

The Current State of Upper-Extremity Neuroprosthetics: A Narrative Review

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Prostheses for the upper extremity are intended to restore function and improve the quality of life, but 20 to 30% of users eventually give up on them, particularly those who use advanced myoelectric devices. A major factor in this is the lack of intuitive sensory feedback, since this can damage the sense of embodiment and increase cognitive load. This review looks at the way these limitations affect the user's experience, embodiment, and decision to abandon the prosthesis. The main point of comparison is between body-powered (BP) and myoelectric (MYO) prostheses, as these two types differ most in the way they provide sensory information. Twenty-three studies were included following a search of PubMed, Google Scholar, and IEEE Xplore. To be eligible, the studies had to be peer-reviewed and must have focused on sensory feedback, embodiment, device performance, cost-effectiveness, or abandonment; publications that were commercial or not peer-reviewed were excluded. The evidence goes in both directions: BP prostheses offer incidental feedback that can help with embodiment even though they limit dexterity, while most MYO devices do not provide a similar means of feedback and place a greater cognitive burden on the user. New haptic and neural feedback systems seem to enhance precision, performance, and embodiment, but the studies supporting this are small and of short duration. The overall conclusion is deliberately cautious: sensory integration is probably a key factor in the use of prostheses, but because of the diversity of the evidence and its short length, this conclusion is not certain, and positive results still depend on assessing the mechanical and neural factors on a case-by-case basis for each individual user.

Keywords: upper-limb prosthesis; abandonment of prosthesis; sensory feedback; embodiment; myoelectric prosthesis; body-powered prosthesis.

Introduction

The loss of a limb means the absence of all or part of it, whether the condition is present from birth or results from surgical amputation due to trauma or disease. A recent estimate of the prevalence in the United States suggests that there are approximately 2.31 million people who have a limb loss, around 9.2% of whom have a loss of an upper extremity¹. Prostheses are designed to restore lost movement and function². They are by no means the same in all cases; both their design and their use in everyday life vary according to the level of amputation and the part being replaced, and even the most advanced prostheses currently available do not match a natural limb in terms of range of motion, precision, or ease of incorporation into daily life³.

Three main types of prosthetic devices are used for the upper extremity, each corresponding to a different user need. Cosmetic prostheses reinstate the look of a limb without restoring any movement; body-powered devices enable a basic degree of movement although only over a fairly restricted range; and myoelectric devices, which are externally powered,

convert the electrical signals from the muscles in the remaining limb into movement. Despite this increased sophistication, acceptance has not risen in proportion. It is estimated that between 20 and 30% of upper-extremity prostheses are eventually rejected⁴, and this problem affects the more advanced devices much more severely. In one study involving children, the use of myoelectric hands fell from 78% to 44% within two years, even though users of body-powered devices expressed higher levels of satisfaction⁵. This discrepancy between capability and adoption is seen repeatedly in the literature, and it is this very tension that the present review aims to look at.

Most of the current research looks at device types or feedback technologies on their own. Only a small number of studies directly compare body-powered and myoelectric systems along the feature that best separates them: intuitive sensory feedback. When viewed in terms of trade-offs, the two approaches reveal conflicting priorities: high functionality can go hand in hand with poor usability, and open-loop motor control means that the user does not have a closed sensory loop. This review sees sensory feedback as a key factor in how fully a prosthesis feels like part of the user's body and in how long it stays in use, a factor that is often underesti-

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mated in present myoelectric designs. Without it, users have to rely on strenuous visual monitoring, embodiment diminishes, and the chance of abandoning the prosthesis increases. A great deal of this problem arises from the loss of naturalistic somatosensation, the sensory system involved in perceiving touch, pressure, and the properties of objects such as texture and hardness⁶. Since a prosthesis cannot match the level of input that an intact limb provides, users are often left with a reduced sense of embodiment and less intuitive control. By focusing on the two systems specifically through the lens of sensory feedback, this review brings together the current findings on somatosensory integration and points the way towards improvements in embodiment, usability, and long-term adoption.

Background

The section here summarises the fundamental neurophysiology and terminology on which the review is based; by putting it before the Results, it enables that section to focus on synthesis. Nerves carry small electrical and chemical signals which control movement and are responsible for the sense of touch⁷. The central nervous system (CNS) processes and regulates these signals in order to coordinate motor control⁷, and is also at the heart of sensory perception, touch being included⁶. In the arm and hand, this biological arrangement is the basis of both movement and sensation.

