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A scoping review of the application of motor learning principles to optimise myoelectric prosthetic hand control

Johnny V. V. Parr (PhD)[1,2], David J. Wright (PhD)[1,3], Liis Uiga (PhD)[1,2], Ben Marshall (PhD)[1,2], Mohamed Omar Mohamed (MSc)[1,2], and Greg Wood (PhD)[1,2]

1. Manchester Metropolitan University Institute of Sport, Manchester UK
2. Research Centre for Musculoskeletal Science and Sports Medicine, Department of Sport and Exercise Sciences, Faculty of Science and Engineering, Manchester Metropolitan University, Manchester, UK
3. Research Centre for Health, Psychology and Communities, Department of Psychology, Faculty of Health, Psychology and Social Care, Manchester Metropolitan University, Manchester, UK

Corresponding author:
Dr Johnny Parr
Manchester Metropolitan University
All Saints Building, All Saints,
Manchester, M15 6BH
johnnyvvparr@gmail.com

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Abstract

Although prosthetic hand rejection rates remain high, evidence suggests that effective training plays a major role in device acceptance. Receiving training early in the rehabilitation process also enhances functional prosthetic use, decreases the likelihood of developing an over-reliance on the intact limb and reduces amputation-related pain. Despite these obvious benefits, there is a current lack of evidence regarding the most effective training techniques to facilitate myoelectric prosthetic hand control and it remains unknown whether training is effective in facilitating the acquisition and transfer of prosthetic skill. In this scoping review, we introduce and summarise key motor learning principles related to attentional focus, implicit motor learning, training eye-hand coordination, practice variability, motor imagery and action observation, and virtual training and biofeedback. We then review the existing literature that has applied these principles for training prosthetic hand control before outlining future avenues for further research. The importance of optimising early and appropriate training cannot be overlooked. While the intuition and experience of clinicians holds enormous value, evidence-based guidelines based on well-established motor learning principles will also be crucial for training effective prosthetic hand control. While it is clear that more research is needed to form the basis of such guidelines, it is hoped that this review highlights the potential avenues for this work.

Keywords: *training; rehabilitation; motor control; motor learning; prosthesis rejection.*

1. Introduction

Recent evidence suggests that prosthetic hand rejection rates are as high as 44%[1], although reported rates appear to vary considerably[2,3]. This is concerning, as amputees who do not use their prosthesis report more difficulty performing activities of daily living, greater overall disability, and lower physical function compared to amputees who choose to use their prosthesis frequently[3]. Those who reject their prosthesis also exhibit an over-reliance on the intact side of their body that often leads to overuse injuries[4]. The factors contributing to prosthesis abandonment are numerous, with users consistently reporting dissatisfaction with prosthesis appearance, weight, comfort, and fitting[1,5,6]. However, a major contributor seems to be related to the poor functionality of these devices and the difficulty users have experienced in learning to control them to interact successfully with their environment[5,7]. To tackle this, efforts have been placed upon developing prosthesis technologies to improve intuitive control through additional sensory feedback mechanisms[8] and EMG pattern recognition[9]. However, these technological efforts might be in vain for most of the intended population given the high cost associated with these systems. This is especially true for children, who may frequently require new prostheses and/or modifications to accommodate for growth and damage.

There is strong evidence to suggest that prosthesis training plays a major role in device acceptance. Early specialised training enhances functional prosthetic use[10], decreases the likelihood of developing an over-reliance on the intact limb[11], and even reduces amputation-related pain[12]. Receiving adequate training is also linked with higher levels of both physical and mental health, suggesting that early intervention can have long-term effects on overall quality of life[3]. However, prosthesis users commonly report dissatisfaction with the training they receive to help them learn to control their device[5] and/or feel that their training did not sufficiently meet their needs[13]. This is important as user perceptions that the training received is *useful* is more closely aligned with prosthesis acceptance than the overall amount of training received[1]. The need to develop quality, well-designed, and patient-tailored training protocols has therefore been highlighted as a priority by users[5] and a clinical imperative to increasing long-term prosthesis use and acceptance[1,3].

