TYPE Review
PUBLISHED 10 December 2025
DOI 10.3389/fmech.2025.1736935

OPEN ACCESS

EDITED BY
Rocco Furferi,
University of Florence, Italy

REVIEWED BY
Dan-Alexandru Szabo,
George Emil Palade University of Medicine, Pharmacy, Sciences and Technology of Târgu Mureş, Romania
Cristina Biris,
Lucian Blaga University of Sibiu, Romania

*CORRESPONDENCE
Giuliana Baiamonte,
giuliana.baiamonte@unict.it

RECEIVED 31 October 2025
REVISED 25 November 2025
ACCEPTED 28 November 2025
PUBLISHED 10 December 2025

CITATION
Baiamonte G, Elrawashdeh Z, Marrone S and Calì M (2025) MEMS sensors and biomechanical integration for the dynamic control of prosthetic hands: a scoping review.
Front. Mech. Eng. 11:1736935.
doi: 10.3389/fmech.2025.1736935

MEMS sensors and biomechanical integration for the dynamic control of prosthetic hands: a scoping review

Giuliana Baiamonte[1]*, Zeina Elrawashdeh[2,3], Salvatore Marrone[4] and Michele Calì[1]

[1]Electric, Electronics and Computer Engineering Department, University of Catania, Catania, Italy, [2]Institut catholique d'arts et métiers (ICAM), Site of Grand Paris Sud, Lieusaint, France, [3]ICB UMR CNRS 6303, University Bourgogne Franche-Comté UTBM, Belfort, France, [4]Department of Neurosurgery, Sant'Elia Hospital, Caltanissetta, Italy

The miniaturization and integration of micro-electromechanical systems (MEMS) have progressively expanded the capabilities of advanced prosthetic hands, enabling not only the replication of human sensory and motor functions but also the implementation of sophisticated mechatronic control, precise manipulation, and adaptive responses to environmental interactions. The aim of this scoping review is to systematically map and evaluate current research on MEMS-integrated prosthetic hands, highlighting how MEMS sensors and mechanical modelling approaches contribute to dynamic control, biomechanical performance and user-centered functionality. Comparative analyses of different modelling techniques and MEMS applications indicate that MEMS-based sensing systems substantially improve the mechanical performance of prosthetic hands by enabling accurate force modulation, enhancing motion stability during dynamic tasks and supporting efficient signal acquisition for real-time control. These features lead to more precise control, smoother movements and enhanced dexterity during activities of daily living (ADL), broadening the functional capabilities of the devices. Microsurgical and neural interface aspects were also examined, including physiological considerations relevant to neural integration and common challenges related to prosthetic implantation, such as potential immunological responses to materials. The increasing role of MEMS in the development of smart, biomimetic prosthetic hands underscores new opportunities for creating highly adaptive devices, optimizing dexterity and environmental interaction and ultimately improving users' quality of life.

KEYWORDS

MEMS sensors, biomechanical modelling, prosthetic hand, mechatronic systems, dynamic control, smart MEMS, smart hand prosthesis

1 Introduction

The micro-nanoscale devices' design offers significant advantages, including precise control, fast response, high energy-density efficiency and cost-effective production. These benefits have driven substantial advances in micro- and nano-electromechanical systems (MEMS and NEMS), leading to the development of different materials and manufacturing techniques that support a wide range of MEMS devices (Welburn et al., 2025). Pressure sensors, accelerometers, gyroscopes and temperature sensors provide essential feedback for fine control and precise handling, while MEMS resonators contribute to frequency stability, efficient signal processing and energy harvesting, increasing the overall performance and autonomy of the prosthetic system. The signals, collected by the sensors, are processed and converted into coordinated movements through miniaturized actuators and integrated mechatronic systems, enabling the hand to perform complex operations, i.e., gripping, rotation and dynamic adaptation to surfaces of varying shapes and textures.

This precise mechanical control, obtained thanks to the synergistic interaction between the MEMS components and the prosthetic structure, is essential to faithfully reproduce the functional dynamics of the human hand, ensuring fluid kinematics and fine dexterity. Recent studies have shown significant advances in the integration of MEMS into prosthetic hands, as well as the application of Machine Learning (ML) methods based on neural networks. The study (Ke et al., 2022) introduced a novel thumb structure and integrated fingertip tactile sensor to enable coupled movement and precision manipulation. The prosthetic hand's geometry was optimized using a new metric and Monte Carlo method, resulting in over 10% improved grasping ability and successful human-like thumb opposition in experiments. For amputees using prostheses without sensory feedback, the biggest challenge is handling unexpected events, especially object slippage during grasp and manipulation tasks. The study (Gentile et al., 2020) introduced a low-cost, low-computational touch-and-slippage detection algorithm for prosthetic hands, relying solely on the normal force component from monoaxial sensors. Results showed a 99.4% success rate in detecting slippage events with a computation time of just 4.9 ms, minimizing false positives/negatives. From materials side, ultra-high molecular weight polyethylene (UHMWPE) is widely used in joint replacements, but its wear debris could cause complications like aseptic loosening. The study (Dalli et al., 2023) evaluated a novel hip prosthesis with a unidirectional cylindrical design, aiming to reduce wear compared to the traditional ball-and-socket design. The study highlighted the importance of considering material behavior like molecular orientation in wear models, especially for innovative prosthesis designs. This insight could improve the durability and performance of future joint replacements. A review (Zhang, et al., 2025) analyzed sEMG-IMU sensor fusion techniques for upper limb movement pattern recognition, breaking down the signal generation of surface electromyography (sEMG) and inertial measurement units (IMU). It examined multisensory fusion strategies to improve accuracy and reliability in movements.

