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1 **A scoping review of the application of motor learning principles to optimise myoelectric**

2 **prosthetic hand control**

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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

109 sensations, an external focus occurs when an individual instead directs their attention towards the

110 outcomes of the movement or the effect the movement has upon the environment. For example, a

111 prosthesis user could either be instructed to focus on "contracting the muscles of the residual limb" (i.e.,

112 internal focus) or to simply focus on "closing the prosthesis" (i.e., external focus) when attempting to

113 grasp an object. By focusing internally (contracting the muscles) it is proposed that the motor system

114 becomes "constrained" and automatic control processes become disrupted, placing greater demands on

115 working memory and attentional resources[21]. By contrast, focusing externally on the effect of movement

116 (the closing of the prosthesis around an object) allows the motor system to self-organise uninhibited by

117 conscious control. Supporting evidence from the sport and human movement literature has shown that

118 an external focus enhances movement accuracy[22], balance performance[23], maximum vertical jump

119 height[24] and maximum force production[25], compared to an internal focus.

120 Despite the apparent advantage of an external focus of attention, it has recently been suggested

121 that conventional prosthesis training mostly promotes an internal focus, with feedback and coaching

122 typically centred on the muscular contractions rather than the actuation of the prosthesis resulting from

123 said contractions[26,27]. It is, therefore, possible that current prosthesis training might be contributing to

124 the difficulty users report controlling their device, especially when considering evidence that internal

125 focus instructions might be less effective than receiving no instructions at all[28]. Indeed, an internal focus

126 of attention appears to disrupt electromyographic (EMG) efficiency, increasing joint stiffness through

127 co-contraction of antagonistic muscle pairs[29,30] and increasing the time to fatigue[30]. On a

128 neurophysiological level, an internal focus appears to disrupt "surround inhibition" in the motor cortex,

129 decreasing the contrast between task-relevant and task-irrelevant motor neurons leading to unnecessary

130 contractions of muscles that are not directly involved in the task[31,32]. Given that fine prosthesis control

131 is dependent on the generation of accurate EMG signals, promoting an internal focus may directly

132 disrupt the effectiveness and efficiency of muscular activation and thus hinder prosthesis myocontrol.

133 Whilst attentional focus remains sparsely investigated in prosthesis control, some researchers

134 have attempted to exploit the benefits of an external focus by employing "serious gaming"[26,27] to aid

135 pattern recognition prosthesis control, and "gaze training"[19] to improve hand-eye coordination (see

136   section 2.3). Although both strategies have shown some advantages over more "conventional" training,

137   any clear advantage has thus far been limited to able-bodied prosthesis users. Evidently, far greater

138   work is needed to clarify (a) the attentional focus strategies employed by upper-limb prosthesis users,

139   (b) how these strategies are promoted through current training protocols, (c) how attentional focus

140   affects prosthesis performance and functionality, and (d) the potential benefits of promoting an external

141   focus.

142   **3.2. Implicit Motor Learning**

143   For a prosthetic hand user, a simple activity like eating in public may be a source of anxiety,

144   resulting in an increased internal focus and conscious control in an attempt to ensure desired movement

145   outcomes. Thus, motor learning strategies that reduce the reliance on conscious processes might benefit

146   prosthesis users. Implicit motor learning, an established alternative to more traditional (explicit) forms

147   of motor learning, aims to reduce the amount of consciously accessible (declarative) task-relevant

148   knowledge[33]. It is argued that learning motor skills explicitly, often through verbally conveyed task

149   rules (such as technique instructions), encourages conscious processing as learners can apply acquired

150   declarative knowledge to the online control of movements[34]. By bypassing the provision of declarative

151   knowledge via implicit motor learning methods, skills can be developed without conscious thought,

152   lowering demands on working memory and freeing up attentional resources for other tasks [35]. The

153   benefits of implicit motor learning include robust performance under pressure, fatigue, and

154   multitasking[36–38]. Furthermore, research has shown that implicit motor learning occurs independent of

155   age, and cognitive and motor impairment[39,40].

