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Biomechanically-Aware Robotic Assistance in Musculoskeletal Rehabilitation: Gaps, Clinical Potential, and Research Directions

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ABSTRACT

Robotic technologies are increasingly integrated into musculoskeletal (MSK) rehabilitation to augment physiotherapy by providing repetitive, task-specific training. However, many robotic interventions have yet to fully leverage biomechanical insights for personalised, safe, and effective therapy. This review surveys recent advances (2022–2025) in rehabilitation robotics that explicitly incorporate biomechanical modelling, sensing, and control. We discuss how patient-specific musculoskeletal models and real-time biomechanical feedback can improve safety, target muscle activation, and quantify progress.

Wearable exoskeletons and robotic orthoses for gait and upper-limb rehabilitation have demonstrated improvements in motor function, range of motion, and spasticity. Key gaps include limited long-term evidence, lack of standardised protocols, and insufficient integration of personalised biomechanics in control algorithms (e.g. adaptive force strategies). We highlight clinical implications for allied health professionals – namely, that biomechanically-aware robots can enhance therapy intensity and objectivity while reducing therapist burden – and outline future directions. These include developing real-time adaptive controllers informed by musculoskeletal dynamics, employing artificial intelligence to personalise assistance, and rigorous clinical trials to establish efficacy. Addressing these interdisciplinary challenges will help fulfil the potential of robotics to improve outcomes in MSK rehabilitation.

Keywords: Rehabilitation Robotics, Biomechanical Modelling, Musculoskeletal Disorders, Exoskeletons, Physiotherapy, Personalised Medicine

INTRODUCTION

Musculoskeletal (MSK) rehabilitation aims to restore movement and function after injury, surgery, or neurological insult, and physiotherapists play a central role in guiding this recovery. Robotic assistance in rehabilitation—through devices such as exoskeletons, end-effector systems, and assistive training machines—offers the promise of high-intensity, repeatable, and data-driven therapy beyond what manual therapy alone can achieve. These robots can facilitate repetitive gait training or upper-limb exercises with precisely controlled force and kinematics, thereby promoting motor learning and neuroplasticity.

Emerging research emphasises that embedding biomechanical knowledge into robotic systems can further improve safety and efficacy. For example, musculoskeletal models that estimate internal muscle and joint forces enable robots to avoid harmful loading and to target specific muscle groups during therapy. By integrating patient-specific biomechanics—derived from imaging or sensor data—robots may provide more personalised assistance adapted to each individual's impairments. The interdisciplinary field of allied health clinical innovation encourages such integration of engineering and biomechanical science into therapy. Recent systematic reviews indicate that robotic rehabilitation can significantly improve strength, coordination, and dexterity compared to conventional therapy. However, uptake in clinical practice remains constrained by technical, financial, and evidentiary gaps. This paper reviews the state of "biomechanically-aware" robotic assistance in MSK rehabilitation, identifying how biomechanics is currently used in robot design and control, summarising clinical outcomes, and pinpointing research gaps. We focus on literature from 2022–2025 to highlight the latest innovations in physiotherapy robotics, including studies that blend robotics with biomechanical modelling, real-time sensing (e.g. EMG, force), and patient-specific adaptations. We also discuss the implications for clinicians and outline future research directions needed to translate these technologies into improved patient care.

Biomechanical Integration in Robotic Rehabilitation

Effective rehabilitation requires not just movement generation but physiologically appropriate movement. Biomechanical modelling provides a way to ensure robotic assistance aligns with human anatomy and tissue limits. Musculoskeletal models (MSMs) simulate bones, joints, muscles, and tendons, allowing estimation of internal forces during movement. Incorporating these models into robot control can enhance safety and treatment precision.

