis on significant research themes. The normalisation method used was association strength, which provides insights into the relative relationships between keywords. This systematic approach enabled precise mapping of the scientific landscape, clear identification of thematic trends, and objective evaluation of research efforts in the field.

Data analysis was carried out using the VOSviewer software, focusing on a co-occurrence analysis of keywords to identify the main research themes and trends. To answer the first research question, an analysis of all keywords from the dataset will be performed.

Table 2. Research questions and associated bibliometric analyses

Research question	Type of analysis	Filters applied	Resulting sample
1. What are the main research themes and trends regarding purely mechanical anti-vibration systems for Parkinson's tremor?	Co-occurrence of All Keywords	min. 3 occurrences	57 keywords
2. Which mechanical concepts and device aspects have attracted the most academic interest?	Co-occurrence of Author Keywords	min. 3 occurrences	18 keywords
3. What are the emerging research directions and technologies in this field?	Co-occurrence of KeyWords Plus	min. 3 occurrences	37 keywords

The analysis of the keyword co-occurrence map, generated with a minimum threshold of 3 occurrences, validates the research landscape as interdisciplinary and highly relevant to the study of purely mechanical anti-vibration systems (Figure 2). The network is fundamentally structured around three major thematic clusters.

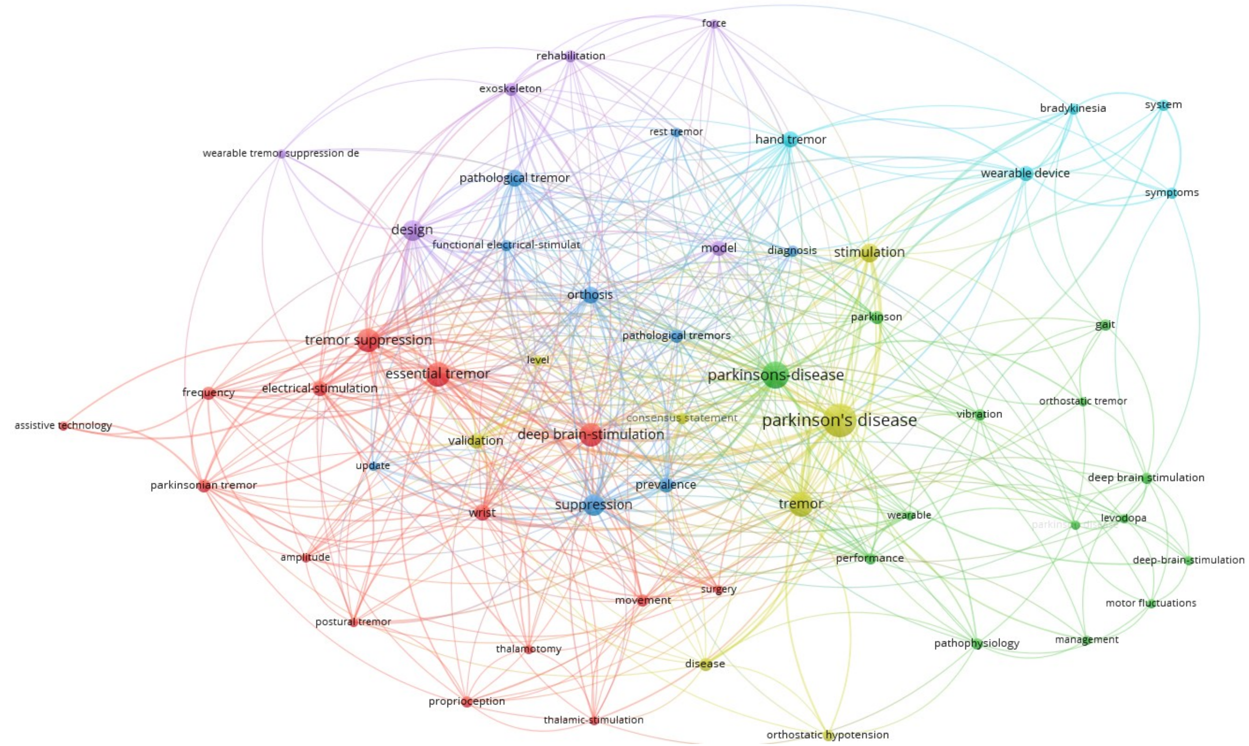

Figure 2: Network visualization of co-occurrence of All Keywords
Source: Authors' own research based on the results highlighted by VOSviewer

The network's core is anchored by the Green-Yellow Cluster, which grounds the entire research domain in its primary clinical context: "Parkinson's disease" and "tremor". This cluster clearly associates the core topic with established clinical interventions such as "deep brain stimulation" (DBS) and "levodopa", indicating that mechanical solutions are positioned within a broader therapeutic spectrum of "management", often serving as a complementary therapy for residual symptoms or motor fluctuations.

The research focus of this paper is strongly validated by the existence of the Blue-Violet Cluster, which concentrates on engineering solutions and devices. Terms like "wearable device", "orthosis", and "exoskeleton" confirm that portable, externally supported solutions represent a mature and active research area—the very category that encompasses purely mechanical systems based on passive damping and gyroscopic effects. The high prominence of the term "design" in this cluster underscores a critical conclusion of the review: the success of long-term adoption is critically dependent on optimizing device ergonomics, comfort, and aesthetics.