Following amputation, the part of the limb that remains is known as the residual limb or stump, and the nerves passing through it are referred to as the residual nerves⁷. The process of amputation interrupts the peripheral nerve pathways, leading in many cases to a deterioration in signal quality and changes in sensory processing, both of which can make motor control and rehabilitation more difficult⁷. Many amputees also have the phenomenon of phantom limb sensation, which is the continued feeling that the missing limb is still there⁸. There is one more term that is relevant: degree of freedom (DOF), which refers to the number of independent movements that a joint or mechanism can carry out. The more degrees of freedom there are, the more complex and precise the movements can be, for example allowing for independent finger movement.

Methods

It is a narrative review which used a selection process guided by the PRISMA guidelines and does not assert that it is as comprehensive as a full systematic review. The literature was found by carrying out searches on PubMed, Google Scholar, and IEEE Xplore for articles published between 1990 and 2026. The search terms included “myoelectric prosthe-

sis,” “body-powered prosthesis,” “neuroprosthetics,” “sensory feedback,” “haptic feedback,” “embodiment,” and “prosthesis abandonment/rejection.” The main Boolean string, modified for each database, was (“myoelectric prosthes” OR “body-powered prosthes” OR neuroprostheth) AND (“sensory feedback” OR haptic OR electrotactile OR vibrotactile OR embodiment OR “phantom limb” OR abandonment OR rejection).

The screening was carried out in several stages according to a PRISMA-style approach. First, the titles and abstracts were checked for relevance to the topic. Those records that passed this stage then went through a full-text examination, during which the figures and the results reported were evaluated for methodological quality, and the number of citations was used as a secondary measure of the study’s influence. A study was included if it was peer-reviewed and if it dealt with upper-extremity prosthesis design, neural or myoelectric control, sensory feedback, embodiment, cost, or abandonment, and if it provided original data, a comparison of clinical outcomes, or a relevant synthesis. Excluded were non-peer-reviewed materials such as websites, blogs, news articles, and manufacturer literature, as well as studies that were limited to lower-limb prostheses, those outside the review’s scope, and those without an accessible full text or with insufficient detail for assessment. Of the 49 records compiled, 23 met the criteria. The other 26 were excluded for specific reasons: 12 because they were off-topic or only loosely related to the focus on body-powered versus myoelectric prostheses and on sensory feedback, 7 because they were redundant with better included studies, 3 because they were not peer-reviewed or were from grey literature, 2 because they concerned only lower-limb prostheses, and 2 because they lacked an accessible full text or adequate detail. Since only one reviewer carried out the screening, selection bias cannot be ruled out; this point is discussed again in the Limitations section. The studies were assessed throughout on the basis of their methodology, design, sample, endpoints, and the limitations that were reported, not on the prestige of the journal in which they were published. Figure 1 gives a summary of the process.

Results and Synthesis

Starting from the background, this section brings together the results from various studies and indicates in which cases the evidence is strong, mixed, or limited. Modern prostheses for the upper extremity are designed to function in coordination with the nervous system by making use of the nerves and muscles that remain in the residual limb. Even after amputation the brain still sends motor commands via the intact neural pathways⁷. Myoelectric devices make use of this fact: electrodes placed on the residual limb pick up the electrical activity caused by the contraction of the muscles⁹, and that activity is then converted into actions such as opening the hand or ro-

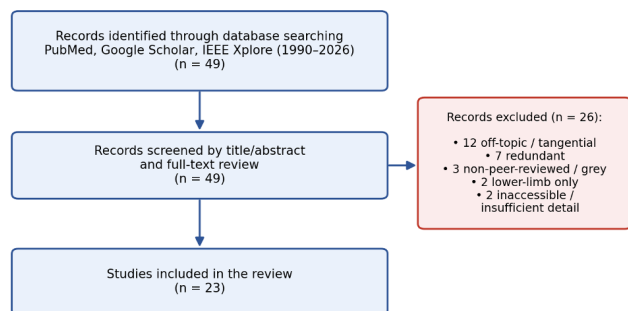


Figure. 1 A flow diagram of the study selection process in the style of PRISMA.

tating the wrist³. More advanced controllers employ pattern recognition, mapping the patterns of muscle activation onto particular movements in order to achieve smoother control¹⁰. A common claim found in these studies is that aligning control with the existing neural pathways can decrease the mental effort required and enhance the user's feeling of being connected to the device¹¹. The evidence supporting this, however, comes mostly from small samples that have been studied in a laboratory setting, so it is still uncertain how great a benefit this will be in everyday life.