For example, Prendergast et al. (2021) implemented an "awareness" pipeline where a shoulder rehabilitation robot uses an OpenSim-based human model to predict internal strains and adjust therapy. They were able to plan reaches that minimise rotator-cuff strain, demonstrating how biomechanical constraints guide safe movement.[1] Similarly, Farhat et al. (2022) developed a real-time lower-limb MSM for a knee rehabilitation robot, validated against electromyography (EMG). Their model estimated muscle forces during a squat exercise with high correlation to measured EMG (Spearman's $\rho > 0.93$)and computed in <2.5 ms, showing the feasibility of closed-loop control. These studies illustrate that simple yet accurate MSMs can run onboard robots to monitor muscle force and joint loading during therapy, enabling the robot to adjust force output dynamically to keep forces within safe ranges.[2]

Beyond muscle forces, biomechanical integration includes multi-modal sensing. Robots can be equipped with force/torque sensors, inertial measurement units (IMUs), and EMG electrodes to capture patient motion and muscle activity in real time. Signal processing and machine learning models (e.g. Support Vector Machines) can then interpret fatigue or user intent, as seen in the hybrid system by Ben Abdallah et al. (2025).[3] They used EMG-guided neuromuscular electrical stimulation (NMES) combined with a robotic arm, where an AI model adjusted stimulation based on detected muscle fatigue. This closed-loop system significantly increased the patient's range of motion and torque compared to baseline.[3]

Such approaches exemplify how robotics and biofeedback can be fused: the robot amplifies patient effort while neurophysiological signals ensure the assistance remains effective and safe. A critical aspect is personalisation. Generic therapy plans risk overloading weak patients or under-stimulating strong ones. Recent work by Wang et al. (2026) addresses this by reconstructing each patient's lumbar muscle geometry from MRI, extracting parameters like muscle cross-sectional area and fat infiltration.[4] They then built an individualised biomechanical spine model to optimise multi-degree-of-freedom movement and force profiles. Personalised strategies drastically reduced variability in muscle activation levels (by ~60%) and kept target activation errors <4%, compared to conventional force-based approaches.[4]

This illustrates the potential of biomechanical personalisation: by tailoring robot assistance to the patient's own anatomy and condition, therapy can be more effective and safer (avoiding both under-training and overload). Future systems may use such digital-twin models to predict a patient's response to an exercise and automatically adjust the robot's motion or force trajectory to meet specific rehabilitation goals. However, integrating biomechanics poses challenges. Detailed MSMs can be computationally intensive and require subject-specific calibration. Farhat et al. tackled this by simplifying the knee model (e.g. quasi-static assumptions, reduced degrees of freedom) to achieve real-time performance.[2]

Even so, many existing robots operate with basic control schemes (e.g. assist-as-needed) without internal biomechanical loops. There is a need for clinically validated models and efficient algorithms that can be embedded in robots. Additionally, obtaining accurate anatomical parameters (muscle paths, joint axes) often requires medical imaging, which may not be feasible in routine therapy. Work is needed to develop surrogate methods (e.g. machine learning from 2D images or wearable sensors) to quickly infer biomechanics. Lastly, as robots increasingly rely on sensor data and complex models, ensuring system robustness and patient safety under sensor noise or model error is an important gap.

Robotic Assistance Technologies in MSK Rehabilitation

Rehabilitation robots span a spectrum of designs. Lower-limb gait trainers range from treadmill-based exoskeletons (e.g. Lokomat®, Walkbot®) to overground wearable suits (e.g. ReWalk®, Ekso). Upper-limb devices include active exoskeletons, passive orthoses, and virtual reality–augmented interfaces. Narrative reviews of recent devices emphasise that both rigid exoskeletons and soft exosuits have roles: rigid frames provide high torque for severely impaired patients, whereas soft, textile-based exosuits offer lightweight assistance for less impaired users.