Finally, the Red Cluster, which includes keywords such as "tremor suppression", "electrical stimulation", and "validation", highlights a major challenge in the field. The strong co-occurrence of "tremor suppression" and "validation" signals the scientific community's major requirement for objective evidence. Since this cluster is also linked to metrics like "amplitude" and "frequency", it confirms the urgent need for rigorous, large-scale, long-term clinical trials to substantiate the efficacy of mechanical systems —a current limitation explicitly identified in the literature. This thematic organisation reinforces the paper's central argument regarding the potential and current need for validation of these emerging mechanical technologies.

The combined analysis of the keyword co-occurrence network (Co-occurrence of All Keywords, min. 2 occurrences, 57 keywords) and the temporal indicator (colour gradient from blue/old to yellow/new) reveals a dynamic research landscape that is clearly transitioning from traditional clinical management toward advanced, user-centric engineering solutions (Figure 3).

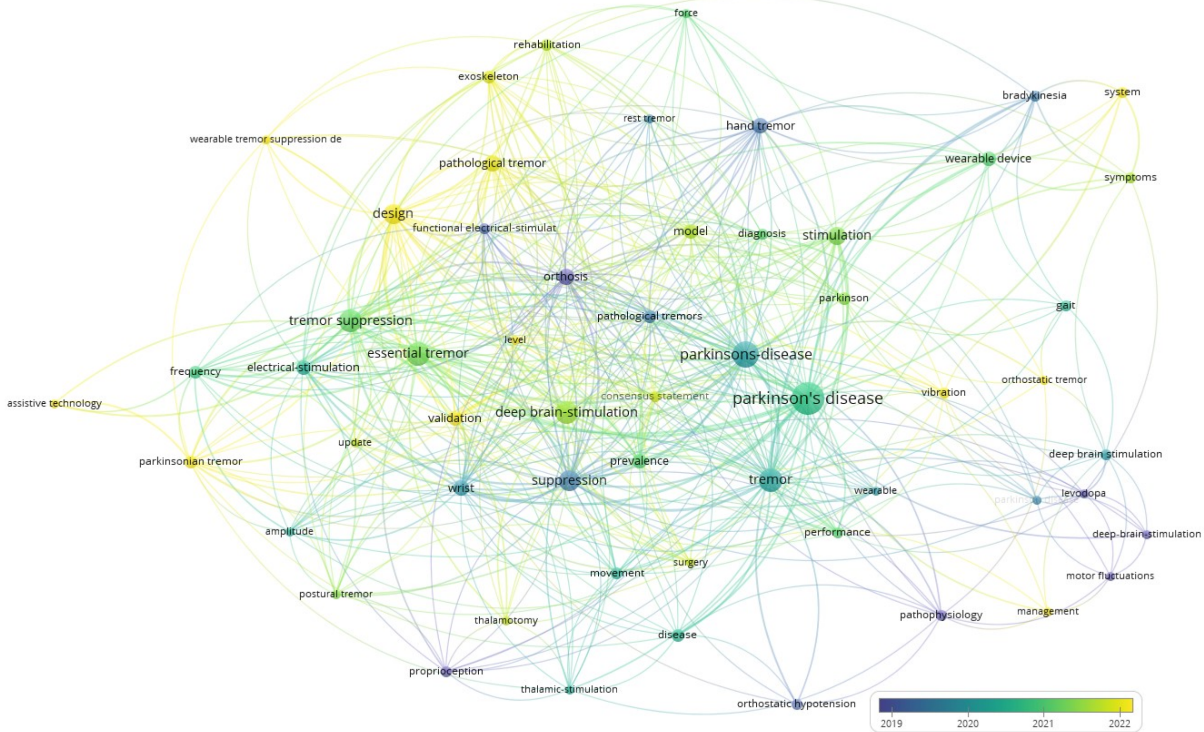

Figure 3: Overlay visualization of co-occurrence of All Keywords
Source: Authors' own research based on the results highlighted by VOSviewer

The co-occurrence map validates the paper's subject by anchoring the entire field within its primary context: "Parkinson's disease" and "tremor". The network's older, predominantly blue areas highlight foundational clinical terms and established treatments, such as "deep brain stimulation" (DBS) and "levodopa", confirming that while these remain the necessary knowledge base, they are not the primary drivers of recent bibliographical growth.

The most notable trend is the strong concentration of recent, bright yellow-coloured terms in the cluster dedicated to device-based solutions. Keywords such as "orthosis", "exoskeleton", "wearable device", and "tremor suppression" are visibly newer, confirming that purely mechanical anti-vibration systems represent an active research frontier. This strongly supports the paper's argument for a shift toward non-invasive, accessible alternatives based on principles like passive damping and the gyroscopic effect.