Advanced sensor data and machine learning algorithms, such as Stacked Bidirectional Long Short-Term Memory (SBLSTM), Adaptive Neuro-Fuzzy Inference System (ANFIS), Convolutional Neural Network (CNN), Logistic Regression (LR), and K-Nearest Neighbours (KNN), were compared, with the SBLSTM model achieving the highest accuracy (96.3%) and fastest inference time (25 ms), making it most suitable for real-time prosthetic control (Kumar and Pratihar, 2025). Another study (Yang et al., 2025) developed a lightweight prosthetic hand with 19 degrees of freedom, using shape-memory alloy actuators to precisely control the fingers and wrist, thus approaching the functionality of the human hand (Sankar et al., 2025). introduced a biomimetic prosthetic hand with soft robotic joints and a rigid exoskeleton, integrating three independent layers of neuromorphic touch sensors for advanced sensory perception. Recent advances in computer-aided design, engineering and manufacturing (CAD-CAE-CAM) have profoundly transformed the design and production of medical devices, offering opportunities for customization, precision and rapid prototyping. In the orthopaedic sector, as in dental one, CAD-based workflows and 3D printing technologies are continuously evolving to reduce treatment procedures, enhance material efficiency and improve patient outcomes. In particular, additive manufacturing plays a pivotal role with its rapid expansion across diverse fields, i.e., maritime, aerospace and civil engineering, that has drastically shortened production times for new products. This approach enables the creation of complex three-dimensional geometries directly from digital models generated within a CAD environment, facilitating accurate and repeatable fabrication processes (Baiamonte et al., 2024). In the field of prosthetic hand design, this evolution is closely linked to the adoption of additive manufacturing, which marks a shift away from traditional subtractive techniques like milling. Additive technologies enable the creation of customized, anatomically accurate medical devices, ultimately improving patient outcomes and restoring the ability to perform daily activities with near-physiological interaction with the environment. Conversely, conventional precision manufacturing remains essential when achieving specific surface roughness and dimensional accuracy is critical, particularly in high-precision mechanical applications where both economic efficiency and product quality must be ensured (Calì et al., 2025). Furthermore, finite element analysis (FEA) is increasingly employed to evaluate the mechanical resistance of components under load, ensuring compliance with defined design and safety requirements (Seminara et al., 2022). Within this scoping review, the current state of prosthetic hand development is analysed, comparing various CAD modeling technologies and highlighting critical mechanical and design aspects. The purpose is to systematically map and evaluate current research on the mechanical modelling approaches and the integration of MEMS sensors with EMG signals in prosthetic hand design, with the aim of identifying their contribution to dynamic control, biomechanical performance and user-centred functionality. Aspects of microsurgery and interface physiology were also considered, including the use of MEMS as electrodes for nerve interaction, common issues with implantable prostheses such as potential immune reactions to materials, and the importance of targeted microsurgical debridement and bone stump curettage, removing avascular or necrotic areas prior to prosthetic implantation. The findings emerging from the analysed literature show that MEMS-based sensing systems significantly enhance grasping force modulation, motion stability and real-time control responsiveness, while advanced mechanical architectures, such as tendon-driven mechanisms, multi-link transmissions and synergy-inspired designs, enable more natural, coordinated and adaptable movements. By consolidating these technological trends, the review provides an updated overview of the most effective strategies currently used to approach human-like dexterity, highlighting both the progress achieved and the challenges that still limit the full biomimetic integration of prosthetic hands. The research study is divided into four sections, excluding the introduction: Section 2 shows the materials and methods adopted, Section 3 draws the results and discussion of the scoping review, Section 4 discusses the microsurgery and physiological

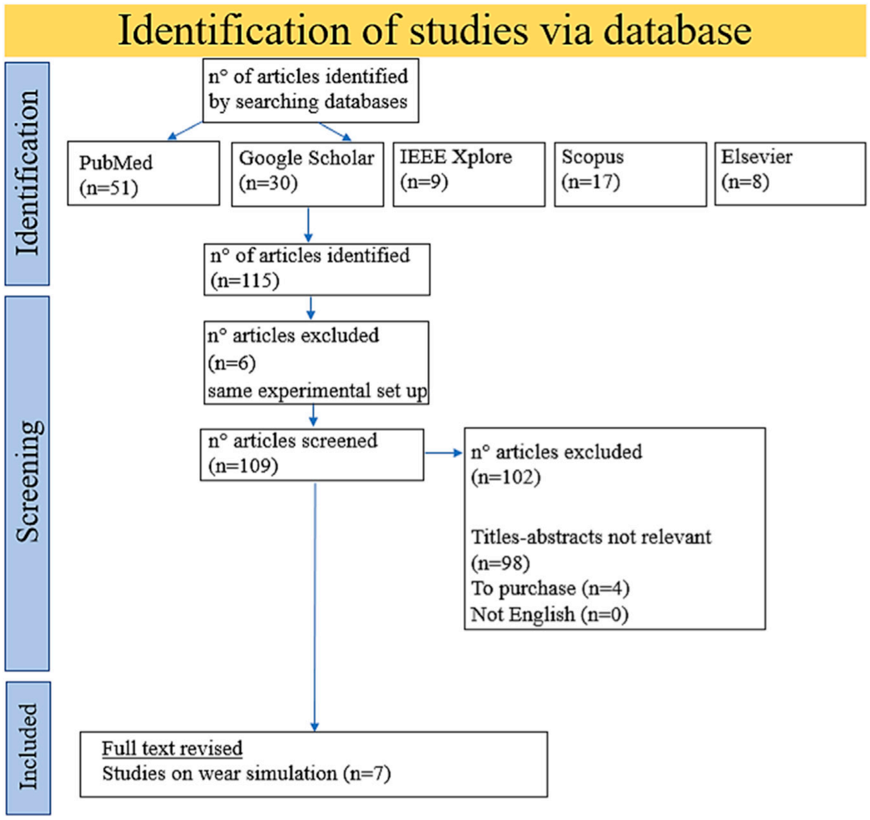

FIGURE 1
PRISMA flow diagram illustrating the study selection process.

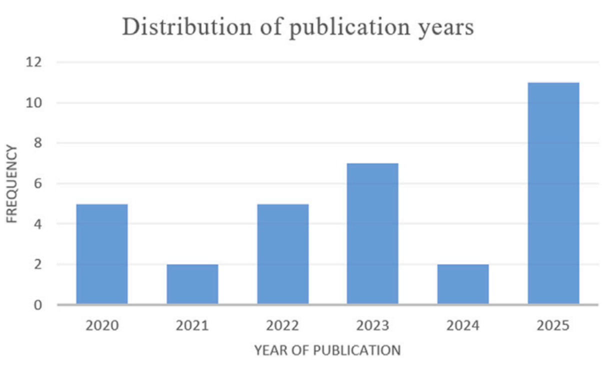

FIGURE 2
Timeline distribution of the included studies and other publications, emerged in recent years.

aspects of interface systems and finally Section 5 describes the conclusions.