156   To our knowledge, there is currently little-to-no research directly investigating the potential

157   benefit of implicit motor learning for upper-limb prosthesis skill acquisition. This is surprising, given

158   the availability of many distinct strategies that can be used to exploit the proposed benefits of implicit

159   learning. For example, error-reduced practice is proposed to encourage implicit learning by decreasing

160   the amount of outcome errors made during skill acquisition, especially during the early stages of

161   learning[37]. Commonly, error-reduced interventions start with an easily achievable task that is

162   incrementally made more difficult throughout practice. For example, a prosthesis user could spend

163   considerable time grasping large malleable objects (e.g., sponge ball) before attempting more precise

164   grasping actions (e.g., picking up coins). By minimising errors, it is argued that learners are less likely

165   to engage in active hypothesis testing in search for alternative movement solutions, lowering cognitive

166   effort and mitigating the accumulation of declarative knowledge[37]. Error-reduced practice has

167   increasingly been employed in rehabilitation, showing benefits among Parkinson's disease patients[41],

168   stroke patients[42], Alzheimer's disease patients[43], and children with cerebral palsy[44]. Interestingly, error-

169   reduced learning has also been shown to enhance the acquisition of prosthetic limb fitting skills in

170   lower-limb amputees compared to typical (trial and error) treatment[45]. Error-reduced practice can also

171   result in performance that is stable under physiological fatigue[38] and robust to secondary task loading[37].

172   Evidently, reducing errors during the initial stages of practice appears an effective implicit motor

173   learning strategy that warrants more direct application to upper-limb prosthesis rehabilitation.

174   Implicit motor learning can also be achieved through the provision of a motor analogy

175   instruction[46]. A motor analogy instruction has been described as an "all encompassing, biomechanical

176   metaphor" that contains all the relevant information about the to-be-learned movement[47]. In this

177   manner, familiarity with a concept in one domain (e.g., a right-angle triangle) can be used to disguise

178   and facilitate the understanding of explicit rules within another domain[46] (e.g., the movement required

179   to achieve a top spin forehand in table tennis). Thus, the new movement can be acquired with minimal

180   load on declarative knowledge and information processing resources, leading to stable performance

181   under pressure[48] and when having to make concurrent complex decisions[49]. Like error-reduced practice,

182   motor analogy instructions have been increasingly used in rehabilitation[50]. For example, Jie et al. [51]

183   instructed Parkinson's disease patients to pretend they were 'following footprints in the sand' during

184   their everyday walking. Jie et al. found that clinically significant improvements for walking velocity

185   were evident following analogy training. Furthermore, participants were able to perform a concurrent

186   secondary task (both cognitive and motor) without affecting walking ability. The authors argued that

187   successful dual-task performance demonstrates a potential transferability of motor analogy learning to

188   activities of daily living.

189   A significant part of rehabilitation for prosthesis users focuses on improving functional ability

190   by (re)learning activities of daily living. Implicit motor learning strategies, which place less demand on

191   cognitive processes, and are more robust under pressure, might complement or even provide better

192   alternatives to more traditional motor learning approaches. It is yet to be established whether implicit

193   motor learning facilitates performance among prosthetic hand users, however, the implications for

194   rehabilitation are promising.