Current prosthetic training programmes are clinic-specific, with rehabilitation centres often using their own, locally developed protocols that are based on intuition and clinical experience[10,14]. Consequently, the training a patient receives is likely to differ due to the varying experience levels of prosthetists and therapists. Due to the current lack of evidence regarding the most effective training techniques to facilitate myoelectric prosthetic hand control, it is unknown whether training is efficient or effective in facilitating the acquisition and transfer of prosthetic skills[15]. Researchers have therefore been advocating for the development of evidence-based training protocols for some time[16], with the goal of maximising the efficiency, effectiveness, and consistency of rehabilitation. Yet, the extant literature dedicated to applying established motor learning principles to prosthetic hand skill acquisition and transfer remains sparse, with many fundamental components of rehabilitation underexplored. It is, therefore, the aim of this paper to review the current literature-base dedicated to understanding the motor learning principles that might contribute to the effectiveness of prosthetic hand learning and transfer. We will begin this paper by addressing key motor learning principles in a section-by-section manner, highlighting the relevant upper-limb prosthesis literature, and suggesting future research agendas based on established evidence-based methods from the fields of human movement, sport, and rehabilitation.

3.1. Focus of attention

The stress and frustration around learning or relearning to move effectively can cause learners to direct their focus internally and consciously attend to *how* they are moving. For example, stroke patients report a higher propensity to consciously monitor aspects of their movements compared to age-matched controls[17], whilst people with Parkinson's disease increase their propensity to consciously monitor aspects of their movement over time[18]. Although no research has directly examined the extent to which prosthesis users focus internally, users have described their device as a "conscious burden" and are highly dependent on vision to monitor their prosthetic hand during movement[19].

An extensive body of research has shown that adopting an internal focus of attention, compared to an external focus of attention, is less effective for motor performance and learning[20]. Whilst an internal focus occurs when an individual directs their attention towards bodily movements and/or sensations, an external focus occurs when an individual instead directs their attention towards the outcomes of the movement or the effect the movement has upon the environment. For example, a prosthesis user could either be instructed to focus on “contracting the muscles of the residual limb” (i.e., internal focus) or to simply focus on “closing the prosthesis” (i.e., external focus) when attempting to grasp an object. By focusing internally (contracting the muscles) it is proposed that the motor system becomes “constrained” and automatic control processes become disrupted, placing greater demands on working memory and attentional resources[21]. By contrast, focusing externally on the effect of movement (the closing of the prosthesis around an object) allows the motor system to self-organise uninhibited by conscious control. Supporting evidence from the sport and human movement literature has shown that an external focus enhances movement accuracy[22], balance performance[23], maximum vertical jump height[24] and maximum force production[25], compared to an internal focus.

Despite the apparent advantage of an external focus of attention, it has recently been suggested that conventional prosthesis training mostly promotes an internal focus, with feedback and coaching typically centred on the muscular contractions rather than the actuation of the prosthesis resulting from said contractions[26,27]. It is, therefore, possible that current prosthesis training might be contributing to the difficulty users report controlling their device, especially when considering evidence that internal focus instructions might be less effective than receiving no instructions at all[28]. Indeed, an internal focus of attention appears to disrupt electromyographic (EMG) efficiency, increasing joint stiffness through co-contraction of antagonistic muscle pairs[29,30] and increasing the time to fatigue[30]. On a neurophysiological level, an internal focus appears to disrupt “surround inhibition” in the motor cortex, decreasing the contrast between task-relevant and task-irrelevant motor neurons leading to unnecessary contractions of muscles that are not directly involved in the task[31,32]. Given that fine prosthesis control is dependent on the generation of accurate EMG signals, promoting an internal focus may directly disrupt the effectiveness and efficiency of muscular activation and thus hinder prosthesis myocontrol.

Whilst attentional focus remains sparsely investigated in prosthesis control, some researchers have attempted to exploit the benefits of an external focus by employing “serious gaming”[26,27] to aid pattern recognition prosthesis control, and “gaze training”[19] to improve hand-eye coordination (see section 2.3). Although both strategies have shown some advantages over more “conventional” training, any clear advantage has thus far been limited to able-bodied prosthesis users. Evidently, far greater work is needed to clarify (a) the attentional focus strategies employed by upper-limb prosthesis users, (b) how these strategies are promoted through current training protocols, (c) how attentional focus affects prosthesis performance and functionality, and (d) the potential benefits of promoting an external focus.