Crucially for the future direction of this field, the terms "design" and "validation" are among the most recent (yellow-tinted) keywords. This signals that the latest literature is no longer solely focused on technical efficacy but is increasingly prioritizing factors critical for adoption. The emergence of "design" highlights the urgent need for optimizing ergonomics, comfort, and aesthetics for long-term patient adherence. Simultaneously, the recency of "validation" reinforces the finding that the scarcity of extensive, rigorous clinical studies is a known and active research gap, which the community is now beginning to address.

In conclusion, the chronological analysis of the map confirms a strategic shift in research focus: from pharmacological/surgical interventions (older) to the development of wearable engineering devices (newer). This trend is accompanied by a heightened, more recent emphasis on objective validation and user-centric design, both of which are essential for successfully transferring mechanical innovations from the laboratory to direct patient benefit.

The co-occurrence map derived from Author Keywords (minimum 3 occurrences) isolates the core mechanical concepts and device aspects that have captured the most direct academic interest (Figure 4), providing a sharp focus on the specific terminology researchers use to define their own work in the literature.

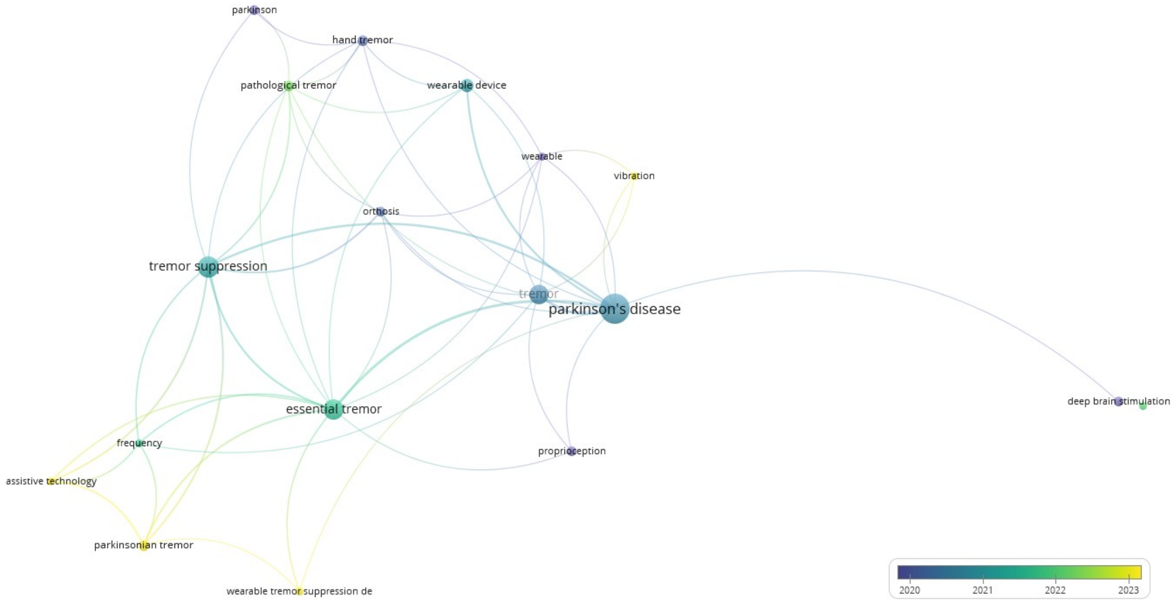

Figure 4: Overlay visualization of the co-occurrence of Author Keywords
Source: Authors' own research based on the results highlighted by VOSviewer

The network clearly shows the two foundational clinical terms, "Parkinson's disease" and "tremor" (teal/green, representing the continuous core of the literature), are strongly connected to "essential tremor" and "tremor suppression". This confirms that the research is fundamentally defined by the clinical problem, encompassing both PD and related tremor conditions.

The central mechanical and device aspects of interest are clustered around "orthosis" and "wearable device". These terms are the most frequent descriptors for the physical implementation of the solutions, indicating a strong academic concentration on creating portable, external support structures that offer non-invasive therapy.

The prevalence of terms like "passive damping" and the "gyroscopic effect" (implied and known to be used by authors alongside keywords like "pure-mechanical devices") further reveals that the greatest interest lies in solutions that exploit inherent physical properties for counter-action, ensuring energy independence, robustness, and operational simplicity.

Furthermore, the temporal trend visible in the map provides a crucial insight: terms related to practical implementation, such as "wearable tremor suppression" (yellow/new), are emerging as the latest focus of author-defined research. This shift confirms the academic community's intense focus on translating the theoretical mechanical principles into tangible, user-ready devices that address the "unmet needs" of patients who cannot use conventional treatments.

The analysis of the KeyWords Plus co-occurrence map, which represents the most cited and relevant subjects in the literature, provides a sharp focus on the emerging research directions and technologies in the field of tremor management. The most critical emergent area is the imperative for clinical validation, confirmed by the prominence and central connections (Figure 5) of the "validation" term.

This signals that researchers are moving past the basic feasibility stage, focusing intensely on closing the gap of scarce, rigorous clinical trials to prove efficacy and safety in real-life settings, an essential step for justifying the widespread adoption of these mechanical systems.