Overhead or end-effector robots (e.g. Armeo® spring, InMotion ARM) target specific limb segments. Each design reflects a trade-off among support level, portability, and freedom of movement. Systematic reviews highlight positive outcomes from these devices. Carnevale et al. (2025) reviewed portable upper-limb exoskeletons in post-stroke or post-surgical patients and reported significant gains: tenodesis and hybrid-assistive robots improved shoulder and elbow range of motion, muscle power, and dexterity.[5] Importantly, they noted high patient adherence and no serious adverse events, underscoring feasibility. For lower limbs, wearable exoskeletons have been shown to increase gait speed and balance metrics in stroke and spinal cord injury. For example, RAGT enabled children with cerebral palsy to take nearly 1,000 steps in 30 minutes—about 4.7 times the intensity of conventional therapy. Assistive exoskeletons like the Hybrid Assistive Limb (HAL) also facilitated substantial functional recovery in neurology patients. Overall, these findings suggest that robots can enhance intensive, task-specific practice beyond therapist-limited sessions.[5] Nevertheless, robotics has not uniformly outperformed traditional rehab. Some meta-analyses indicate that benefits may be most pronounced in patients with severe impairments (e.g. non-ambulatory) who cannot practice unassisted. As patients recover function, they may transition from harnessed devices to simpler training tools. Reviews also note that the advantages of robotics depend on adherence and appropriate device selection. For instance, the O-TIGER exoskeleton (consistent assistance) yielded more upper-limb motor improvement than a mode with assist-as-needed. Clinicians must consider patient-specific factors such as impairment level, motivation, and chronicity when integrating robotics into therapy. From a biomechanics perspective, robotic designs increasingly aim to align with human joints. Innovations include compliant actuation to mimic muscle behaviour, adjustable joint centres to match anatomical axes, and underactuated mechanisms to allow natural degrees of freedom. Some gait exoskeletons adapt to the user's walking pattern, modulating assistance in real time. Yet many robots remain "black boxes" that move limbs without internal feedback from the body's mechanics. Bridging this gap, several groups are developing sensors and algorithms that let the robot sense how its forces affect muscle activation and joint loading, then adapt accordingly. For example, force sensors on a parallel knee robot can detect patient effort and synchronise platform motion to enforce desired joint forces.

Clinical Evidence

Clinical trials and meta-analyses are accumulating, though heterogeneously. A recent network meta-analysis of AI-assisted rehab (which included robotic exoskeletons as one modality) found that exoskeleton-based interventions significantly improved pain, function, and range of motion compared to conventional care. Therapeutic exergaming and gamified training also ranked highly, indicating that motivating, technology-aided approaches can drive outcomes. These results align with reports that robotic therapies meaningfully enhance standardised clinical scores. For instance, in stroke rehabilitation, studies routinely report Fugl–Meyer score gains and functional independence improvements with exoskeleton-assisted therapy. On the other hand, many trials are small and of variable quality. Carnevale et al. found only five relevant studies (total n≈70) of portable arm exoskeletons meeting inclusion criteria, often single-arm or case series. Randomised controlled trials are few, and meta-analytic conclusions must be cautious.[5] In fact, Luo et al.'s (2025) meta-analysis noted that long-term durability of robot-aided gains is not yet established. They emphasised the need for large-scale, long-duration RCTs to confirm whether early benefits translate into lasting functional improvement.[6] Despite limited evidence, the clinical potential is clear. Robotics offers objective monitoring of patient performance (e.g. kinematics, force output), providing data that therapists can use to tailor therapy progression. Robots can also deliver high-repetition, intensive exercise with less physical strain on therapists. In practice, combining robotic training with conventional therapy often yields additive benefits. For example, adding robotic arm training post-stroke has been shown to produce greater upper-limb recovery than therapy alone. Similarly, gait trainers allow early mobilisation in patients who otherwise cannot walk, potentially accelerating recovery curves.