2 Materials and methods

This scoping literature review was conducted following the PRISMA guidelines (Moher et al., 2009). For all studies, the authors performed an electronic search, conducted to identify articles that address the adopted techniques for MEMS sensors and mechanical modelling of prosthetic hands; the authors manually screened reference lists of included articles. The approach adopted can be considered inclusive, as a wide range of studies were considered, identifying gaps in research and without applying overly restrictive selection criteria. This has allowed authors to obtain a more complete picture of what has already been studied and to identify any areas that are still unexplored, as well as providing a basis for more detailed future studies. The following PRISMA flow diagram (Figure 1) describes the literature screening process adopted in the scoping review and inclusion process (Figure 2).

2.1 Literature search and study selection

The search strategy combined keywords related to prosthetic hands, MEMS-based sensing and biomechanical modelling. The Boolean operators AND and OR were used to refine the search with combination of the MeSH Terms reported in Table 1 i.e., prosthetic hand, MEMS sensors, biomechanical modeling, mechanical modeling and mechatronic system, to make it appear in the title of the publication. A structured and comprehensive literature search was performed from 21 July 2025 to 15 September 2025 across five major databases (PubMed, Scopus, Google Scholar, Elsevier, IEEE Xplore), selected for their combined coverage of biomedical engineering, sensor technology and mechanical design research.

TABLE 1 An overview of the databases consulted, the search phrases used to find the articles and the number of records identified in each search.

Database	No. Articles	Search phrase
PubMed	51	-
Scopus	17	Biomechanical modeling AND dynamic control AND prosthetic hand OR mechatronic systems
Google scholar	30	Biomechanical modeling AND prosthetic hand OR MEMS sensors AND prosthetic hand
Elsevier	8	Dynamic control AND prosthetic hand
IEEE Xplore	9	Mechatronic system OR MEMS sensors AND mechanical modeling

The selection of these databases was specifically designed to encompass a broad spectrum of medical and engineering publications, ensuring a comprehensive exploration of the interdisciplinary nature of the study. The search covered publications from 2020 to 2025 to capture recent research, highlighting potential advancements and improvements over time. The scoping literature search in the after-mentioned databases identified 7 records. All titles and abstracts of retrieved articles were screened from the electronic database searches and any discrepancies between the authors were resolved via discussion when necessary.

2.2 Eligibility criteria

The screening process was carried out in two stages. First, titles and abstracts were independently reviewed to exclude articles clearly unrelated to MEMS-based prosthetic hand technologies. Subsequently, the full texts of potentially eligible articles were examined in detail. Two reviewers independently conducted both screening steps and disagreements were resolved by discussion and consensus. The inclusion criteria were considered to capture studies published in English, combining the following topics: prosthetic hand systems integrating MEMS sensors or micro-scale sensing technologies; mechanical design, structural modelling, actuation systems, CAD-based modelling or biomechanical analysis. Exclusion criteria were applied to remove studies lacking technical, mechanical or biomedical relevance and repetitive research works. This filtering process ensured that the final selection of studies provided both methodological consistency and scientific relevance, supporting a critical comparison of existing approaches.

2.3 Data extraction

Particular attention was paid to studies reporting on MEMS sensors and the mechanical modelling of hand prostheses, with a focus on the most recent and advanced techniques employed in these fields. All extracted information and reported results were systematically compared across studies and discussed. The synthesis and interpretation phases were conducted collaboratively by all authors, who jointly reviewed the evidence to establish consensus on the relevance and implications of the reported findings.

2.4 Data synthesis

After data extraction, a single reviewer independently synthesized the collected information. First, all data were organized into structured tables to provide a clear overview of the material currently available in the literature. The results were then analyzed and reported, emphasizing the main similarities and differences among the included studies, with the aim of comprehensively addressing the key questions of the scoping review.

2.5 Research questions

To guide the analysis of the collected data, two main research questions were formulated to investigate how the integration of MEMS sensors and mechanical components contributes to the development of advanced hand prostheses. Specifically, the review examined how MEMS sensors improve the acquisition and processing of biomechanical signals and how mechanical modelling and structural design enable the precise reproduction of grasping dynamics. By addressing these complementary aspects, the analysis aimed to assess their combined influence on achieving reliable and responsive force feedback, which is crucial for enhancing the functionality, adaptability and overall user experience of smart prosthetic hands.

RQ1: What is the role of MEMS sensors in enabling accurate and responsive grasping force feedback in hand prostheses?
RQ2: Which mechanical modelling approaches are used to replicate the complexity and natural movement of the human hand in prosthesis design?"

These research questions were defined to structure and guide the analysis of the collected data. Their formulation is based on gaps identified in the existing literature and on the need to obtain a clearer understanding of the techniques and devices adopted to date. In particular, they were organized according to the Population, Concept, Context (PCC) framework, analyzing hand prosthesis designs, the concept of integrating MEMS sensors with mechanical and mechatronic modelling and the context of dynamic control strategies and smart prosthetic applications. The resulting data collected in this review were summarized and presented in the following sections.

TABLE 2 Mechanical design features of existing robotic prosthetic hands.

Authors	Material	Actuation system	Type of motion	Wearable weight (g)	Application	Perception method	Force applied (N)
Annatto, G. P. et al.	PLA, 3Dprinted (weight reduction 37%)	Linear actuator on arm (reducing torsion) + lead-screw mechanism + DC motor (1DOF per finger)	Flexion–extension, hook grasp; adaptive contact	564	Adult, teenager trans-radial amputees	N/A	49 N by upper finger; FEM simulation on components to measure displacements of elements during the applied load; maximum stress in connection between palm and arm (17.60 MPa)
Yang, H. et al.	Polymer composite, SLA3D- printer (Form2, Formlabs) Photopolymer resin (FLGPWH04) for hand and forearm	38 SMA micro-actuators + tendon-driven mechanism + battery on forearm's external shell	19DOF (bending/ rolling); max 2.5 kg load capability	370	Trans-radial, partial-hand amputees	Voice command modules with a closed-loop control system + Hall sensors	7
Zhang T. et al.	Silicon on fingertips	Miniaturized-DC motors + cable-driven joints; 3-axis tactile sensor in fingertips; motor for abduction-adduction	Hand open, power grasp, tip, tripod	N/A	Trans-radial amputees	EMG pattern recognition + desired angles of each finger calculated on inverse kinematics and grasping posture	Fingertip grasping force: 12N (able to handle fragile, rigid objects)
Mohammadi, A. et al.	3D printed TPU + Silicon pads (flexible materials)	Single servomotor spool in forearm; tendon connected to servomotor + whiffletree mechanism; transmission to fingers (1 DOF per finger)	Pinch grasp	50–500	Wide range of application	Actuation force + inverse model achieving desired finger synergy-joint angles; nonintegrated EMG sensor	N/A
Krepsky, D. V. et al.	3D printed in PLA	6×MG90S servomotors into hand casing; transmission via double-rocker/ four-bar for each finger; charging system; wristwatch (RTC DS3231 module, GC9A01 display); microprocessor integration	6DOF (opened-closed hand, grasping in different orientations)	2,300 (shopping bag)	Low-cost hand prosthesis for ADL	EMG signal processing (noise at 60 Hz minimized by low-pass filter; second-order Butterworth filter (cutoff frequency of 5 Hz)	N/A
Mughal, F. M. et al.	N/A	Two control joints operated by Faulhaber DC micro-motor (series 2224SR) + gearbox + rotational spring + rotary dampers	Rotational motion; no degree of freedom between mid-distal inter-phalange	N/A	Partial amputations	Arduino controller; auto-tuned-PID control blocks	N/A