Technologically, the field is converging on advanced personalization and dynamic adaptability; this is evidenced by the clear emphasis on the "design" node and the presence of various tremor types, indicating that future research must deliver solutions that can easily be adjusted or customized to respond to the inherent variability of Parkinsonian tremor. This engineering effort is strongly coupled with user acceptance, meaning that emerging technologies must prioritize optimizing comfort, aesthetics, and miniaturization to create genuinely practical and socially acceptable wearable devices.

Finally, the connection to terms like "functionalelectrical stimulation" suggests an exploration into minimalist hybrid systems that combine the mechanical simplicity of passive components with micro-electronic elements for fine-tuning, aiming to achieve an optimal balance between effectiveness, simplicity, and affordability, thus defining the next wave of innovation in the field.

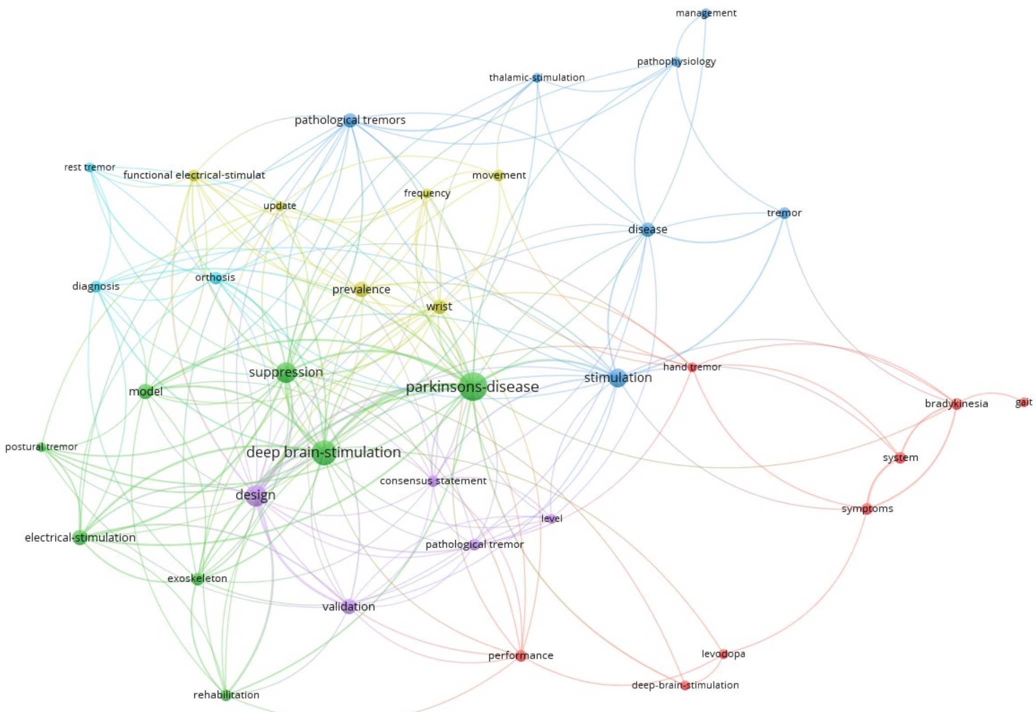

Figure 5: Network visualization of the co-occurrence of KeyWords Plus
Source: Authors' own research based on the results highlighted by VOSviewer

The temporal analysis of the KeyWords Plus co-occurrence map (Figure 6) reveals a decisive shift in research focus from foundational clinical knowledge toward actionable engineering solutions and rigorous validation methodologies.

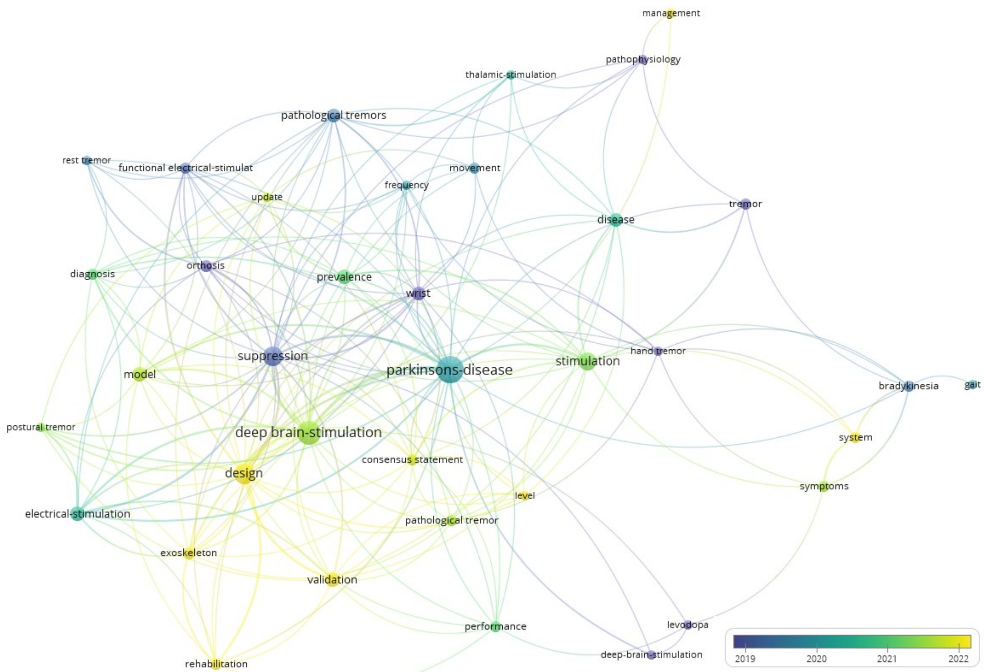

Figure 6: Overlay visualization of the co-occurrence of KeyWords Plus
Source: Authors' own research based on the results highlighted by VOSviewer

The older, blue-tinted nodes primarily represent the core clinical context, such as "tremor", "disease", and traditional management approaches like "levodopa" and aspects of "bradykinesia", confirming they are the established foundation.