The design of a prosthesis has a major effect on the things it is able to do. The choice of materials is important, since lightweight and strong ones like carbon fiber allow the device to be light while at the same time maintaining durability, and every prosthesis has to combine joints, cable systems, motors, and circuitry into one working unit³. In the case of body-powered prostheses, movement is produced by a cable-and-harness system which is operated by the residual limb or the shoulder¹². Because of their simpler mechanical structure these prostheses are cheaper and more accessible, a factor that is especially important in low-resource environments². When the prosthetic joint is unable to get to the position that is required, users resort to compensating movements, thereby overusing their shoulder or trunk and taking on extra physical strain¹³. This is supported by kinematic analyses: both body-powered users and myoelectric users change their joint coordination during ordinary tasks when compared to able-bodied controls¹⁴. These compensations have a direct bearing on the central issue of the review, since they involve both physical and cognitive costs, and costs of this magnitude lead users to abandon the device.

Sensory feedback refers to the information that the nervous system picks up as the body moves and interacts with its surroundings, allowing the brain to understand touch, force, and the position of the limbs^{6,15}. In myoelectric systems, surface electrodes are used to pick up the control signals, but their

accuracy is reduced due to signal distortion and interference from unwanted muscle activity or electrical noise⁷. Body-powered prostheses provide feedback by accident. Since physical force causes the movement, the cable-and-harness system gives back a resistance that is proportional to the force applied, so the user can feel the grip force and the position of the limb without needing any extra equipment¹². Most commercial myoelectric prostheses have no similar channel and rely almost completely on visual monitoring¹². This difference is at the heart of the argument put forward in this review. The advantage of body-powered prostheses lies in an incidental closed sensory loop which sends information back to the user while movement is taking place¹⁶. The deficiency with myoelectric prostheses is the opposite: it is an open loop that shifts the sensing function onto vision and working memory.

In order to overcome these limitations, externally powered feedback systems have been created to function together with myoelectric prostheses¹⁵. These systems range from noninvasive vibrotactile cues to invasive neural interfaces that stimulate either peripheral nerves or central structures^{6,17}. Haptic feedback, which provides tactile information about grip force, contact, and the position of the limb, has been the subject of the most research¹¹. With regard to one particular aspect, the evidence is in agreement: adding either haptic or neural feedback generally leads to better task accuracy, fewer grip-force errors, and a greater sense of limb ownership when compared to situations with no feedback^{6,11}. However, when it comes to more detailed issues, the findings become uncertain. It is not clear which modality is best or whether the benefits last beyond the laboratory environment; in fact, a single direct comparison found no significant difference between vibrotactile and joint-torque feedback¹⁸, and there is a lack of long-term data from home use⁹. Each of the different modalities has its own features. Vibrotactile feedback uses small motors attached to the skin and is relatively easy to learn¹⁹. Electrotactile feedback involves the application of mild electrical stimulation and is capable of encoding more graded information²⁰. Mechanotactile feedback physically moves the skin to mimic natural contact, although it might cause discomfort²¹. When these results are considered in this way, they suggest that feedback can reduce the sensory gap and promote a sense of embodiment, while comfort, durability, and user acceptance are still unresolved and could ultimately decide whether the improvements seen in the laboratory lead to continuous use.

Sophisticated devices combine fine engineering with neural control. The DEKA Arm, which is generally known as the "LUKE" arm, is one of the most capable upper-limb prostheses currently in clinical use. In terms of its hardware, the DEKA/LUKE system offers up to ten powered degrees of freedom, comprising powered wrist and humeral rotation features that are missing from most commercially available devices, and it allows for several control inputs rather than

just one, these including surface EMG, inertial measurement units, and pressure switches; the exact setup has differed in various studies and among individual fittings²². As for the outcome evidence, a Veterans Affairs study found that the use of DEKA was linked to changes in perceived disability, levels of engagement in daily tasks, and activity performance when compared with conventional prostheses³. Research into advanced systems also shows an opposing effect: the greater mechanical complexity and the extra degrees of freedom increase the cognitive and physical demands of operating the device, especially during the early stages of use²³, so it is largely the training and adaptation that determine whether the extra capabilities result in real functional improvements²⁴. Surface-electrode control is still vulnerable to variability in the signal due to electrode placement, muscle fatigue, and skin condition⁷, a factor that can reduce accuracy. Altogether, the DEKA literature reflects the central dilemma discussed in the review. Increasing capability without at the same time providing a sensory channel can increase the user's burden, which helps to explain why greater sophistication by itself does not ensure that the device will be adopted^{23,25}.