195   **3.3. Hand-eye coordination and the utility of gaze training**

196   A commonly cited reason for prosthesis rejection is the high cognitive burden imposed on users

197   to visually monitor ongoing actions to accommodate for the severe reductions in hand-related sensory

198   feedback. Indeed, prosthetic hand users display a high tendency to watch the hand or objects being

199   manipulated by the hand[19,52,53], a behaviour rarely observed during able-bodied reaching and grasping

200   [54]. The tendency to watch the hand is typically associated with an initial stage of learning, where vision

201   is used to check the consequences of actions so that errors can be identified and corrected online[55]. With

202   increasing skill, however, learners can typically better predict the consequences of their actions,

203   allowing vision to retrieve feedforward (i.e., look at the object to be grasped) rather than a feedback

204   (i.e., look at the hand when reaching for the object) information, as observed in typical anatomic hand

205   control. These skill-related changes in visuomotor behaviours have been observed when learning to use

206   laparoscopic surgical tools[56] and chopsticks[57], with skilled behaviour seemingly underpinned by an

207   increased ratio of target-related (feedforward) compared to tool-related (feedback) fixations. It would

208   therefore be reasonable to assume that (a) the demands on the visual system to monitor prosthesis

209   control would naturally decrease with experience, and that (b) gaze behaviour could be used to

210   determine the skill level of prosthesis users and thus the degree of device integration. However,

211   evidence thus far has failed to support these assumptions, with gaze strategies among experienced

212   prosthesis users highly variable and seemingly unrelated to prosthesis functionality[16] or usage in the

213   real-world[53]. Why, then, does the typical relationship between skill level and hand (tool) focused gaze

214   not arise in prosthesis users as it does is other human-tool interactions (e.g., laparoscopy and

215   chopsticks)?

216   One likely explanation is that prosthetic devices might be inherently too unpredictable to allow

217   the development of reliable mapping rules. Unlike rigid 'tools' that have fixed intrinsic properties, the

218   reliability of prosthesis responsiveness can fluctuate as a result of EMG signal artefact arising from

219   sweating, poor fitting and/or fatigue[58]. Indeed, recent evidence has shown that prosthesis users who

220   experience a greater frequency of undesired activations (hand accidentally opening/closing, no

221   prosthesis response, or incorrect prosthesis response) during a shoulder flexion task are also more likely

222   to exhibit decreased functionality and an increased time watching the prosthesis during a multi-stage

223   functional task[59]. This tentatively suggests that the expectation of an undesired prosthesis response (i.e.,

224   users do not trust their device) drives both poor performance and the over-reliance on gaze to visually

225   monitor prosthesis control and safeguard against (the possibility of) task failure. Addressing the issue

226   of prosthesis unpredictability could therefore be crucial to the development of effective prosthesis

227   visuomotor control and the alleviation of cognitive resources dedicated to continuous prosthesis

228   monitoring[59].

229   Whilst the influence of prosthesis unpredictability cannot be overlooked, Parr et al. [19] provided

230   evidence that the gaze strategies used to control a prosthesis can also be strongly influenced by the

231   nature of training instructions. Specifically, Parr et al. administered one week of "gaze training"

232   designed to encourage learners to adopt a "target focused" gaze strategy and avoid visually fixating the

233   prosthesis, a method shown to expedite the acquisition of laparoscopic surgical skills[60]. Compared to a

234   group who received explicit technique focused instructions (i.e., "movement training"), the gaze

235   training group visually focused on the prosthesis less, completed the tasks quicker, and displayed more

236   efficient brain activity (as indexed by electroencephalography; see[61]) at retention and delayed retention.

237   These findings have several potential implications for our understanding of the visuomotor

238   control strategies observed in prosthesis users. For example, unless told otherwise, it appears that

239   learners will maintain an overreliance on gaze to visually monitor prosthesis actions. As this behaviour

240   has been observed in experienced prosthesis users, it likely reflects a compensatory behaviour to

241   safeguard against task failure in the face of prosthesis unpredictability. However, the findings of Parr

242   et al. suggest that this behaviour is not a prerequisite of prosthesis control, and users can be encouraged

243 to relinquish their reliance on vision to control movement. By doing so, users may become more

244 proficient at utilising other "back-up" modalities of sensory information (e.g., auditory / proprioceptive

245 feedback). It would therefore appear that prosthesis unpredictability might prevent the natural

246 development of feedforward gaze control rather than the possibility of achieving it through intentional

247 practice. Adopting feedforward gaze control also resulted in quicker movements and increased neural

248 efficiency, possibly by encouraging an external focus of attention and bypassing the provision of

249 explicit, movement-related instructions (i.e., implicit learning)[19]. Given that an internal focus of

250 attention, and the tendency to consciously control motor actions, has been associated with less-effective

251 and less-consistent myocontrol, it is important to recognise that prosthesis unpredictability might (to

252 some extent) be user-driven by the cognitive strategies employed during prosthesis control.