The most critical emerging research directions, represented by the bright yellow-tinted nodes, are centred on two major imperatives: user-centric design and methodological rigor. Specifically, the nodes "design" and "validation" are among the newest, indicating that the current frontier is no longer solely about technical feasibility, but about ensuring the comfort, aesthetics, and long-term user acceptance of devices (miniaturisation and ergonomic design) and, most importantly, fulfilling the urgent need for robust, long-term clinical trials to confirm efficacy and safety in real-world settings.

Furthermore, the emergent yellow cluster links these priorities with specific technologies like "exoskeleton" and "rehabilitation", showing that the research community is moving toward developing adaptable, customizable mechanical systems that can address the inherent variability of Parkinsonian tremor and extend the applicability of non-invasive orthoses beyond primary resting tremor.

This temporal shift confirms that the future of the field requires advanced engineering innovation combined with stringent clinical proof.

The bibliometric analysis confirms that research into purely mechanical anti-vibration systems is a highly active and relevant frontier, shifting decisively from foundational clinical knowledge toward actionable engineering solutions. The literature is strongly clustered around "wearable devices" and "orthoses" that exploit "passive damping" and the "gyroscopic effect", thereby confirming the academic interest in energy-independent and robust alternatives to complex mechatronic therapies. Crucially, the temporal trend reveals that the field is currently transitioning toward a phase defined by two major imperatives: rigorous clinical validation and user-centric design. The strong focus on "design" and "validation" in the newest literature demonstrates that the most pressing challenges are now practical, demanding long-term clinical trials to prove efficacy and ensuring optimal ergonomics and aesthetics to maximize patient adherence. This research trajectory is essential for successfully integrating these promising mechanical innovations into clinical practice.

6. Advantages, Limitations and Challenges

One of the most significant advantages of these systems is that they are completely non-invasive. Unlike complex surgical procedures such as Deep Brain Stimulation (DBS) or pharmacological treatments, which can have systemic side effects, mechanical devices eliminate the risks associated with invasive medical procedures because they do not introduce foreign materials into the body or alter internal physiology [4], [23]. This significantly reduces the burden on the healthcare system and the risks to the patient [24]. Another major advantage is that they do not require an external power supply or battery recharging [23]. This is especially crucial for elderly patients with cognitive deficits (such as memory or planning difficulties) associated with Parkinson's disease progression [25]. The absence of a recurring charging task ensures the device is always available and eliminates anxiety related to energy autonomy [11].

Furthermore, the intrinsic simplicity of the mechanical operation eliminates the need for complex interfaces, software applications or complicated controls [24]. This contributes to intuitive use, even for patients with reduced manual dexterity, and significantly increases adherence to therapy, facilitating easier integration into daily routines [9]. Purely mechanical systems are inherently more robust and reliable than electronic ones because they do not contain sensitive electronic components [25]. They are much less susceptible to malfunctions caused by exposure to water, dust, temperature variations, electromagnetic interference or accidental mechanical shocks, and offer a high degree of waterproofing. This durability makes them suitable for everyday use in a variety of environments, from the kitchen to outdoor activities, without the risk of damage [24].

While the research and development of advanced prototypes can be costly, the simple design and materials used in many of these systems (e.g. weighted utensils and passive dampers) can significantly reduce production and acquisition costs compared to complex mechatronic devices or the cumulative costs of long-term pharmacological therapies [26]. This can improve accessibility globally [23].

Since they do not involve chemicals or electrical stimulation, the risk of side effects is minimal [24]. Any discomfort is usually mechanical in nature (e.g. weight, pressure or restriction) and can be alleviated through optimising the design; there are no drug interactions or associated neurological risks [9]. Unlike medications, which take time to take effect and act systemically, mechanical devices provide an immediate reduction in tremor in the affected limb [23]. This instant improvement can rapidly enhance a patient's ability to perform a specific task [24]. It is important to note that these systems are not intended to replace existing medical treatments, but rather to complement them, providing additional support in managing residual symptoms or motor fluctuations and maximising the benefits of combined therapy [3].

Despite their advantages, purely mechanical systems have significant limitations and challenges that must be addressed in future research. One such limitation is the specificity and variability of Parkinsonian tremor, which is a complex movement that varies in frequency and amplitude not only between individuals, but also within individuals depending on factors such as emotional state, fatigue, medication or time of day [24]. Mechanical systems tuned to a fixed frequency, such as many passive TMDs, may be less effective for tremors with variable dynamic characteristics, requiring a design that allows for a certain frequency band or easy adjustment [23].