User experience is also influenced by psychological, neurological, and clinical factors. Although cosmetic prostheses have no mechanical function, studies of clinical outcomes connect their appearance, comfort, and the satisfaction that goes with them to acceptance and the decision to continue using them²⁶. Phantom limb sensations occur when the nervous system keeps on producing perceptions of the limb that is missing⁸. These are linked to maladaptive cortical reorganization that takes place after normal afferent input is lost²⁷. In some people this develops into phantom limb pain which hinders their daily activities⁸. Clinical and biomechanical evidence indicates, though mostly based on small or cross-sectional samples, that interventions which improve body representation and embodiment may lessen phantom-limb symptoms by reducing sensory mismatch²⁷. This line of reasoning supports the proposed mechanism in that embodiment seems to be connected with both the severity of symptoms and with acceptance of the device, and its significance extends well beyond cosmetic considerations.

Discussion

The conclusions drawn earlier point to a mechanism which this review makes clear. When sensory feedback is reduced, there is greater reliance on visual monitoring and a higher cognitive load, which in turn weakens the sense of embodiment, the feeling that the device is part of the body, and less embodiment then leads to lower satisfaction and an increased chance of the device being abandoned. The evidence in support of this sequence is mainly associative and based on cross-sectional studies rather than experimental ones. It should therefore be

seen as a well-justified hypothesis; it does not prove causation.

The reason for the body-powered advantage in terms of embodiment seems to lie in the presence of an incidental closed sensory loop, while the disadvantage associated with myoelectric systems stems from an open loop. It follows that the more important design aim should be to close the loop rather than merely increasing the number of degrees of freedom. Therefore, myoelectric developments should be directed towards closed-loop systems in which motor decoding is combined with feedback that the user can actually make use of. Although present haptic methods, such as vibrotactile, electrotactile, and mechanotactile ones, have already been shown to improve grip control and task performance, they still need to be optimised with regard to comfort, reliability, and practical use¹¹.

The second priority is to achieve advances in neural interfacing. Although surface electromyography is the standard control method since it is noninvasive, it is susceptible to variations in the signal caused by fatigue, electrode displacement, and changes to the skin⁷. Implanted electrodes, regenerative peripheral nerve interfaces, and nerve transfers offer more stable and more selective signals, but their use will depend on long-term safety, clinical results, and user acceptance²⁸. Currently, there are few longitudinal studies concerning the stability and function of neural signals, and the field could benefit from having more such studies⁷.

The effectiveness of prostheses is not the same for all users; it depends on the level of amputation, the anatomy of the remaining limb, and the user's previous experience²⁴, which is why it is necessary to use adaptive control and customizable feedback settings together with patient-reported outcomes such as comfort, embodiment, and satisfaction if real-world usability is to be captured beyond what can be measured in the laboratory^{23,24}. Similarly, abandonment has both real-world and psychosocial causes. A number of studies make use of short-term laboratory tasks that do not reflect everyday use or long-term adaptation²⁹, while evidence from rehabilitation shows that structured and ongoing rehabilitation is essential for achieving functional recovery and for the successful integration of advanced prostheses³⁰. Future research should include longitudinal, home-based studies and look more closely at how cosmetic and hybrid prostheses affect body image and acceptance^{3,9}.

There are some limitations to these conclusions. Since this is a narrative rather than a systematic review, the search was targeted and the studies were selected by one reviewer only, which means that selection bias is present. The scope of the databases searched was limited, and it is possible that it has omitted papers from Scopus and the Web of Science. The number of studies included is small, just 23, and they are highly varied; no quantitative synthesis or meta-analysis was carried out. A great deal of the evidence upon which this re-

view is based comes from small, short-term laboratory studies, and the review brings together a range of work involving body-powered systems, myoelectric systems, advanced bidirectional technologies, cosmetic applications, biomechanics, and rehabilitation, all of which address different questions and therefore should not be given equal weight.