253 ### 3.4. Practice variability and contextual interference

254 Practice variability is a fundamental component of rehabilitation design. For example, if several

255 prosthesis tasks must be learned within a single therapy session (e.g., different grip patterns), a learner

256 could be asked to repetitively perform multiple trials of the same task (i.e., low variability) or to

257 adaptively switch between different tasks or task variants on a trial-by-trial basis (i.e., high variability).

258 Importantly, the Contextual Interference (CI) effect is a robust motor learning phenomenon that

259 suggests the choice between either high or low practice variability is far from arbitrary and can have

260 cascade effects on both immediate performance and long-term motor adaptation. Specifically, the CI

261 effect states that practicing a "block" of repetitive trials of a single motor task before moving on to a

262 new task (i.e., Blocked practice) facilitates performance during practice, but does not facilitate long-

263 term learning. Conversely, constantly switching between different tasks in a random order (i.e., Random

264 practice) increases performance error during practice (via task interference) but is more optimal for

265 long-term motor adaptation at retention[62,63]. It is proposed that the frequent task switching imposed by

266 a random schedule increases cognitive effort and thus memory consolidation[64], supported by

267 neurophysiological evidence that random practice elevates the activation of the cognitive, sensory, and

268 motor regions of the brain[65,66].

269   Only two studies have investigated whether the principles of the CI effect can be applied to the

270   learning of upper-limb prosthesis skills – both of which utilised able-bodied users of prosthesis

271   simulators. The first study, by Weeks et al.[67], found that two days of random practice facilitated more

272   proficient transfer of skills to novel tasks compared to blocked practice. This is important, as day-to-

273   day prosthesis use will likely impose similar demands on an individual's ability to transfer clinic-based

274   training to unpredictable contexts and situations. In contrast, Bouwsema et al.[68] found that one day of

275   either blocked or random practice resulted in similar performance levels during delayed retention and

276   task-transfer tests. As the blocked practice facilitated greater performance during acquisition, the

277   authors advocated a blocked schedule for prosthesis rehabilitation to achieve faster performance gains

278   and thus optimise motivation. Such an interpretation should, however, be treated with caution given the

279   small amount of practice (total 60 trials) included in the study.

280   These inconsistent results follow the observation that the typical CI effect is less robust when

281   applied to non-laboratory skills[69]. To explain this, researchers have suggested that task complexity

282   (relative to the performer) is likely to moderate the CI effect, and that task variability should be

283   manipulated in a manner that brings about an "optimal challenge"[70]. However, as the challenge

284   presented by a motor task will dynamically decrease with respect to an individual's increasing skill

285   proficiency, researchers have advocated for practice schedules that dynamically moderate CI (and thus

286   challenge) across the practice session. For example, benefits have been shown for mixing blocked and

287   random practice[71], and systematically increasing CI across learning[72]. Benefits have also been shown

288   for 'learner adaptive' practice schedules that regulate the frequency of task-switching based on trial-to-

289   trial performance[73,74]. Typically, these adaptive schedules are designed to encourage increased task-

290   switching when learners are performing well (increasing challenge) but decreased task-switching when

291   learners are performing poorly (decreasing challenge), thus continually manipulating the appropriate

292   levels of challenge. Research is needed to determine the utility of these adaptive schedules for prosthesis

293   training and to determine the optimal success criteria for a task-switch (e.g., one versus two consecutive

294   successes), which is a critical aspect of these schedules for moderating CI.