3 Results and discussion

A total of 115 articles were initially identified through the database search and 109 remained after duplicate removal. Following a detailed screening process and full-text assessment, 7 studies met the inclusion criteria and were included in this scoping review. Table 2 summarizes the main technical and mechanical characteristics of the analyzed prosthetic hand systems, including mechanism placement, wearable weight, force capabilities, and clinical applications. The following sections provide a more in-depth comparative discussion of these technologies, focusing on the key findings and highlighting how each approach contributes to improve dexterity, adaptability and sensory feedback in modern prosthetic hands.

 10.3389/fmech.2025.1736935

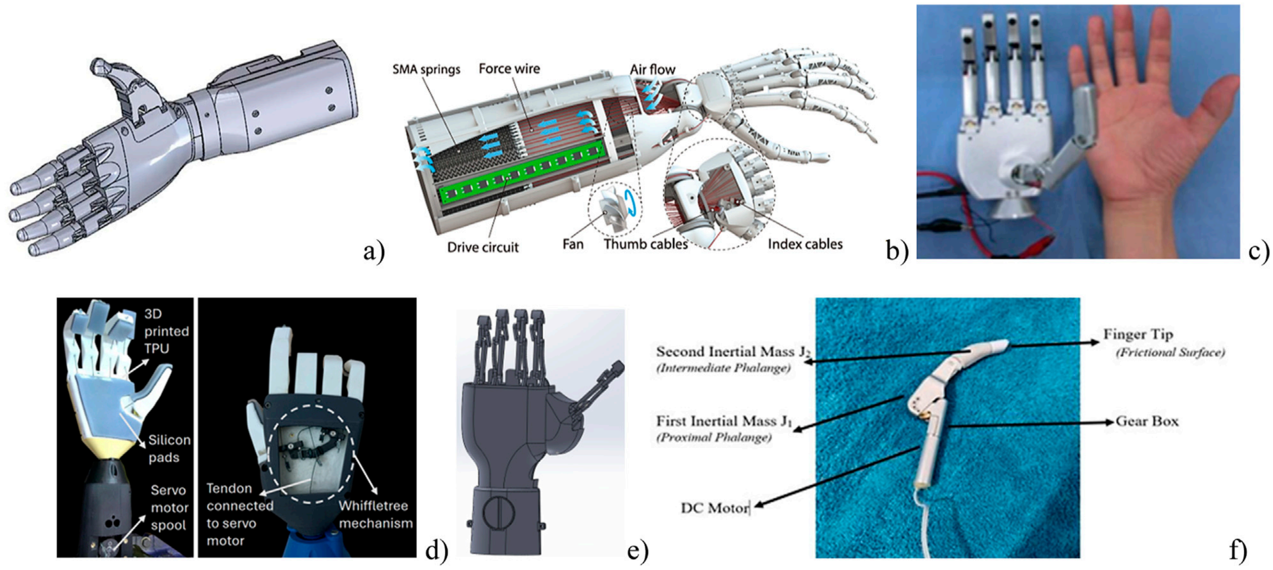

FIGURE 3
(a) Active prosthetic hand: Asto V.4 (Annanto et al., 2021); **(b)** Prosthetic hand with 19-DOF dexterity (Sankar et al., 2025); **(c)** Dexterous Prosthetic Hand (Zhang et al.,2022); **(d)** Single-Actuator Soft Robotic Prosthetic Hand (Mohammadi et al., 2025); **(e)** Low-Cost Biomechanical Hand Prosthesis (Krepsky et al., 2025); **(f)** Robotic finger with mechanical assemblies (Mughal and Mughal, 2023).

3.1 Biomechanical modeling for prosthetic hand design

The research work (Annanto et al., 2021) described the Asto Hand V4, an optimized version of the previous Asto Hand V3.5 designed for trans-radial amputees (Figure 3a). The upgraded model emphasizes mechanical balance, reduced mass and improved ergonomic performance to enhance comfort and functionality under dynamic loading conditions. Structurally, it consists of four main components, i.e., upper finger, lower finger, palm and arm segment, tested under a hook grasp configuration. All structural elements were manufactured in PLA through 3D printer, chosen for its good mechanical properties and low weight. It provides an optimal trade-off between lightweight design and mechanical strength with elastic modulus equal to 3.5 GPa, yield strength equal to 70 MPa, ultimate tensile strength of about 73 MPa. The overall mass was reduced to 564 g (−37%) and the palm–forearm length decreased from 163 mm to 141 mm (−13%), improving usability for younger users. Finite element simulations, under a 112.8 N load, confirmed stress values well below material failure limits, supporting structural reliability and functional durability.