3.2. Implicit Motor Learning

For a prosthetic hand user, a simple activity like eating in public may be a source of anxiety, resulting in an increased internal focus and conscious control in an attempt to ensure desired movement outcomes. Thus, motor learning strategies that reduce the reliance on conscious processes might benefit prosthesis users. Implicit motor learning, an established alternative to more traditional (explicit) forms of motor learning, aims to reduce the amount of consciously accessible (declarative) task-relevant knowledge[33]. It is argued that learning motor skills explicitly, often through verbally conveyed task rules (such as technique instructions), encourages conscious processing as learners can apply acquired declarative knowledge to the online control of movements[34]. By bypassing the provision of declarative knowledge via implicit motor learning methods, skills can be developed without conscious thought, lowering demands on working memory and freeing up attentional resources for other tasks [35]. The benefits of implicit motor learning include robust performance under pressure, fatigue, and multitasking[36–38]. Furthermore, research has shown that implicit motor learning occurs independent of age, and cognitive and motor impairment[39,40].

To our knowledge, there is currently little-to-no research directly investigating the potential benefit of implicit motor learning for upper-limb prosthesis skill acquisition. This is surprising, given the availability of many distinct strategies that can be used to exploit the proposed benefits of implicit learning. For example, error-reduced practice is proposed to encourage implicit learning by decreasing the amount of outcome errors made during skill acquisition, especially during the early stages of learning[37]. Commonly, error-reduced interventions start with an easily achievable task that is incrementally made more difficult throughout practice. For example, a prosthesis user could spend considerable time grasping large malleable objects (e.g., sponge ball) before attempting more precise grasping actions (e.g., picking up coins). By minimising errors, it is argued that learners are less likely to engage in active hypothesis testing in search for alternative movement solutions, lowering cognitive effort and mitigating the accumulation of declarative knowledge[37]. Error-reduced practice has increasingly been employed in rehabilitation, showing benefits among Parkinson's disease patients[41], stroke patients[42], Alzheimer's disease patients[43], and children with cerebral palsy[44]. Interestingly, error-reduced learning has also been shown to enhance the acquisition of prosthetic limb fitting skills in lower-limb amputees compared to typical (trial and error) treatment[45]. Error-reduced practice can also result in performance that is stable under physiological fatigue[38] and robust to secondary task loading[37]. Evidently, reducing errors during the initial stages of practice appears an effective implicit motor learning strategy that warrants more direct application to upper-limb prosthesis rehabilitation.

Implicit motor learning can also be achieved through the provision of a motor analogy instruction[46]. A motor analogy instruction has been described as an "all encompassing, biomechanical metaphor" that contains all the relevant information about the to-be-learned movement[47]. In this manner, familiarity with a concept in one domain (e.g., a right-angle triangle) can be used to disguise and facilitate the understanding of explicit rules within another domain[46] (e.g., the movement required to achieve a top spin forehand in table tennis). Thus, the new movement can be acquired with minimal load on declarative knowledge and information processing resources, leading to stable performance under pressure[48] and when having to make concurrent complex decisions[49]. Like error-reduced practice, motor analogy instructions have been increasingly used in rehabilitation[50]. For example, Jie et al. [51] instructed Parkinson's disease patients to pretend they were 'following footprints in the sand' during their everyday walking. Jie et al. found that clinically significant improvements for walking velocity were evident following analogy training. Furthermore, participants were able to perform a concurrent secondary task (both cognitive and motor) without affecting walking ability. The authors argued that successful dual-task performance demonstrates a potential transferability of motor analogy learning to activities of daily living.

A significant part of rehabilitation for prosthesis users focuses on improving functional ability by (re)learning activities of daily living. Implicit motor learning strategies, which place less demand on cognitive processes, and are more robust under pressure, might complement or even provide better alternatives to more traditional motor learning approaches. It is yet to be established whether implicit motor learning facilitates performance among prosthetic hand users, however, the implications for rehabilitation are promising.