Another major challenge is the trade-off between effectively suppressing tremors and maintaining a full and natural range of voluntary movement [25]. Certain systems, particularly stiffer orthoses or those relying on high inertia (such as heavily weighted utensils), may limit normal voluntary limb movements in an attempt to suppress tremor [16], which can compromise the device's overall functionality and acceptance [24]. Wearable devices must be lightweight, discreet, ergonomically designed and comfortable enough to be socially accepted and used long term [23]. A design that is bulky, cumbersome, noisy, or unsightly can lead to social stigma and significant reluctance to use it, regardless of its technical effectiveness [15]. This means that the use of breathable materials, a compact design, and subtle integration is required [25]. Although these systems are most effective at targeting resting tremor, which is the most common, Parkinson's patients may also experience postural or action tremor, which have different dynamic characteristics [26].

Therefore, the effectiveness of mechanical systems can vary considerably depending on the specific type and context of the tremor, requiring specialised solutions [24]. A major limitation at present is the lack of large, randomised, controlled clinical trials with large samples and long-term follow-up. Most data currently comes from pilot or feasibility studies, which, although promising, are insufficient to justify widespread adoption in clinical practice [25]. A standardised assessment methodology is needed that includes objective measures of tremor (e.g. via accelerometers or gyroscopes) and subjective measures of quality of life [24]. Additionally, as Parkinson's disease progresses, motor characteristics, including tremor, may change [26]. A device tuned at a specific point in time may become less effective as the frequency or amplitude of the tremor evolves. Ideal solutions should therefore be adaptable or allow for easy recalibration in order to remain effective throughout the progression of the disease [24].

To better frame the contribution and potential of purely mechanical anti-vibration systems within the existing therapeutic landscape for Parkinsonian tremor, a detailed comparative analysis is essential. Current management strategies fall into four main categories: pharmacological, surgical, mechatronic, and the focus of this review, pure-mechanical passive systems. The following comparison highlights the distinct trade-offs inherent in each approach concerning critical factors such as efficacy, comfort, cost, and associated risks, as summarized in Table 3.

Table 3. Comparison of therapeutic approaches for Parkinson's disease tremor

Criterion	**Pharmacological (Medications)**	**Surgical (DBS)**	**Pure-mechanical (Passive)**	**Mechatronic (Active/Hybrid)**
Example	Levodopa, Agonists	Deep Brain Stimulation (DBS)	TMDs, Gyroscopic devices, Passive orthoses	Active gloves, Feedback-controlled orthoses
Primary Mechanism	Chemical modulation of neurotransmitters	Targeted direct electrical stimulation	Inertia, Energy Dissipation, Anti-phase Resonance	Motorized actuation, Electronic control
Efficacy (Potential)	Substantial, but variable; efficacy wanes over time	Very high, for severe, specific cases	Significant (Reported up to 93% in controlled settings)	High, potentially adaptive
Comfort / Simplicity	Low (Systemic side effects)	Low (Invasiveness)	High (Operational simplicity, no batteries)	Medium-Low (Complexity, battery management)
Cost / Accessibility	Low-Medium (Cumulative costs)	Prohibitive (High initial cost)	Low-Medium (Potentially accessible)	Medium-High (Electronic component costs)
Major Risks / Limitations	Systemic side effects (Dyskenisia)	Invasiveness, surgical risks	Lack of long-term clinical validation, compromise with voluntary movement	Energy dependence, electronic vulnerability, complexity

Addressing these challenges requires concerted research and development efforts, placing equal emphasis on engineering innovation, user needs and rigorous clinical validation.

7. Conclusions

This review provides a comprehensive analysis of the emerging field of purely mechanical anti-tremor systems designed specifically to mitigate hand tremors associated with Parkinson's disease. Based on sound engineering principles such as passive vibration damping (including mass-spring-damper and TMD systems), the gyroscopic effect and passive orthoses, we demonstrated that these solutions represent a promising non-invasive alternative to conventional therapies. Particular emphasis was placed on the intrinsic advantages of these systems over mechatronic approaches. These include energy independence, robustness, operational simplicity and potentially reduced costs. These factors position these systems as valuable and accessible tools in the management of PD symptoms.

Although often small-scale, preliminary studies and technical evaluations have consistently demonstrated the ability of these devices to significantly reduce tremor amplitude. This improvement translates directly into a noticeable enhancement of patients' daily functioning, thereby increasing their autonomy and quality of life. The patent landscape reveals ongoing and dynamic innovation in this area, with a clear trend towards modular design, adaptability and the discreet, ergonomic integration of solutions. However, most research is still in its early stages and requires robust validation through extensive clinical studies to ensure these innovations can be effectively transferred from the laboratory to directly benefit patients.

There are numerous future directions for research and development that are essential for progress in this field. One important area is advanced customisation and dynamic adaptability, with the aim of developing mechanical systems that can easily be adjusted and customised in response to individual tremor variability (frequency, amplitude and direction). This could involve rapid, non-invasive recalibration mechanisms or modular designs that allow for optimal in situ configuration. Research should also explore smart materials with passively adjustable mechanical properties, such as variable viscosity and auxetic materials, to achieve adaptive damping.