Other authors (Yang et al., 2025) introduced an ultra-lightweight, anthropomorphic prosthetic hand integrating 19 degrees of freedom (DOF), designed to closely replicate human hand biomechanics. The system integrates compliant and rigid elements within a hybrid architecture to ensure both strength and flexibility, achieving a total weight of approximately 370 g (Figure 3b). A study (Zhang et al., 2022) proposed a sensorimotor-inspired prosthetic hand, designed to replicate the interaction between sensory perception and motor execution during grasping tasks. The device includes five anthropomorphic finger modules, each composed of two links with both joints driven by a single motor via a cable system; an additional motor controls thumb abduction and adduction. Experimental tests showed stable manipulation of fragile objects, i.e., eggs, fruit and glass items without slippage or deformation, confirming precise control, dynamic stability and suitability for daily use (Figure 3c). Mohammadi et al. (2025) developed a soft robotic hand actuated by a single servo motor, with two flexure joints per finger: the metacarpophalangeal (MCP) and the proximal interphalangeal (PIP) joints. The entire structure was 3D-printed in thermoplastic polyurethane (TPU, Shore 85A), whose elastic properties provide both durability and flexibility during high-deformation tasks. Using inverse design optimization, joint stiffness parameters were optimized to reproduce desired hand postures, specifically power and pinch grasps, achieved with tendon displacements of approximately 57 mm. The motor and transmission components were integrated into the forearm near the wrist, improving balance and ergonomics (Figure 3d). (Krepsky et al., 2025) proposed a low-cost biomechanical prosthetic hand with all components 3D-printed in PLA. Experimental tests demonstrated that the hand could lift loads up to 2.3 kg, performing daily manipulation tasks with approximately 90% success in vertical grasping and 80% in varied orientations (Figure 3e).

A study (Mughal and Mughal, 2023) developed a biomechanical model of a prosthetic finger with a frictional surface at the fingertip for improved grip, along with an electromechanical assembly composed of gears, springs and dual-link configuration. Simulation results showed that adjusting stiffness and damping parameters significantly affects movement smoothness, force transmission, energy efficiency and overall system stability (Figure 3f).

3.2 Sensor-based actuation methods

Several sensor-based actuation strategies have been proposed in recent literature, each aiming to improve the precision, responsiveness and naturalness of motion in upper-limb prostheses. The studies reviewed demonstrate how different mechanical layouts, motor technologies and control algorithms can be integrated to achieve stable and adaptable grasping functions (Annanto et al., 2021). Repositioned linear actuators from the palm to the forearm to reduce torsional stresses on the residual limb and to optimize internal space for embedded control electronics (Yang et al., 2025). Developed a prosthetic hand in which each finger includes three active DOFs, driven by 38 shape memory alloy (SMA) micro-actuators coupled to tendon-based transmission systems, while the thumb includes four DOFs, allowing opposition and circumduction movements similar to a natural hand. A differential mechanism integrated into the palm distributes forces during grasping. Control is achieved through a voice-command interface that allows users to drive finger and wrist movements, significantly improving functional autonomy. The SMA actuators can deliver up to 7 N of usable force, supporting grasping of objects up to approximately 2.5 kg.

(Zhang et al., 2022) employed a distributed actuation configuration in which each finger is driven by miniaturized DC motors linked to cable-based joints, while triaxial tactile sensors embedded in the fingertips detect shear and normal forces during object interaction. An adaptive admittance control algorithm modulates motor output to prevent slippage during manipulation, enabling stable and precise contact with surfaces of varying geometry. In the soft robotic hand (Mohammadi et al., 2025) actuation relies on linear screw-driven mechanisms coupled with compliant flexure joints at the MCP and PIP levels. This configuration enables smooth flexion/extension and hook grasp movements using a single motor. Although sensory or EMG-based feedback has not yet been integrated, the mechanical system supports multiple grasp types suitable for objects of different shapes and size.

(Krepsky et al., 2025) designed a prosthetic hand actuated by six MG90S servo motors embedded within the palm, each driving a finger through double-rocker and four-bar linkages that replicate the motion of the three human phalanges. All electronic components are housed within the prosthesis shell, and jumper connections ensure compact and reliable wiring. This configuration enables coordinated flexion/extension with anthropomorphic kinematics in a lightweight and manufacturable form factor. The prosthetic system (Mughal and Mughal, 2023) employs a Faulhaber 2224SR DC micro-motor to achieve biomimetic flexion/extension with minimal mechanical complexity. A PID-based control architecture, implemented in MATLAB/Simulink using the Simscape Toolbox, ensure stable angular control architecture with rise times below 0.2 s. Hardware-in-the-loop testing confirmed the accuracy of angular and velocity profiles even under extreme operating conditions, demonstrating reliable system responsiveness suitable for prosthetic finger applications.

3.3 MEMS sensor types in prostheses

Although MEMS devices differ from natural skin in structure and energy transduction, they can detect a wide range of contact forces with fast response, high precision, and broad sensitivity (Ge and Cretu, 2022). In prosthetic applications, sensors capable of detecting the low-impact forces typical at the fingertips are most effective. Generally, circular capacitive and piezoresistive pressure sensors have been considered in MEMS with composite membranes made of silicon, silicon nitride and silicon oxide (Mishra et al., 2019). For example (Masteller et al., 2021), developed a two-layer linear array capacitive MEMS sensor to enhance texture recognition through improved sensitivity and spatial resolution. Moreover, these prosthetic systems can be integrated with EMG control, enabling MEMS sensors to translate signals from residual muscles into precise movements while providing tactile and positional feedback. Thus, the combination of EMG and MEMS-based sensing delivers comprehensive sensory feedback, significantly enhancing prosthetic control.

By using six EMG electrodes on the left arm, the prosthesis mechanically replicates the seven kinetic phases of natural grasping, i.e., reach, load, lift, hold, replace, unload, and release via a biomimetic joint system, that enables smooth flexion and adaptive contact (Zhang et al., 2022). The control system, developed by (Krepsky et al., 2025), is based on surface electromyography and through a simplified acquisition chain and an ESP32 microcontroller, it is possible to transmit signals to an Arduino with real-time filtering. Although there are still some difficulties in using these devices to grasp rigid or small objects, due to the limited adaptability of the fingers and occasional false positives from the EMG sensors, they represent a promising solution for daily activities in resource-limited settings.

4 Microsurgery and physiological aspects of interface systems

As early as the beginning of the 20th century, Roy envisioned scenarios in which neurosurgery could enable functional restoration or even augmentation of body parts through the implantation of small electronic devices, then referred to as “smart systems” (Roy et al., 2001). MEMS are electrodes that can work as sensors or actuators, and they played a key role in the development of so-called interface systems, so points of interaction with a specific anatomical structure (i.e., brain, muscle, nerve) (Guo et al., 2022; HajjHassan et al., 2008). Indeed, the name of these systems changes depending on the structure with which the electrode interfaces, therefore we mainly distinguish between muscle-interface and neural-interface systems. In myoelectric interfaces, signals are derived from electromyographic recordings of agonist-antagonist muscle groups in the limb stump, obtained via surface electrodes applied to the skin or through implantable electrodes (Tapia et al., 2020; Chen et al., 2023). Among the latter, epimysial electrodes are sutured onto the connective tissue sheath, while intramuscular electrodes penetrate the epimysium (Earley et al., 2025; Yildiz et al., 2020).