3.3. Hand-eye coordination and the utility of gaze training

A commonly cited reason for prosthesis rejection is the high cognitive burden imposed on users to visually monitor ongoing actions to accommodate for the severe reductions in hand-related sensory feedback. Indeed, prosthetic hand users display a high tendency to watch the hand or objects being manipulated by the hand[19,52,53], a behaviour rarely observed during able-bodied reaching and grasping [54]. The tendency to watch the hand is typically associated with an initial stage of learning, where vision is used to check the consequences of actions so that errors can be identified and corrected online[55]. With increasing skill, however, learners can typically better predict the consequences of their actions, allowing vision to retrieve feedforward (i.e., look at the object to be grasped) rather than a feedback (i.e., look at the hand when reaching for the object) information, as observed in typical anatomic hand control. These skill-related changes in visuomotor behaviours have been observed when learning to use laparoscopic surgical tools[56] and chopsticks[57], with skilled behaviour seemingly underpinned by an increased ratio of target-related (feedforward) compared to tool-related (feedback) fixations. It would therefore be reasonable to assume that (a) the demands on the visual system to monitor prosthesis control would naturally decrease with experience, and that (b) gaze behaviour could be used to determine the skill level of prosthesis users and thus the degree of device integration. However, evidence thus far has failed to support these assumptions, with gaze strategies among experienced prosthesis users highly variable and seemingly unrelated to prosthesis functionality[16] or usage in the real-world[53]. Why, then, does the typical relationship between skill level and hand (tool) focused gaze not arise in prosthesis users as it does is other human-tool interactions (e.g., laparoscopy and chopsticks)?

One likely explanation is that prosthetic devices might be inherently too unpredictable to allow the development of reliable mapping rules. Unlike rigid 'tools' that have fixed intrinsic properties, the reliability of prosthesis responsiveness can fluctuate as a result of EMG signal artefact arising from sweating, poor fitting and/or fatigue[58]. Indeed, recent evidence has shown that prosthesis users who experience a greater frequency of undesired activations (hand accidentally opening/closing, no prosthesis response, or incorrect prosthesis response) during a shoulder flexion task are also more likely to exhibit decreased functionality and an increased time watching the prosthesis during a multi-stage functional task[59]. This tentatively suggests that the expectation of an undesired prosthesis response (i.e., users do not trust their device) drives both poor performance and the over-reliance on gaze to visually monitor prosthesis control and safeguard against (the possibility of) task failure. Addressing the issue of prosthesis unpredictability could therefore be crucial to the development of effective prosthesis visuomotor control and the alleviation of cognitive resources dedicated to continuous prosthesis monitoring[59].

Whilst the influence of prosthesis unpredictability cannot be overlooked, Parr et al. [19] provided evidence that the gaze strategies used to control a prosthesis can also be strongly influenced by the nature of training instructions. Specifically, Parr et al. administered one week of "gaze training" designed to encourage learners to adopt a "target focused" gaze strategy and avoid visually fixating the prosthesis, a method shown to expedite the acquisition of laparoscopic surgical skills[60]. Compared to a group who received explicit technique focused instructions (i.e., "movement training"), the gaze training group visually focused on the prosthesis less, completed the tasks quicker, and displayed more efficient brain activity (as indexed by electroencephalography; see[61]) at retention and delayed retention.

These findings have several potential implications for our understanding of the visuomotor control strategies observed in prosthesis users. For example, unless told otherwise, it appears that learners will maintain an overreliance on gaze to visually monitor prosthesis actions. As this behaviour has been observed in experienced prosthesis users, it likely reflects a compensatory behaviour to safeguard against task failure in the face of prosthesis unpredictability. However, the findings of Parr et al. suggest that this behaviour is not a prerequisite of prosthesis control, and users can be encouraged to relinquish their reliance on vision to control movement. By doing so, users may become more proficient at utilising other “back-up” modalities of sensory information (e.g., auditory / proprioceptive feedback). It would therefore appear that prosthesis unpredictability might prevent the natural development of feedforward gaze control rather than the possibility of achieving it through intentional practice. Adopting feedforward gaze control also resulted in quicker movements and increased neural efficiency, possibly by encouraging an external focus of attention and bypassing the provision of explicit, movement-related instructions (i.e., implicit learning)[19]. Given that an internal focus of attention, and the tendency to consciously control motor actions, has been associated with less-effective and less-consistent myocontrol, it is important to recognise that prosthesis unpredictability might (to some extent) be user-driven by the cognitive strategies employed during prosthesis control.

3.4. Practice variability and contextual interference

Practice variability is a fundamental component of rehabilitation design. For example, if several prosthesis tasks must be learned within a single therapy session (e.g., different grip patterns), a learner could be asked to repetitively perform multiple trials of the same task (i.e., low variability) or to adaptively switch between different tasks or task variants on a trial-by-trial basis (i.e., high variability). Importantly, the Contextual Interference (CI) effect is a robust motor learning phenomenon that suggests the choice between either high or low practice variability is far from arbitrary and can have cascade effects on both immediate performance and long-term motor adaptation. Specifically, the CI effect states that practicing a “block” of repetitive trials of a single motor task before moving on to a new task (i.e., Blocked practice) facilitates performance during practice, but does not facilitate long-term learning. Conversely, constantly switching between different tasks in a random order (i.e., Random practice) increases performance error during practice (via task interference) but is more optimal for long-term motor adaptation at retention[62,63]. It is proposed that the frequent task switching imposed by a random schedule increases cognitive effort and thus memory consolidation[64], supported by neurophysiological evidence that random practice elevates the activation of the cognitive, sensory, and motor regions of the brain[65,66].