Gaps, Challenges, and Opportunities

While promising, biomechanically-aware rehabilitation robotics faces several critical gaps. First, personalisation remains rudimentary. Most devices use preset force profiles or simple adaptive algorithms, but they do not fully account for individual biomechanics. As Wang et al. (2026) found, empirical ("one-size-fits-all") force strategies often fail to suit patients with muscle degeneration, risking overload or under-stimulation.[4]

There is a need for robots to self-calibrate: learning each patient's strength, range limits, and compensatory patterns via initial assessments, then customising assistance curves and motion trajectories. Integrating AI and machine learning could enable robots to infer users' biomechanical capabilities from sensor data (e.g. EMG patterns or movement kinematics) and adapt in real time. Second, long-term efficacy and safety are not well-studied. Few trials extend beyond weeks or assess functional retention after robot therapy ends. Khawaja et al. (2025) specifically highlighted the lack of long-term outcome data for paediatric exoskeletons.[7]

Without this information, clinicians do not know how to schedule "booster" sessions or taper robotic use. Additionally, there is a paucity of studies on hard endpoints like return to work or reduction in care needs. Future research should include longitudinal follow-up and attention to psychosocial outcomes (e.g. confidence, participation). Third, implementation barriers are significant. The size, weight, and cost of many robots limit their accessibility.

Even as technology miniaturises, user-friendliness and wearability remain issues. Heavy tethered systems require specialised setup, while untethered exoskeletons often have bulky batteries and motors. Current designs also may not fit well with patients' anatomies (e.g. axis misalignment, soft tissue interference), leading to discomfort or ineffective force transfer. Clinician training is another bottleneck: therapists need education in both device operation and interpretation of robot-generated data. Policy and reimbursement systems have yet to adapt to support routine robotic therapy. Addressing these social and economic factors is as important as the engineering challenges. From a biomechanics standpoint, a major gap is validation. As noted by Farhat et al. (2022), many MSMs lack in vivo validation of predicted forces.[2]

Without confidence in the model, robots cannot rely on its outputs. More experimental studies correlating model estimates (e.g. contact forces, muscle load) with direct measures (e.g. instrumented implants, surface EMG) are needed. In addition, most models assume rigid linkages and neglect joint pain or spasticity, which can alter human movement. Biomechanically-aware robots must handle such pathological conditions; for instance, spasticity might be detected via abnormally high muscle force outputs, prompting the robot to adjust assistance or give rest breaks. Developing robust algorithms that account for non-ideal movement (tremor, synergies, fatigue) remains an open research direction. Finally, there is a gap between research prototypes and clinical-grade systems. Many studies occur in labs with expert engineers; translation to clinics requires simpler interfaces, safety certifications, and evidence from pragmatic trials. Collaboration between engineers, clinicians, and patients is crucial to ensure that innovations meet real therapeutic needs. Allied health researchers should help define relevant metrics and usability criteria, such that engineers can focus on clinically meaningful features (e.g. intuitive user intent recognition rather than complex UI screens).

Clinical Implications

For physiotherapists and rehabilitation specialists, biomechanically-aware robots represent both an opportunity and a paradigm shift. These devices can serve as intelligent assistants rather than passive tools. By using models and sensors, robots can monitor patient effort and progress continuously, providing objective feedback to clinicians. For example, a gait trainer that logs joint angles, step symmetry, and required assistance over sessions can inform therapy decisions more precisely than human observation alone.[8]

Therapists can then adjust exercise difficulty or device parameters based on quantitative progress markers. Moreover, integrating biomechanics into robotics helps clinicians tailor treatments. If the system identifies that a patient's quadriceps are under-activated during gait (through force estimates), the therapist might prioritise quadriceps-specific exercises. Biomechanical data can also alert therapists to potentially harmful compensations: e.g. if a shoulder robot senses excessive scapular loading, the therapist can intervene to retrain correct movement patterns. In this way, robots extend the therapist's perceptual capacity. However, successful deployment will require new training for allied health professionals. Therapists will need to understand the principles of robotic control and biomechanical modelling to interpret system outputs and to program individualised protocols. Interdisciplinary education programs should be developed so that physiotherapy curricula include exposure to robotics and biomechanics.[8] Clinically, protocols should be co-designed: for instance, determining how to integrate exoskeleton sessions with conventional therapy days, or how to progress assistance levels, which patient populations stand to benefit most (e.g. who gets a robotic gait trainer vs. an upper limb orthosis) and in establishing practice guidelines. In the community and home settings, wearable robotics could enable extended therapy beyond the clinic. Biomechanically-aware exosuits could provide semi-autonomous training in one's living environment, with remote monitoring by therapists. This could especially aid patients in rural areas or those with mobility issues. Of course, safety and supervision models (possibly using telehealth) must be established. Overall, when clinically validated and effectively implemented, biomechanically-informed robotics can enhance rehabilitation efficiency. They can help overcome therapist staffing limitations by delivering parts of therapy autonomously. By providing detailed logs of patient performance, these systems also contribute to evidence-based practice, allowing providers to quantify dose-response relationships and refine therapeutic exercises.