Caution should therefore be exercised when making causal or universal claims. Although it is reasonable to say that improving sensory integration is important for reducing rejection and this claim is generally supported in direction, it has not been consistently shown within the diverse body of evidence, and it is very likely that there are exceptions. The summary table in Appendix A classifies the studies according to design, device type, method of feedback, endpoint, and length of follow-up, making the evidence upon which each claim is based clear.

Conclusion

Prostheses for the upper extremity are designed to restore function and improve quality of life, but rejection still occurs even though there have been considerable advances in mechanical design and control. The evidence presented here is in line with, although it does not definitively prove, the idea that limitations in sensory feedback lead to a reduced sense of embodiment, an increased cognitive load, and eventual abandonment, and that body-powered and myoelectric systems differ most significantly in whether or not they close the sensory loop. The DEKA Arm, for example, shows what can be achieved by combining advanced mechanics with neural control, even as it highlights the compromise between capability and user burden²³. Taking all the evidence into account and considering the variety of it, it is likely that enhancing sensory integration will be important for achieving wider adoption. Future development should therefore go beyond simple mechanical improvements and focus on closed-loop, user-oriented designs that are in line with human neurobiology and lived experience.

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Appendix

Appendix A. Summary of Reviewed Studies

Summary of the 23 reviewed studies, sorted by reference number and stratified by design, device class, feedback modality, end-point, and follow-up.