In neural-interface systems, the main structures interacting with electrodes are the brain or the peripheral nerve (Russell et al., 2019). Brain-computer interfaces rely on electro-encephaloghraphy (EEG) recordings, in which cortical waves represent inputs to generate signals translated into motion, and the interaction electrodes may be surface electrodes placed by a scalp helmet (Orban et al., 2022) or subdural electrodes implanted directly on the motor cortex (Mokienko 2024). Electrodes that interact with the nerve can be classified as either extra-neural or intraneural. The former varies in shape and can be sutured onto the epineurium or arranged around the nerve (helical, spiral cuff) (Yildiz et al., 2020; Larson and Meng, 2020). Implantation of intraneural electrodes requires exposure of nerve fascicles after an epineurium incision, taking care not to compromise the microcirculation (vasa nervorum). The electrode is then inserted perpendicularly, trying to involve as many fascicles as possible (Bumbaširević et al., 2019). Radial and ulnar nerves are most commonly used in intraneural microsurgery, as they have both sensory and motor components (Yildiz et al., 2020; Larson and Meng, 2020). The electrode records depolarisation propagating in a "saltatory way" along the Ranvier nodes, where voltage-dependent Na^+ channels alternate along the myelinated motor fibers (Stadelmann et al., 2019). It may also record the resulting striated muscle contraction electromyographically, which occurs once the action potential has reached the neuro-muscular junction (Chen et al., 2023). As evinced from recent studies, targeted electrical stimulation may modify muscle physiology inducing muscle adaptation thanks to an optimal recruitment of fast-twitch fibers (Lin et al., 2025). The development of neuromas at the distal end of damaged nerve is a post-amputation phenomenon that can occur later. To reduce this risk, some techniques to stimulate axonal sprouting have been developed, such as the regenerative peripheral nerve interface (RPNI) and targeted muscle reinnervation (TMR). In RPNI, the free end of the nerve is implanted into free devascularised muscle clusters, after microsurgical neuroma excision if necessary (Leach et al., 2023). TMR involves grafting the main upstream nerves (radial, ulnar, median and muscolocutaneous nerves) into the pectoralis muscles. Once the nerve signal could activate pectoral muscles contraction, it is recorded by chest electrodes and translated into prosthetic movement (Mauch et al., 2023). A common challenge for all implantable prostheses is the risk of a hyperactive immune response, in which the body recognizes the implant as foreign, potentially leading to rejection (Mariani et al., 2019). Bioengineering advances in recent decades have encouraged the study and development of biocompatible materials that do not hinder bio-integration thanks to their very low immunogenicity, but rather accompany the linear growth of tissues (Ciulla et al., 2023). Although peripheral Schwann cells can replicate and stimulate nerve regeneration, a phenomenon known as Wallerian degeneration may occur after amputation. In these cases, if the stump nerve is not properly stimulated and is subjected to mechanical or inflammatory stress, it can degenerate, hindering the engraftment of sutures (Tian et al., 2024). Some malignant tumours, such as hand sarcomas, may destroy adjacent tissues prior to resection, compromising the integrity of vessels and nerves. In these cases, adjuvant radiotherapy could also slow down the phases of osseointegration and peripheral myelin regeneration, leading to the development of excessive fibrotic scar tissue around neurovascular structures and making microsurgery particularly challenging (Zagardo et al., 2025). In such cases, a targeted microsurgical debridement and curettage of the bone stump, removing avascular or necrotic areas, should be performed before prosthetic implantation. Secondary conditions following limb loss, such as phantom limb syndrome (PLS), involve maladaptive neuroplasticity and may hinder functional integration of the prosthesis due to excessive pain (Kaur and Guan, 2018). However, when prosthetic implantation is combined with targeted physiokinesitherapy, it may promote adaptive neuroplasticity in cerebral area of hand control, counteracting PLS development (Makin and Flor, 2020). Ultimately, a multidisciplinary collaboration between neurosurgeons and biomedical engineers in the refinement of these devices will be essential to optimize treatment strategies, improve quality of life, and support the patient's psychological well-being (Marrone et al., 2025).

5 Conclusion

The upper limbs are essential not only for performing daily tasks such as grasping, holding and manipulating objects, but also for enabling social and communicative interactions, including gestures and handshakes. Consequently, for individuals experiencing upper-limb amputation, the sudden loss of motor functionality results in physical and socio-economic consequences, severely reducing independence and overall quality of life. This scoping review on MEMS sensors and mechanical design for prosthetic hand control highlights how innovations in mechanical design, actuation systems and materials engineering are progressively narrowing the performance gap between artificial and biological hands. The prosthetic prototypes examined range from highly articulated, sensor-rich hands featuring MEMS-based control, to simplified tendon- or linkage-driven mechanisms, each pursuing an optimal balance between dexterity, compactness and mechanical robustness. Relocating actuators in the forearm to reduce distal inertia, incorporating compliant mechanisms for adaptive grasping and optimizing gear ratios, stiffness, and damping parameters, contribute to achieve human-like motion dynamics under realistic loading conditions.

Regarding the first research question, results clearly demonstrate that MEMS sensors significantly enhance prosthetic hand performance by enabling accurate and responsive grasp force feedback. Their high-resolution pressure, inertial and thermal measurements allow fine modulation of gripping forces, improve stability during dynamic manipulation and support robust real-time control loops that closely approximate physiological sensorimotor pathways. Thus, interaction with objects of varying stiffness and geometry is improved. Regarding the second research question, the analysis shows that a wide range of mechanical modelling approaches, including tendon-driven systems, differential mechanisms, multi-link kinematic chains, flexure-based joints and synergy-inspired concepts, are employed to reproduce the complexity of human hand motion. Supported by CAD parametric modelling, finite element analysis (FEA) and dynamic simulation, these models enable refinement of joint biomechanics, improvements in transmission efficiency and in motion patterns, closely mirroring anatomical function.