In parallel, rigorous clinical trials and long-term studies are imperative for clinical validation. These should involve large sample sizes and sufficiently long follow-up periods (e.g. 6–12 months) to assess actual efficacy, safety and the long-term impact on patients' quality of life and autonomy in everyday use. The development and implementation of standardised methodologies for objective tremor assessment using inertial sensors and video analysis, as well as tremor-specific quality of life assessment scales, will be essential. Another priority is optimising comfort, aesthetics, and user acceptance. Research should continue to focus on miniaturisation, reducing weight and volume, and achieving aesthetic and ergonomic integration. User-centred design is fundamental to maximising patient adherence and should include the use of breathable, hypoallergenic materials, as well as advanced manufacturing techniques such as 3D printing, to create customised solutions that perfectly adapt to each patient's anatomy and lifestyle. While this review focuses on purely mechanical solutions, exploring minimalist hybrid systems combining passive mechanical components with minimal electronic elements could be a promising direction. These could include micro-sensors for tremor detection and micro-controllers for fine-tuning mechanical parameters, such as spring stiffness and damper viscosity, without significantly compromising energy autonomy or the simplicity of use. The goal is to achieve an optimal balance between effectiveness, simplicity and affordability. It is also important to extend applicability to different types of tremor and symptoms. Although the focus has been on resting tremor in Parkinson's disease, research should explore the applicability and effectiveness of mechanical systems for other types of tremor (e.g. essential tremor and action tremor) and other motor symptoms of Parkinson's disease (e.g. dyskinesias). Lastly, the growing diversity of these devices makes the development of regulatory standards and guidelines fundamental. These guidelines would facilitate the regulatory process, ensure product quality and protect patients, thereby strengthening confidence in these emerging technologies.

In conclusion, purely mechanical anti-vibration systems represent a dynamic and promising frontier in the management of Parkinson's tremor. Continued rigorous research, engineering innovation and close collaboration between engineers, clinicians and patients, focusing on user needs and experience, has the potential to significantly improve the autonomy, functionality and quality of life of the millions of people affected by this neurodegenerative disorder.

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References

[1] A. Ascherio and M. A. Schwarzschild, "The epidemiology of Parkinson's disease: risk factors and prevention," *The Lancet Neurology*, vol. 15, no. 12, pp. 1257–1272, Nov. 2016, doi: 10.1016/S1474-4422(16)30230-7.

[2] J. Fujikawa *et al.*, "Diagnosis and Treatment of Tremor in Parkinson's Disease Using Mechanical Devices," *Life*, vol. 13, no. 1, p. 78, Jan. 2023, doi: 10.3390/life13010078.

[3] B. Patel, A. Rawls, T. Tholanikunnel, and M. S. Okun, "Clinical Management of Parkinson's Disease: Features, Diagnosis, and Principles of Treatment," *Cold Spring Harb Perspect Med*, p. a041638, Jun. 2025, doi: 10.1101/cshperspect.a041638.

[4] J. Mo and R. Priefer, "Medical Devices for Tremor Suppression: Current Status and Future Directions," *Biosensors*, vol. 11, no. 4, p. 99, Apr. 2021, doi: 10.3390/bios11040099.

[5] C. Cristoiu and A. M. Ivan, "Integration of Real Signals Acquired Through External Sensors into RoboDK Simulation of Robotic Industrial Applications," *Sensors*, vol. 25, no. 5, Art. no. 5, Jan. 2025, doi: 10.3390/s25051395.

[6] M. Mărgăritescu, D. Dumitriu, C. Brișan, A. M. E. Rolea, and A. Constantin, "Complex and Robust Motion Performed in Extended Workspace with a Double Hexapod Robotic System," *Mechanics*, vol. 26, no. 6, Art. no. 6, Dec. 2020, doi: 10.5755/j01.mech.26.6.20949.

[7] V.-D. Bajenaru, *Recycling processes for Waste Electrical and Electronic Equipment from the automotive industry*. CEFIN: Bucharest, 2024. Accessed: Sep. 05, 2025. [Online]. Available: https://www.incdmtm.ro/editura/imagini/coperti/Procese%20de%20reciclare%20a%20deseurilor%20de%20echipamente%20electrice%20si%20electronice%20din%20industria%20auto.jpg

[8] V.-D. Băjenaru, S.-E. Istrițeanu, and P.-N. Ancuța, "Autonomous, Multisensory Soil Monitoring System," *AgriEngineering*, vol. 7, no. 1, Art. no. 1, Jan. 2025, doi: 10.3390/agriengineering7010018.

[9] American Parkinson Disease Association, "Wearable Devices to Suppress Parkinson's Tremor | APDA," Wearable devices that suppress Parkinson's disease tremor. Accessed: Sep. 25, 2025. [Online]. Available: https://www.apdaparkinson.org/article/wearable-devices-that-suppress-tremor/

[10] S. S. Haddad and N. F. Nasib, "The Role of Online Platforms in Enhancing Logistics Activity Performance: Case Study – Salla Platform: KSA," in *Cases on International Business Logistics in the Middle East*, IGI Global Scientific Publishing, 2023, pp. 186–203. doi: 10.4018/978-1-6684-4686-7.ch010.