Ref	Author (Year)	Design	Sample	Device / feedback focus	Key findings	Strengths / weaknesses	Gaps
1	Nat'l Academies (2017)	Consensus report (cost chapter)	n/a	Cost by device class	Approx. cost: BP \$4,400; MYO transradial \$15,100; transhumeral \$56,200; hybrid \$19,200	Strength: authoritative cost benchmarks. Weakness: US-only; not peer-reviewed	Prices may differ internationally / from actual
2	Rivera et al. (2024)	Epidemiological prevalence/projection	US national data	Limb-loss prevalence	~2.31M with limb loss; UE ~9.2%	Strength: recent national estimate. Weakness: modeling assumptions	Not prosthesis- or feedback-specific
3	Resnik et al. (2018)	Clinical outcome comparison (VA)	23 users (15 in home phase)	DEKA outcomes	DEKA slightly slower than conventional but more capable	Strength: real-user outcomes. Weakness: home-study confounders	Not a device-tech description; modality varied
4	Raspovic et al. (2014)	Proof-of-concept, invasive intraneural	1 participant (single amputee)	Real-time bidirectional feedback	First real-time closed-loop sensory prosthesis; participant distinguished object stiffness/shape and modulated grasp force	Strength: landmark bidirectional. Weakness: n=1; invasive	Durability, generalizability
5	Vu et al. (2023)	Longitudinal, RPNI + implanted EMG	2 participants	Long-term control; peripheral-nerve background	Stable long-term control; strong peripheral-nerve background	Strength: long-term implanted signals. Weakness: very small n	Broader adoption
6	Stankevicius et al. (2021)	Systematic rapid review	Pooled studies	Phantom limb pain/sensation	High prevalence of PLP/PLS post-amputation	Strength: systematic. Weakness: heterogeneity	Mechanism, treatment linkage
9	Schofield et al. (2020)	Long-term home-use study	3 participants (2 sensate, 1 control)	Sensory-motor integrated bidirectional arm	Functional, perceptual & cognitive gains at home	Strength: home-use, longitudinal. Weakness: very small n	Controlled/RCT evidence
11	Marasco et al. (2021)	Experimental neurobotic feedback	TMR users (small cohort)	Touch + kinesthesia + movement fusion	Marked improvement on grip/other tests; intrinsic brain behaviors & ownership	Strength: multimodal feedback. Weakness: low sample; TMR-specific	General MYO users
12	Gonzalez et al. (2021)	Experimental incidental-feedback (VR)	9 limb-loss + 9 anatomical	Incidental feedback BP vs MYO vs hand	BP more accurate & less variable at grasp/stiffness than MYO; MYO gives almost no proprioceptive feedback	Strength: isolates incidental feedback. Weakness: virtual environment; small n	Real-world use
13	Bouwsema et al. (2010)	Experimental movement analysis	6 users (3 hybrid, 3 myoelectric)	Goal-directed task kinematics	Characteristic compensations & timing	Strength: detailed kinematics. Weakness: lab tasks	Ecological validity
14	Carey et al. (2009)	Comparative kinematic (case)	1 subject (bilateral)	Kinematics of common activities	Shoulder ROM better in MYO; elbow ROM better in BP	Strength: early comparative. Weakness: single subject; old	Modern devices, larger n
15	D'Anna et al. (2019)	Proof-of-concept closed-loop	2 amputees	Intraneural tactile + position feedback	Near-natural proprioceptive accuracy; good object-size distinction	Strength: closed-loop bidirectional. Weakness: n=2; invasive	Long-term / home
16	Engdahl et al. (2020)	Comparative embodiment study	9 prosthesis users	Embodiment BP vs MYO	No large difference in perceived embodiment BP vs MYO	Strength: directly on embodiment. Weakness: only 9 users; cross-sectional	Causal direction over time
17	Tan et al. (2014)	Proof-of-concept, peripheral nerve electrodes	2 participants	Long-term natural touch percepts	Restored natural touch 16–24 mo; felt pressure/tapping/vibration	Strength: percept stability. Weakness: small n; invasive	Scale-up, home use
18	Thomas et al. (2019)	Comparative feedback modalities (testbed)	12 non-amputee participants	Vibrotactile (MYO) vs joint-torque (BP)	No significant difference between joint-torque and vibrotactile feedback	Strength: head-to-head. Weakness: exoskeleton testbed	Durability, best modality
19	Witteveen et al. (2015)	Experimental vibrotactile feedback	10 upper-limb-loss subjects	Vibrotactile grasp-force / aperture feedback	Vibrotactile feedback improved grasping performance	Strength: on-topic vibrotactile. Weakness: lab; daily-life value unclear	Real-world value
20	Garenfeld et al. (2023)	Closed-loop control study	10 non-disabled + 1 amputee	Anatomically congruent electro tactile feedback	Improved position control; graded proprioceptive/force info	Strength: full-state electro tactile. Weakness: complex; lab	Long-term learning
21	Schoepp et al. (2018)	Engineering design + validation	1 participant	Inexpensive mechanotactile feedback	User correctly identified stimulated finger; low-cost feasible	Strength: cheap translational device. Weakness: n=1; motor noise	Clinical trials
22	Resnik et al. (2014)	Device description (VA study)	n/a (device)	DEKA/LUKE features & control	Up to 10 powered DOF; EMG/IMU/pressure control inputs	Strength: primary technical source. Weakness: single device line	Independent replication
23	Metzger et al. (2010)	Experimental reaching study	Transradial amputees (small case-control)	Feedforward control in reaching	Characterized feedforward strategies	Strength: control-strategy insight. Weakness: lab task	Feedback integration
24	Engdahl & Gates (2021)	Experimental movement-quality study	9 users + 9 controls	Movement quality in ADLs	Differences in movement quality BP vs MYO	Strength: ADL relevance. Weakness: small sample; variation	Matched-factor, long-term
25	Hussaini et al. (2017)	Observational categorization	4 users + 20 able-bodied	Compensatory motions	Taxonomy of compensatory movements	Strength: clinical classification. Weakness: descriptive	Intervention/prevention
26	Fitzgibbons & Medvedev (2015)	Narrative / clinical review	n/a	Functional & clinical UE outcomes	Appearance/comfort/satisfaction affect acceptance	Strength: clinical overview. Weakness: non-systematic	Quantitative outcomes
27	Granata et al. (2020)	Cortical plasticity (TMS/mapping)	3 transradial amputees	Cortical reorganization & feedback	Feedback training linked to more normal cortical maps	Strength: mechanism-level. Weakness: small; focused	Longitudinal effect on pain
28	Salminger et al. (2019)	Longitudinal implant (~2.5 yr)	3 above-elbow amputees	Intramuscular sensors + nerve transfers	Implanted sensors outperformed surface electrodes; everyday gains	Strength: long-term implant. Weakness: small n; invasive cost	Cost-benefit, broad adoption
29	Williams et al. (2021)	Comparative simulation (motion capture)	3 MYO users + 12 non-disabled (simulated)	Compensatory strategies	Similar shoulder/trunk compensations across groups	Strength: control comparison. Weakness: only 3 MYO users; simulated	Real users, BP comparison
30	Sturma et al. (2022)	Clinical rehab (Delphi/scoping)	Delphi expert consensus	Rehabilitation after TMR	Structured rehab supports functional outcomes	Strength: clinical rehab focus. Weakness: specialized population	Standardized protocols