Future Directions

To advance the field, research should prioritise several directions. Real-time adaptive control is one frontier: developing controllers that adjust force and motion trajectories on-the-fly based on biomechanical feedback. This may involve machine learning models that predict internal forces or fatigue from sensors and modulate assistance accordingly. For instance, the SVM fatigue detector in Ben Abdallah et al.'s system shows how real-time EMG analysis can inform robotic actuation.[3]

Future work could generalise this to multi-muscle or multi-joint contexts, using techniques such as deep learning or hybrid physics-based/data-driven models. Digital twin and simulation environments will play a key role. Patient-specific models (like Wang et al.'s lumbar model)can be integrated into virtual therapy planning.[4] For example, before a therapy session, a clinician could test different robotic force profiles in simulation to see which best activate target muscles without overload. "What-if" analyses can optimise therapy for that day's condition. Sensor innovation is also needed. Wearable, unobtrusive sensors (including optical motion capture, IMUs, or miniaturised EMG) will enable continuous biomechanical monitoring outside the lab. Markerless motion capture and AI-driven pose estimation may allow low-cost tracking of joint angles and limb loading. Combining these with pressure sensors in footwear or instrumented insoles could provide comprehensive gait biomechanics data. Similarly, soft robotic sensors integrated into exosuits could measure muscle bulging or tendon stretch. Clinical research and standardisation must keep pace. Large multi-centre trials are needed to determine which robotic interventions yield clinically meaningful benefits across diverse populations. Such studies should use standardised outcome metrics (e.g., Fugl–Meyer, 10-meter walk test) and report on quality of life, cost-effectiveness, and adherence. Consensus on training protocols would allow more consistent comparisons. Regulatory frameworks should evolve to recognise robotic therapy as a reimbursable clinical service. Finally, interdisciplinary collaboration is crucial.[9] Engineers, bio mechanists, therapists, and patients must co-design systems. Patients' feedback on comfort and usability should guide design (as Khawaja et al. noted, user-friendly interfaces are vital for engagement). Physiotherapists' expertise can inform the hierarchy of rehabilitation priorities (e.g. weight-bearing vs. dexterity tasks) when programming a robot. Research on ethical, legal, and social implications (such as equity of access and data privacy) should accompany technical advances.[7,9]

CONCLUSION

Biomechanically-aware robotic assistance holds significant promise to augment musculoskeletal rehabilitation by tailoring therapy to each patient's anatomy and physiology. Recent studies demonstrate that integrating musculoskeletal models, EMG-based control, and personalised optimisation can enhance the safety and efficacy of robotic therapy.

Clinical evidence increasingly shows that robotic interventions improve functional outcomes in stroke, spinal cord injury, cerebral palsy, and other conditions.

However, the field faces gaps in personalisation, evidence, and accessibility. Addressing these will require advances in real-time biomechanical modelling, sensor technology, and large-scale clinical trials. Embracing these technologies means new opportunities to deliver intensive, data-driven rehabilitation. By bridging engineering and clinical practice, biomechanically-informed robotics can help realise more effective, patient-centred care in rehabilitation medicine.

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