Only two studies have investigated whether the principles of the CI effect can be applied to the learning of upper-limb prosthesis skills – both of which utilised able-bodied users of prosthesis simulators. The first study, by Weeks et al.[67], found that two days of random practice facilitated more proficient transfer of skills to novel tasks compared to blocked practice. This is important, as day-to-day prosthesis use will likely impose similar demands on an individual's ability to transfer clinic-based training to unpredictable contexts and situations. In contrast, Bouwsema et al.[68] found that one day of either blocked or random practice resulted in similar performance levels during delayed retention and task-transfer tests. As the blocked practice facilitated greater performance during acquisition, the authors advocated a blocked schedule for prosthesis rehabilitation to achieve faster performance gains and thus optimise motivation. Such an interpretation should, however, be treated with caution given the small amount of practice (total 60 trials) included in the study.

These inconsistent results follow the observation that the typical CI effect is less robust when applied to non-laboratory skills[69]. To explain this, researchers have suggested that task complexity (relative to the performer) is likely to moderate the CI effect, and that task variability should be manipulated in a manner that brings about an "optimal challenge"[70]. However, as the challenge presented by a motor task will dynamically decrease with respect to an individual's increasing skill proficiency, researchers have advocated for practice schedules that dynamically moderate CI (and thus challenge) across the practice session. For example, benefits have been shown for mixing blocked and random practice[71], and systematically increasing CI across learning[72]. Benefits have also been shown for 'learner adaptive' practice schedules that regulate the frequency of task-switching based on trial-to-trial performance[73,74]. Typically, these adaptive schedules are designed to encourage increased task-switching when learners are performing well (increasing challenge) but decreased task-switching when learners are performing poorly (decreasing challenge), thus continually manipulating the appropriate levels of challenge. Research is needed to determine the utility of these adaptive schedules for prosthesis training and to determine the optimal success criteria for a task-switch (e.g., one versus two consecutive successes), which is a critical aspect of these schedules for moderating CI.

Taken together, the variability of a practice schedule is an aspect of rehabilitation design that should not be overlooked. A crucial point is that performance gains achieved during a practice (or therapy) session are not necessarily a good index of long-term motor adaptation. Consequently, both therapists and learners are potentially at risk of wrongly endorsing a highly repetitive (i.e., blocked) training strategy that seemingly facilitates more immediate performance, potentially to the detriment of long-term skill acquisition. Increasing the variability of practice through a random schedule could therefore be used to increase task difficulty, cognitive effort and the potential for learning and transfer. However, therapists should be mindful that a strictly random schedule might be too challenging for those learners struggling to control their prosthesis, leading to discouragement if the learner does not feel they are improving as well as might be expected[75]. This is problematic when considering that rehabilitation sessions are typically short in nature, thus minimising the time available to both the patient and therapist to observe meaningful practice benefits. Task variability could therefore be adaptively manipulated in a manner that brings about an optimal challenge for learners, maintaining moderate levels of performance error without disrupting motivation and the perceived usefulness of training. However, far greater research is needed to apply adaptive practice schedules to the context of prosthesis rehabilitation.

3.5. Motor Imagery and Action Observation

The implementation of mental simulation techniques could help facilitate the ability to use upper limb prosthetic devices. Action observation involves the observation of successful movement execution[76], whilst motor imagery involves the intentional internal generation of visual and kinaesthetic aspects of movement[77]. Jeannerod's simulation theory[78] proposed that action observation and motor imagery are simulated forms of action, which elicit activity in similar brain regions to those involved in movement execution. Meta-analyses of neuroimaging data have confirmed that various brain regions active during movement execution are also active during both action observation and motor imagery[79,80]. Activation of motor-related brain regions through these processes is presumed to facilitate subsequent motor execution, with the repeated activation in this manner assumed to promote Hebbian plasticity in a similar manner to physical practice[81]. The efficacy of these techniques has been explored in various movement rehabilitation contexts. Both techniques, when implemented alongside physical therapy, can promote improvements in motor function in individuals with motor impairments associated with stroke[82], Parkinson's Disease[83], and Developmental Coordination Disorder[84].