Despite substantial advancements, including lighter structures, improved stability and increased control precision several challenges remain. These include achieving higher force-to-weight ratios, ensuring long-term structural durability and improve the adaptability of the fingers, minimizing false positives from the EMG sensors. Ultimately, the future of prosthetic hand development lies in advanced materials and neural interfacing, incorporating myoelectric or peripheral nerve interfaces that directly connect artificial limbs with the nervous system. This approach will develop devices that combine structural robustness with the natural adaptability and perceptual feedback characteristic of the human hand.

Author contributions

GB: Conceptualization, Writing – review and editing, Investigation, Methodology, Supervision, Writing – original draft. ZE: Writing – review and editing, Investigation, Writing – original draft. SM: Writing – review and editing, Investigation. MC: Validation, Writing – review and editing, Supervision.

Funding

The author(s) declared that financial support was not received for this work and/or its publication.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that generative AI was not used in the creation of this manuscript.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

References

Annanto, G. P., Haryanto, I., and Ismail, R. (2021). "A computational stress analysis of active prosthetic hand "Asto Hand V4" for the loaded hook position," in 2021 IEEE International Biomedical Instrumentation and Technology Conference (IBITeC) (IEEE), 130–135.

Baiamonte, G., Ambu, R., Laudani, G., Di Martino, G., and Calì, M. (2024). "Design and additive manufacturing of customized orthotic parts using innovative bio-composite thermoplastic filaments," in International Conference on Flexible Automation and Intelligent Manufacturing, Cham (Springer Nature Switzerland), 74–82.

Bumbaširević, M., Lešić, A., Palibrk, T., Georgescu, A. V., Matei, I. R., Vučetić, Č., et al. (2019). What microsurgeon, orthopaedic and plastic surgeon should know about bionic hand. *Injury* 50 (Suppl. 5), S137–S140. doi:10.1016/j.injury.2019.10.065

Calì, M., Baiamonte, G., Laudani, G., Di Martino, G., and Grasso, M. (2025). An accurate roughness prediction in milling processes through analytical evaluation and KNN regression approach. *Int. J. Adv. Manuf. Technol.* 138 (1), 137–154. doi:10.1007/s00170-024-14526-3

Chen, Z., Min, H., Wang, D., Xia, Z., Sun, F., and Fang, B. (2023). A review of myoelectric control for prosthetic hand manipulation. *Biomimetics (Basel)* 8 (3), 328. doi:10.3390/biomimetics8030328

Ciulla, M. G., Massironi, A., Sugni, M., Ensign, M. A., Marzorati, S., and Forouharshad, M. (2023). Recent advances in the development of biomimetic materials. *Gels* 9 (10), 833. doi:10.3390/gels9100833

Dalli, D., Fanton, L., Mallia, B., Wismayer, P. S., Buhagiar, J., and Mollicone, P. (2023). Polyethylene wear simulation models applied to a prosthetic hip joint based on unidirectional articulations. *Journal Mechanical Behavior Biomedical Materials* 142, 105882. doi:10.1016/j.jmbbm.2023.105882

Earley, E. J., Kristoffersen, M. B., and Ortiz-Catalan, M. (2025). Comparing implantable epimysial and intramuscular electrodes for prosthetic control. *Front. Neurosci.* 19, 1568212. doi:10.3389/fnins.2025.1568212

Ge, C., and Cretu, E. (2022). Bionic MEMS for touching and hearing sensations: recent progress, challenges, and solutions. *J. Bionic Eng.* 19 (3), 590–615. doi:10.1007/s42235-022-00159-3

Gentile, C., Cordella, F., Rodrigues, C. R., and Zollo, L. (2020). Touch-and-slippage detection algorithm for prosthetic hands. *Mechatronics* 70, 102402. doi:10.1016/j.mechatronics.2020.102402

Guo, Z., Wang, F., Wang, L., Tu, K., Jiang, C., Xi, Y., et al. (2022). A flexible neural implant with ultrathin substrate for low-invasive brain-computer interface applications. *Microsyst. Nanoeng.* 8, 133. doi:10.1038/s41378-022-00464-1

HajjHassan, M., Chodavarapu, V., and Musallam, S. (2008). NeuroMEMS: neural probe microtechnologies. *Sensors (Basel)* 8 (10), 6704–6726. doi:10.3390/s8106704

Kaur, A., and Guan, Y. (2018). Phantom limb pain: a literature review. *Chin. J. Traumatol.* 21 (6), 366–368. doi:10.1016/j.cjtee.2018.04.006

Ke, A., Huang, J., Wang, J., Xiong, C., and He, J. (2022). Optimal design of dexterous prosthetic hand with five-joint thumb and fingertip tactile sensors based on novel precision grasp metric. *Mech. Mach. Theory* 171, 104759. doi:10.1016/j.mechmachtheory.2022.104759

Krepsky, D. V., Cardoso, J. P. D. S., Gt, G. C., Lickfeld, D. H., Rincon, L. M., and El Youssef, E. S. (2025). "Development of a low-cost biomechanical hand prosthesis prototype," in 2025 Brazilian Conference on Robotics (CROS) (IEEE), 1–6.

Kumar, V., and Pratihar, D. K. (2025). Wearable sensor-based intent recognition for adaptive control of intelligent ankle-foot prosthetics. *Meas. Sensors* 39, 101865. doi:10.1016/j.measen.2025.101865

Larson, C. E., and Meng, E. (2020). A review for the peripheral nerve interface designer. *J. Neurosci. Methods* 332, 108523. doi:10.1016/j.jneumeth.2019.108523

Leach, G. A., Dean, R. A., Kumar, N. G., Tsai, C., Chiarappa, F. E., Cederna, P. S., et al. (2023). Regenerative peripheral nerve interface surgery: anatomic and technical guide. *Plast. Reconstr. Surg. Glob. Open* 11 (7), e5127. doi:10.1097/GOX.0000000000005127

Lin, X., Hu, Y., and Sheng, Y. (2025). The effect of electrical stimulation strength training on lower limb muscle activation characteristics during the jump smash performance in badminton based on the EMS and EMG sensors. *Sensors* 25 (2), 577. doi:10.3390/s25020577

Makin, T. R., and Flor, H. (2020). Brain (re)organisation following amputation: implications for phantom limb pain. *Neuroimage* 218, 116943. doi:10.1016/j.neuroimage.2020.116943