295   Taken together, the variability of a practice schedule is an aspect of rehabilitation design that

296   should not be overlooked. A crucial point is that performance gains achieved during a practice (or

297   therapy) session are not necessarily a good index of long-term motor adaptation. Consequently, both

298   therapists and learners are potentially at risk of wrongly endorsing a highly repetitive (i.e., blocked)

299   training strategy that seemingly facilitates more immediate performance, potentially to the detriment of

300   long-term skill acquisition. Increasing the variability of practice through a random schedule could

301   therefore be used to increase task difficulty, cognitive effort and the potential for learning and transfer.

302   However, therapists should be mindful that a strictly random schedule might be too challenging for

303   those learners struggling to control their prosthesis, leading to discouragement if the learner does not

304   feel they are improving as well as might be expected[75]. This is problematic when considering that

305   rehabilitation sessions are typically short in nature, thus minimising the time available to both the patient

306   and therapist to observe meaningful practice benefits. Task variability could therefore be adaptively

307   manipulated in a manner that brings about an optimal challenge for learners, maintaining moderate

308   levels of performance error without disrupting motivation and the perceived usefulness of training.

309   However, far greater research is needed to apply adaptive practice schedules to the context of prosthesis

310   rehabilitation.

3.5. Motor Imagery and Action Observation

312   The implementation of mental simulation techniques could help facilitate the ability to use

313   upper limb prosthetic devices. Action observation involves the observation of successful movement

314   execution[76], whilst motor imagery involves the intentional internal generation of visual and kinaesthetic

315   aspects of movement[77]. Jeannerod's simulation theory[78] proposed that action observation and motor

316   imagery are simulated forms of action, which elicit activity in similar brain regions to those involved

317   in movement execution. Meta-analyses of neuroimaging data have confirmed that various brain regions

318   active during movement execution are also active during both action observation and motor

319   imagery[79,80]. Activation of motor-related brain regions through these processes is presumed to facilitate

320   subsequent motor execution, with the repeated activation in this manner assumed to promote Hebbian

321   plasticity in a similar manner to physical practice[81]. The efficacy of these techniques has been explored

322 in various movement rehabilitation contexts. Both techniques, when implemented alongside physical

323 therapy, can promote improvements in motor function in individuals with motor impairments associated

324 with stroke[82], Parkinson's Disease[83], and Developmental Coordination Disorder[84].

325   Given the positive effects reported for action observation and motor imagery in movement

326 rehabilitation contexts, it is noteworthy that these techniques have received relatively little research

327 attention in relation to upper-limb prosthesis training. However, several researchers have explored the

328 efficacy of action observation training on the acquisition of prosthetic hand control. For example,

329 Cusack et al.[85] showed that those who trained to use a prosthesis by observing and imitating the

330 movements of prosthesis users were able to execute actions with reduced movement variability,

331 compared to those who trained by observing and imitating the movements of intact limbs. Bayani et

332 al.[86] reported similar findings, with greater kinematic improvements following training involving action

333 observation of a prosthesis user compared to action observation of an intact limb. Eye-tracking

334 measures also revealed that different gaze strategies underpinned the kinematic differences, with those

335 observing intact limbs directing their gaze primarily to the start and end points of the observed action,

336 and those observing prosthesis use directing their gaze towards the path of the prosthesis in action and

337 the shoulders.

338   There have been some attempts to develop upper-limb prosthetic devices that can be controlled

339 by motor imagery through a brain-computer interface[87]. However, we are not aware of any research that

340 has investigated the efficacy of motor imagery techniques to aid the learning of a prosthetic device.

341 This is surprising in relation to myoelectric prosthetic devices, as the use of kinaesthetic imagery to

342 mentally rehearse the generation of the signals required to activate the device could conceivably aid

343 users in learning the control mechanisms of the device.