Given the positive effects reported for action observation and motor imagery in movement rehabilitation contexts, it is noteworthy that these techniques have received relatively little research attention in relation to upper-limb prosthesis training. However, several researchers have explored the efficacy of action observation training on the acquisition of prosthetic hand control. For example, Cusack et al.[85] showed that those who trained to use a prosthesis by observing and imitating the movements of prosthesis users were able to execute actions with reduced movement variability, compared to those who trained by observing and imitating the movements of intact limbs. Bayani et al.[86] reported similar findings, with greater kinematic improvements following training involving action observation of a prosthesis user compared to action observation of an intact limb. Eye-tracking measures also revealed that different gaze strategies underpinned the kinematic differences, with those observing intact limbs directing their gaze primarily to the start and end points of the observed action, and those observing prosthesis use directing their gaze towards the path of the prosthesis in action and the shoulders.

There have been some attempts to develop upper-limb prosthetic devices that can be controlled by motor imagery through a brain-computer interface[87]. However, we are not aware of any research that has investigated the efficacy of motor imagery techniques to aid the learning of a prosthetic device. This is surprising in relation to myoelectric prosthetic devices, as the use of kinaesthetic imagery to mentally rehearse the generation of the signals required to activate the device could conceivably aid users in learning the control mechanisms of the device.

In the past decade, there has been an increased focus on the combined and simultaneous use of action observation and motor imagery (i.e., AOMI). This approach involves instructing individuals to observe an action on video, whilst engaging simultaneously in kinaesthetic imagery of the sensations associated executing the observed movement. Neurophysiological research has shown that this approach elicits increased activity in the motor system than either independent action observation or independent motor imagery[88]. There is also evidence that this combined approach is effective in facilitating motor performance. For example, Marshall et al.[89] showed that AOMI improves eye-hand coordination and performance in a novel visuomotor task to a greater extent than action observation alone. AOMI could therefore prove to be effective for the learning of myoelectric prosthetic devices, as the action observation component would convey important kinematic information, such as the optimal limb orientation and positioning required to interact successfully with objects, whilst the motor imagery component could facilitate the learning of the control mechanisms associated with generating myosignals to activate the device.

Exploration of the effects of motor simulation techniques on learning to use a prosthetic hand would be a worthwhile line of future investigation. If found to be effective, these strategies could have considerable implications for prosthesis training. For example, as these techniques do not require overt action it would be possible for individuals to begin the process of learning to use a prosthesis at an earlier point, prior to planned amputations, as well as during the pre-prosthetic phase post-amputation when movement is impaired. This could enhance the rate at which individuals become skilled in using their prosthesis, potentially enhancing prosthesis adoption rates. Training through action observation and motor imagery techniques could also alleviate fatigue and soreness associated with repetitive physical training with the prosthesis in the initial days and weeks post-amputation. These methods could also offer a convenient and cost-effective therapy to be prescribed by occupational therapists, which can be employed at the user's convenience, either alongside regular training or in isolation.

3.6. Virtual Training and Biofeedback

Virtual training and biofeedback are becoming increasingly important aspects in the upper-limb prosthesis rehabilitation process. These methods are advantageous, as they do not require a fully healed stump, meaning they can be implemented far before the initiation of conventional prosthesis training. This is especially important considering that starting training early has been shown to result in higher acceptance and use of the prosthesis[90]. The main premise of virtual training and biofeedback in upper-limb rehabilitation is to enhance someone's myocontrol, which is the ability to control the opening and closing of a myoelectric prosthesis through surface EMG signals derived from the action potentials produced by (usually two) muscles[91]. Good myocontrol is a prerequisite of functional prosthesis use, especially considering the increasing dexterity of the latest myoelectric devices. Indeed, experienced users of a myoelectric prosthesis have been shown to generate more consistent prosthesis control following EMG biofeedback[92]. However, the ability to produce distinct myosignals is not intuitive and can vary on an individual basis[93]. Therefore, virtual training and biofeedback provide potentially promising techniques to develop myocontrol in the pre-prosthetic stage.