Mariani, E., Lisignoli, G., Borzì, R. M., and Pulsatelli, L. (2019). Biomaterials: foreign bodies or tuners for the immune response? *Int. J. Mol. Sci.* 20 (3), 636. doi:10.3390/ijms20030636

Marrone, S., Gueli, I. A., Lo Coco, R., Scalia, L., Rizzica, S., Baiamonte, G., et al. (2025). Brain metastases from primary cardiac tumors: a systematic review of diagnosis, treatment, and prognosis. *Cancers* 17 (10), 1621. doi:10.3390/cancers17101621

Masteller, A., Sankar, S., Kim, H. B., Ding, K., Liu, X., and All, A. H. (2021). Recent developments in prosthesis sensors, texture recognition, and sensory stimulation for upper limb prostheses. *Ann. Biomedical Engineering* 49 (1), 57–74. doi:10.1007/s10439-020-02678-8

Mauch, J. T., Kao, D. S., Friedly, J. L., and Liu, Y. (2023). Targeted muscle reinnervation and regenerative peripheral nerve interfaces for pain prophylaxis and treatment: a systematic review. *PM R.* 15 (11), 1457–1465. doi:10.1002/pmrj.12972

Mishra, R. B., Santosh Kumar, S., and Mukhiya, R. (2019). "Modeling and fem-based simulations of composite membrane based circular capacitive pressure sensor," in Advances in VLSI, Communication, and Signal Processing: Select Proceedings of VCAS 2018 (Singapore: Springer Singapore), 497–506.

Mohammadi, A., Han, K. H., Bani, M. A., Raschke, S. U., Tan, Y., Choong, P., et al. (2025). "Encoding desired postural synergies in a single-actuator soft robotic prosthetic hand through finger joint stiffness modulation," in 2025 International Conference On Rehabilitation Robotics (ICORR) (IEEE), 693–698.

Moher, D., Liberati, A., Tetzlaff, J., Altman, D. G.PRISMA Group (2009). Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *Bmj* 339, b2535. doi:10.1136/bmj.b2535

Mokienko, O. A. (2024). Brain-computer interfaces with intracortical implants for motor and communication functions compensation: review of recent developments. *Sovrem. Tekhnologii Med.* 16 (1), 78–89. doi:10.17691/stm2024.16.1.08

Mughal, F. M., and Mughal, A. M. (2023). "Modeling and analysis of design parameters selection for biomechanical movement of prosthetic finger," in 2023 25th International Multitopic Conference (INMIC) (IEEE), 1–6.

Orban, M., Elsamanty, M., Guo, K., Zhang, S., and Yang, H. (2022). A review of brain activity and EEG-based brain-computer interfaces for rehabilitation application. *Bioeng. (Basel)* 9 (12), 768. doi:10.3390/bioengineering9120768

Roy, S., Ferrara, L. A., Fleischman, A. J., and Benzel, E. C. (2001). Microelectromechanical systems and neurosurgery: a new era in a new millennium. *Neurosurgery* 49 (4), 779–797. doi:10.1097/00006123-200110000-00003

Russell, C., Roche, A. D., and Chakrabarty, S. (2019). Peripheral nerve bionic interface: a review of electrodes. *Int. J. Intell. Robot. Appl.* 3, 11–18. doi:10.1007/s41315-019-00086-3

Sankar, S., Cheng, W. Y., Zhang, J., Slepyan, A., Iskarous, M. M., Greene, R. J., et al. (2025). A natural biomimetic prosthetic hand with neuromorphic tactile sensing for precise and compliant grasping. *Sci. Adv.* 11 (10), eadr9300. doi:10.1126/sciadv.adr9300

Seminara, E., Laudani, G., Baiamonte, G., and Calì, M. (2022). The wing structure of an F3J/F5J competition sailplane: topological optimisation with Simplex method and additive manufacturing. 15. 359. doi:10.15866/iremos.v15i6.23066

Stadelmann, C., Timmler, S., Barrantes-Freer, A., and Simons, M. (2019). Myelin in the central nervous system: structure, function, and pathology. *Physiol. Rev.* 99 (3), 1381–1431. doi:10.1152/physrev.00031.2018

Tapia, B., Soto, I., Martinez, D., and Candolfi, N. (2020). Myoelectric interfaces and related applications: current state of EMG signal Processing–A systematic review. *IEEE Access* 1. doi:10.1109/ACCESS.2019.2963881

Tian, R., Zhou, Y., Ren, Y., Zhang, Y., and Tang, W. (2024). Wallerian degeneration: from mechanism to disease to imaging. *Heliyon* 11 (1), e40729. doi:10.1016/j.heliyon.2024.e40729

Welburn, L., Javadi, A. M. M., Nguyen, L., and Desai, S. (2025). Prospects and trends in biomedical microelectromechanical systems (MEMS) devices: a review. *Biomolecules* 15 (6), 898. doi:10.3390/biom15060898

Yang, H., Tao, Z., Yang, J., Ma, W., Zhang, H., Xu, M., et al. (2025). A lightweight prosthetic hand with 19-DOF dexterity and human-level functions. *Nat. Commun.* 16 (1), 955. doi:10.1038/s41467-025-56352-5

Yildiz, K. A., Shin, A. Y., and Kaufman, K. R. (2020). Interfaces with the peripheral nervous system for the control of a neuroprosthetic limb: a review. *J. Neuroeng Rehabil.* 17 (1), 43. doi:10.1186/s12984-020-00667-5

Zagardo, V., Scalia, G., Fichera, C., Matera, D., Umana, G. E., and Ferini, G. (2025). Radiotherapy as an adjunct to surgery in the management of adult soft tissue sarcomas of the hand: the first case report using stereotactic technology and a brief review of radiation effects. *Ann. Ital. Chir.* 96 (7), 894–904. doi:10.62713/aic.3970

Zhang, T., Zhang, N., Li, Y., Zeng, B., and Jiang, L. (2022). Design and experimental evaluation of a sensorimotor-inspired grasping strategy for dexterous prosthetic hands. *IEEE Trans. Neural Syst. Rehabilitation Eng.* 31, 738–748. doi:10.1109/TNSRE.2022.3231972

Zhang, H., Sid'El Moctar, S. M., Boudaoud, S., and Rida, I. (2025). A comprehensive review of sEMG-IMU sensor fusion for upper limb movements pattern recognition. *Inf. Fusion*, 103422. doi:10.1016/j.inffus.2025.103422