344   In the past decade, there has been an increased focus on the combined and simultaneous use of

345 action observation and motor imagery (i.e., AOMI). This approach involves instructing individuals to

346 observe an action on video, whilst engaging simultaneously in kinaesthetic imagery of the sensations

347 associated executing the observed movement. Neurophysiological research has shown that this

348 approach elicits increased activity in the motor system than either independent action observation or

349 independent motor imagery[88]. There is also evidence that this combined approach is effective in

350 facilitating motor performance. For example, Marshall et al.[89] showed that AOMI improves eye-hand

351 coordination and performance in a novel visuomotor task to a greater extent than action observation

352 alone. AOMI could therefore prove to be effective for the learning of myoelectric prosthetic devices, as

353 the action observation component would convey important kinematic information, such as the optimal

354 limb orientation and positioning required to interact successfully with objects, whilst the motor imagery

355 component could facilitate the learning of the control mechanisms associated with generating

356 myosignals to activate the device.

357 Exploration of the effects of motor simulation techniques on learning to use a prosthetic hand

358 would be a worthwhile line of future investigation. If found to be effective, these strategies could have

359 considerable implications for prosthesis training. For example, as these techniques do not require overt

360 action it would be possible for individuals to begin the process of learning to use a prosthesis at an

361 earlier point, prior to planned amputations, as well as during the pre-prosthetic phase post-amputation

362 when movement is impaired. This could enhance the rate at which individuals become skilled in using

363 their prosthesis, potentially enhancing prosthesis adoption rates. Training through action observation

364 and motor imagery techniques could also alleviate fatigue and soreness associated with repetitive

365 physical training with the prosthesis in the initial days and weeks post-amputation. These methods could

366 also offer a convenient and cost-effective therapy to be prescribed by occupational therapists, which

367 can be employed at the user's convenience, either alongside regular training or in isolation.

368 **3.6. Virtual Training and Biofeedback**

369 Virtual training and biofeedback are becoming increasingly important aspects in the upper-limb

370 prosthesis rehabilitation process. These methods are advantageous, as they do not require a fully healed

371 stump, meaning they can be implemented far before the initiation of conventional prosthesis training.

372 This is especially important considering that starting training early has been shown to result in higher

373 acceptance and use of the prosthesis[90]. The main premise of virtual training and biofeedback in upper-

374 limb rehabilitation is to enhance someone's myocontrol, which is the ability to control the opening and

375 closing of a myoelectric prosthesis through surface EMG signals derived from the action potentials

376 produced by (usually two) muscles[91]. Good myocontrol is a prerequisite of functional prosthesis use,

377 especially considering the increasing dexterity of the latest myoelectric devices. Indeed, experienced

378 users of a myoelectric prosthesis have been shown to generate more consistent prosthesis control

379 following EMG biofeedback[92]. However, the ability to produce distinct myosignals is not intuitive and

380 can vary on an individual basis[93]. Therefore, virtual training and biofeedback provide potentially

381 promising techniques to develop myocontrol in the pre-prosthetic stage.

382 Three main methods for training the myosignal have been examined by research. The first

383 simply involves displaying a live feed of EMG signals on a computer screen, representative of basic

384 biofeedback. The second and third are more representative of virtual training and involve either

385 displaying a virtual prosthesis on a screen that is manipulated via the myosignal in the exact manner as

386 an actual prosthesis[94], or incorporating control of the myosignal into controlling an aspect of a computer

387 game[95]. These methods have shown positive results for enhancing control of the myosignal in upper-

388 limb prostheses. For example, Bouwsema et al.[93] found training with a virtual hand to be equivalent to

389 training with a physical prosthesis, advocating virtual training as a vital component of prosthesis

390 training to enhance motivation and expedite learning during the early stages of skill development.