Three main methods for training the myosignal have been examined by research. The first simply involves displaying a live feed of EMG signals on a computer screen, representative of basic biofeedback. The second and third are more representative of virtual training and involve either displaying a virtual prosthesis on a screen that is manipulated via the myosignal in the exact manner as an actual prosthesis[94], or incorporating control of the myosignal into controlling an aspect of a computer game[95]. These methods have shown positive results for enhancing control of the myosignal in upper-limb prostheses. For example, Bouwsema et al.[93] found training with a virtual hand to be equivalent to training with a physical prosthesis, advocating virtual training as a vital component of prosthesis training to enhance motivation and expedite learning during the early stages of skill development. Nakamura et al.[96] demonstrated that training with virtual myocontrol software transferred to a grasping task performed with a physical prosthesis, namely a box and block test, with improvements in both the number of blocks moved and the orientation of the hand on approach. There is also some evidence that the benefits of virtual training may extend beyond convenience and efficiency. For example, in a study using virtual avatars and EEG, Fernandez-Vargas et al.[97] found that imitating movements presented virtually resulted in greater parietal alpha desynchronisation during motion, which may be suggestive of lower attentional demands for the trainee. Most of the studies advocating the use of virtual training to date have been performed with healthy participants but in a recent study with upper-extremity amputees, Perry et al.[98] found that training with a virtual avatar controlled by the myosignal improved movement accuracy across three different motion sets of varied complexity.

Although these methods have been shown to have comparable learning advantages for prosthesis training[91], various authors have suggested that a computer game would be most beneficial as it has the potential to be more engaging and fun than the other methods[91]. For example, Radhakrishnan et al.[99] developed a game-based pre-prosthesis training environment designed to challenge users to reach higher scores. Using an evaluation questionnaire, they found that participants responded positively to the games, reporting enjoyment regarding the varied levels of difficulty and motivation to return to the game. Participants also reported that they believed the games could be used to improve their muscular control. However, this study was performed with healthy participants and further investigation with limb-loss patients is warranted.

These virtual systems benefit from being low cost, portable, and easy to use, allowing users to practice at home without a therapist and have autonomy over practice type and difficulty. Additionally, the level of myocontrol displayed during pre-prosthetic training can also be used to determine the suitability of potential prosthesis control components, making for a more personalised device. However, the field needs an easily administrable test to identify myocontrol learning ability and standardise this protocol[91]. Another important point for consideration is the distinct difference between operating a virtual and physical prosthesis. Training with a physical prosthesis poses postural kinetic and kinematic challenges that are not addressed by virtual training. This may limit the application of virtual training to myoelectric control primarily. Furthermore, if virtual training is to be applied into a prosthesis training protocols, more information is needed about how it would be implemented and whether it could be integrated with the motor learning principles discussed in the present review. Research into this area could significantly enhance the already promising learning benefits of virtual training and biofeedback, optimizing the time an amputee spends in the pre-prosthetic stage.

4. Conclusion

Current rates of upper-limb prosthesis abandonment remain high, with technological advancements yet to achieve any significant impact on user satisfaction[1]. The importance of optimising early and appropriate training therefore cannot be overlooked. While the intuition and experience of clinicians holds enormous value, evidence-based guidelines based on well-established motor learning principles will also be crucial for training effective prosthetic hand control. Important to the design of any such guidelines is the realisation that the level of limb-loss and the type of device are important factors in need of consideration. For example, patients with more proximal levels of limb-loss have difficulties with bimanual tasks[100], higher abandonment rates [101], report less satisfaction[102], and lower perceived functionality[103] compared to users of below elbow prostheses. There is also evidence that prosthetic devices with pattern-recognition technology can optimise intuitive control and alleviate cognitive demands compared to more traditional devices using direct control schemes[104,105]. We therefore are not proposing the pursuit of a 'gold-standard' one size fits all approach to training, instead we are advocating for an evidence-based approach that provides applied practitioners with a 'tool-box' of research-informed techniques that can be used in a client-centred manner based on their experiential knowledge. It is clear that more research is needed before this is achieved and it is hoped that this review highlights the potential avenues for such work. Finally, a challenge moving forward is ensuring that any growth in academic knowledge achieves some degree of clinical translation. Future attempts to optimise prosthesis training should therefore attempt to engage in multi-stakeholder collaborations between users, researchers, clinicians, charity representatives and industry specialists to achieve greater impact and benefit for the target population[106].

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