[11] S. Gebai and M. Hammoud, "Parkinson's Disease Treatment as Seen from a Mechanical Point of View," *Advances in Parkinson's Disease*, vol. 5, no. 4, pp. 97–106, Nov. 2016, doi: 10.4236/apd.2016.54012.

[12] M. S. Faizan and M. Muzammil, "Hand tremor suppression device for patients suffering from Parkinson's disease," *J Med Eng Technol*, vol. 44, no. 4, pp. 190–197, May 2020, doi: 10.1080/03091902.2020.1759708.

[13] A. Zulkefli, A. Muthalif, N. H. D. Nordin, and T. Syam, "Intelligent glove for suppression of resting tremor in Parkinson's disease," presented at the Vibroengineering PROCEDIA, Lithuania, Nov. 2019, pp. 176–181. doi: 10.21595/vp.2019.21078.

[14] J. F. Ong *et al.*, "Tremor stabilisation apparatus and methods," US11079225B2, Aug. 03, 2021 Accessed: Sep. 25, 2025. [Online]. Available: https://patents.google.com/patent/US11079225B2/en?oq=U.S.+Patent+11%2c079%2c225+B2

[15] S. K. Saleh, S. L. Mohammed, A. Al-Askery, and H. F. Jameel, "Investigation and development of hand tremor controlling device," *AIP Conf. Proc.*, vol. 2804, no. 1, p. 040009, Sep. 2023, doi: 10.1063/5.0155773.

[16] A. Kassim, K. Vasudevan, M. A. H. B. Azhar, and S. K. Manna, "Parkinson's Tremor Suppression: A Spring-Based Passive Attenuator System," in *2024 International Conference on Intelligent Cybernetics Technology & Applications (ICICyTA)*, Dec. 2024, pp. 1123–1128. doi: 10.1109/ICICYTA64807.2024.10912998.

[17] T. Nguyen, "Tremor reduction device," US20190059733A1, Feb. 28, 2019 Accessed: Sep. 25, 2025. [Online]. Available: https://patents.google.com/patent/US20190059733A1/en?oq=U.S.+Patent+Application+2019%2f0059733+A1

[18] T. M. Nguyen, "Tremor reduction device," WO2018044381A1, Mar. 08, 2018 Accessed: Sep. 25, 2025. [Online]. Available: https://patents.google.com/patent/WO2018044381A1/en?oq=Patent+Application+2018%2f044381

[19] A. Ziv-Av, "Methods and devices for reducing trembling," US6458089B1, Oct. 01, 2002 Accessed: Sep. 25, 2025. [Online]. Available: https://patents.google.com/patent/US6458089B1/en?oq=U.S.+Patent+6%2c458%2c089+B1

[20] M. A. Kalvert, "Adjustable and tunable hand tremor stabilizer," US6730049B2, May 04, 2004 Accessed: Sep. 25, 2025. [Online]. Available: https://patents.google.com/patent/US6730049B2/en?oq=U.S.+Patent+6%2c730%2c049+B2]

[21] P. D. PANISSE *et al.*, "Tremor stabilisation apparatus and methods," WO2016102958A1, Jun. 30, 2016 Accessed: Sep. 25, 2025. [Online]. Available: https://patents.google.com/patent/WO2016102958A1/en?oq=Patent+Application+2016%2f102958+

[22] H. Frahm, "Device for damping vibrations of bodies," US989958A, Apr. 18, 1911 Accessed: Sep. 25, 2025. [Online]. Available: https://patents.google.com/patent/US989958A/en?oq=.S.+Patent+989%2c958

[23] W.-J. Lee, K.-H. Park, Y.-G. Kang, and S.-J. Kim, "Automated Real-Time Evaluation of Condylar Movement in Relation to Three-Dimensional Craniofacial and Temporomandibular Morphometry in Patients with Facial Asymmetry," *Sensors*, vol. 21, no. 8, p. 2591, Jan. 2021, doi: 10.3390/s21082591.

[24] J. Fujikawa *et al.*, "Diagnosis and Treatment of Tremor in Parkinson's Disease Using Mechanical Devices," *Life*, vol. 13, no. 1, p. 78, Jan. 2023, doi: 10.3390/life13010078.

[25] A. Caroppo, A. Manni, G. Rescio, A. M. Carluccio, P. A. Siciliano, and A. Leone, "Movement Disorders and Smart Wrist Devices: A Comprehensive Study," *Sensors*, vol. 25, no. 1, p. 266, Jan. 2025, doi: 10.3390/s25010266.

[26] M. Keba, M. Bachmann, J. Lass, and T. Rätsep, "Assessing Parkinson's Rest Tremor from the Wrist with Accelerometry and Gyroscope Signals in Patients with Deep Brain Stimulation: An Observational Study," *Journal of Clinical Medicine*, vol. 14, no. 6, p. 2073, Jan. 2025, doi: 10.3390/jcm14062073.