391 Nakamura et al.[96] demonstrated that training with virtual myocontrol software transferred to a grasping

392 task performed with a physical prosthesis, namely a box and block test, with improvements in both the

393 number of blocks moved and the orientation of the hand on approach. There is also some evidence that

394 the benefits of virtual training may extend beyond convenience and efficiency. For example, in a study

395 using virtual avatars and EEG, Fernandez-Vargas et al.[97] found that imitating movements presented

396 virtually resulted in greater parietal alpha desynchronisation during motion, which may be suggestive

397 of lower attentional demands for the trainee. Most of the studies advocating the use of virtual training

398 to date have been performed with healthy participants but in a recent study with upper-extremity

399 amputees, Perry et al.[98] found that training with a virtual avatar controlled by the myosignal improved

400 movement accuracy across three different motion sets of varied complexity.

401 Although these methods have been shown to have comparable learning advantages for

402 prosthesis training[91], various authors have suggested that a computer game would be most beneficial as

403   it has the potential to be more engaging and fun than the other methods[91]. For example, Radhakrishnan

404   et al.[99] developed a game-based pre-prosthesis training environment designed to challenge users to

405   reach higher scores. Using an evaluation questionnaire, they found that participants responded

406   positively to the games, reporting enjoyment regarding the varied levels of difficulty and motivation to

407   return to the game. Participants also reported that they believed the games could be used to improve

408   their muscular control. However, this study was performed with healthy participants and further

409   investigation with limb-loss patients is warranted.

410   These virtual systems benefit from being low cost, portable, and easy to use, allowing users to

411   practice at home without a therapist and have autonomy over practice type and difficulty. Additionally,

412   the level of myocontrol displayed during pre-prosthetic training can also be used to determine the

413   suitability of potential prosthesis control components, making for a more personalised device. However,

414   the field needs an easily administrable test to identify myocontrol learning ability and standardise this

415   protocol[91]. Another important point for consideration is the distinct difference between operating a

416   virtual and physical prosthesis. Training with a physical prosthesis poses postural kinetic and kinematic

417   challenges that are not addressed by virtual training. This may limit the application of virtual training

418   to myoelectric control primarily. Furthermore, if virtual training is to be applied into a prosthesis

419   training protocols, more information is needed about how it would be implemented and whether it could

420   be integrated with the motor learning principles discussed in the present review. Research into this area

421   could significantly enhance the already promising learning benefits of virtual training and biofeedback,

422   optimizing the time an amputee spends in the pre-prosthetic stage.

423   **4. Conclusion**

424   Current rates of upper-limb prosthesis abandonment remain high, with technological

425   advancements yet to achieve any significant impact on user satisfaction[1]. The importance of optimising

426   early and appropriate training therefore cannot be overlooked. While the intuition and experience of

427   clinicians holds enormous value, evidence-based guidelines based on well-established motor learning

428   principles will also be crucial for training effective prosthetic hand control. Important to the design of

429   any such guidelines is the realisation that the level of limb-loss and the type of device are important

430 factors in need of consideration. For example, patients with more proximal levels of limb-loss have

431 difficulties with bimanual tasks[100], higher abandonment rates [101], report less satisfaction[102], and lower

432 perceived functionality[103] compared to users of below elbow prostheses. There is also evidence that

433 prosthetic devices with pattern-recognition technology can optimise intuitive control and alleviate

434 cognitive demands compared to more traditional devices using direct control schemes[104,105]. We

435 therefore are not proposing the pursuit of a 'gold-standard' one size fits all approach to training, instead

436 we are advocating for an evidence-based approach that provides applied practitioners with a 'tool-box'

437 of research-informed techniques that can be used in a client-centred manner based on their experiential

438 knowledge. It is clear that more research is needed before this is achieved and it is hoped that this review

439 highlights the potential avenues for such work. Finally, a challenge moving forward is ensuring that

440 any growth in academic knowledge achieves some degree of clinical translation. Future attempts to

441 optimise prosthesis training should therefore attempt to engage in multi-stakeholder collaborations

442 between users, researchers, clinicians, charity representatives and industry specialists to achieve greater

443 impact and benefit for the target population[106].

444

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