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Effectiveness and acceptance of assistive technologies for people with tetraplegia: A systematic review

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ABSTRACT

Individuals with tetraplegia rely on assistive devices to perform Activities of Daily Living (ADLs) and enhance independence. This review evaluates their effectiveness and user acceptance for supporting independence. A systematic literature search was conducted across seven databases from September 2004–2024 (PROSPERO: CRD42022370351). Studies evaluating assistive devices in experimental or real-world settings with individuals with tetraplegia that reported performance (task achievement) and perception (user experience) outcomes were included. Risk of bias was assessed with the Downs and Black checklist modified for nonintervention studies. From 1,670 initial records, 34 articles met inclusion criteria, involving 366 participants. Robotic arms, wearable exoskeletons, computer interfaces, powered wheelchairs, and functional electrical stimulation systems demonstrated varying effectiveness. Performance outcomes were often task-specific, and perception depended on ease of use, comfort, and adaptability. Few studies measured impact on quality of life or long-term adoption. Invasive technologies showed promising results but faced adoption barriers related to complexity and aesthetics. Heterogeneity prevented meta-analysis. While some assistive technologies improve independence, better usability and customization are needed for wider adoption. Technologies must offer substantial improvements to justify adaptation efforts. Reporting should be clearer and more standardized to facilitate comparison. Demographic biases (overrepresentation of spinal cord injury, global north, and males) limited generalizability.

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Assistive technology; daily living; quality of life; tetraplegia

Introduction


Tetraplegia, the total or partial paralysis of all four limbs, severely affects mobility, sensation, and communication (Fridén & Gohritz, 2015; Kirshblum et al., 2011). People with tetraplegia need lifelong and extensive physical care to perform most activities of daily living (ADLs) (Yavuz et al., 1999), resulting in dependence on family, friends, and caregivers (Simpson et al., 2012). The condition can severely impact quality of life (QoL), as it is associated with depression (Khazaeipour et al., 2015), strain in family relationships (Charlifue et al., 2016), and financial and emotional burden in caregivers (Nogueira et al., 2012). In the UK, the lifetime cost of care for a person with tetraplegia is estimated at 1.12 million, contributing to a total of 1.43 billion per year (McDaid et al., 2019).

Efforts in tetraplegia care currently focus on improving patient autonomy and self-reliance, associated with greater emotional health, employment, life satisfaction, adaptability, and self-esteem (Simpson et al., 2012; Weitzenkamp et al., 2001). Assistive devices can support independence and increase QoL by enabling individuals to perform ADLs with various degrees of autonomy (Baldassin et al., 2018; Folan et al., 2015; Rigby et al., 2011), while facilitating community participation, leisure pursuits,

and professional engagements. Despite their potential benefits, assistive devices can have high discontinuation rates (Almeida et al., 2025; Federici et al., 2016; Sugawara et al., 2018), and their real-world application remains limited. User acceptance plays a crucial role in device adoption, as even technically sound devices can be abandoned if they provide poor user experience, operate slowly, exhibit high complexity, cause high fatigue, or require excessive physical effort (Federici et al., 2016; Jafar & Nagesh 2023; Sugawara et al., 2018; Wielandt et al., 2006, and works therein). Furthermore, tetraplegia has a diverse etiology, resulting from injuries, neuro-degenerative conditions, and strokes. Thus, as users' needs evolve over time (Alizadeh et al., 2019; Schnetzer et al., 2023), individuals necessitate highly personalized and adaptable solutions (Motahar & Wiese, 2024; Orejuela-Zapata et al., 2019). Therefore, understanding the device's functionality, the user's experience and acceptance, and the relationship between an individual's condition and current abilities, is crucial for designing assistive technologies that are both effective and widely adopted.

To this end, this systematic review aims to assess current technology and its utility in supporting the independence of individuals with tetraplegia. The key objectives of this review

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are: to identify experimental studies with both performance and perception metrics, to determine the features contributing to usability, and to identify barriers impeding their use.

Methods

The UTAUT model holds that the strongest predictor toward tech use is the *performance expectancy*: “the degree to which an individual believes that using the system will help them to attain gains in job performance” (Venkatesh et al., 2003). Similarly, applications of the UTAUT model have shown how intent to use depends strongly on perception of performance and its ease of use (Marikyan & Papagiannidis, 2025). Thus, this work targeted two core outcomes: *performance*, defined as “how well the device performs to achieve a task” (e.g., success rate in drinking from a glass of water, accuracy of right-clicks on a webpage), and *perception*, “how a device is perceived by the user” (e.g., comfort, satisfaction).

This review was conducted according to the PRISMA protocol (Moher et al., 2015) and was registered with PROSPERO (CRD42022370351). The PROSPERO protocol was modified to amend researchers on the team, and to limit the span to 20 years to focus on recent developments (September 2004 to September 2024) and to extend the final date.

Scope & eligibility criteria

To ensure the review captured generalizable evidence on assistive technology effectiveness for individuals with tetraplegia,

the following inclusion and exclusion criteria were established: First, studies needed to demonstrate device applicability across multiple individuals to ensure findings could be generalized beyond case studies. Thus, studies were required to include at least two users with tetraplegia (i.e., not bespoke solutions). Second, focus was placed on functional ADL outcomes rather than abstract data acquisition to ensure real-world utility of device function. Third, the focus prioritized experimental evidence over subjective reports to provide controlled objective assessment of device effectiveness.

Tetraplegia was considered independent of etiology, including conditions such as Spinal Cord Injury (above C8), ALS, CP, MS, DMD, TBI, and Stroke. Assistive technology was defined as actuated devices controlled by the user to complete ADLs. Thus, studies that focused on device development without ADL evaluation, purely surgical approaches, passive devices, or devices for rehabilitation only (e.g., strengthening of grip, exercising) were excluded. Other exclusion criteria included: 1) not focused on the experience of users, such as expert opinion and case reports, or single-participant case studies; 2) not published in peer-reviewed publications; 3) written in languages other than English; 4) being surveys without experimental evidence; or 5) containing underspecified information.

Articles deemed potentially eligible were screened by 2 authors (EDNS and NZ) by reviewing the title and abstract. Duplicates were removed, then exclusion criteria were applied by title and abstract for the screening phase. Full text was then reviewed against the criteria for final selection (see Figure 1). Articles with unclear eligibility were

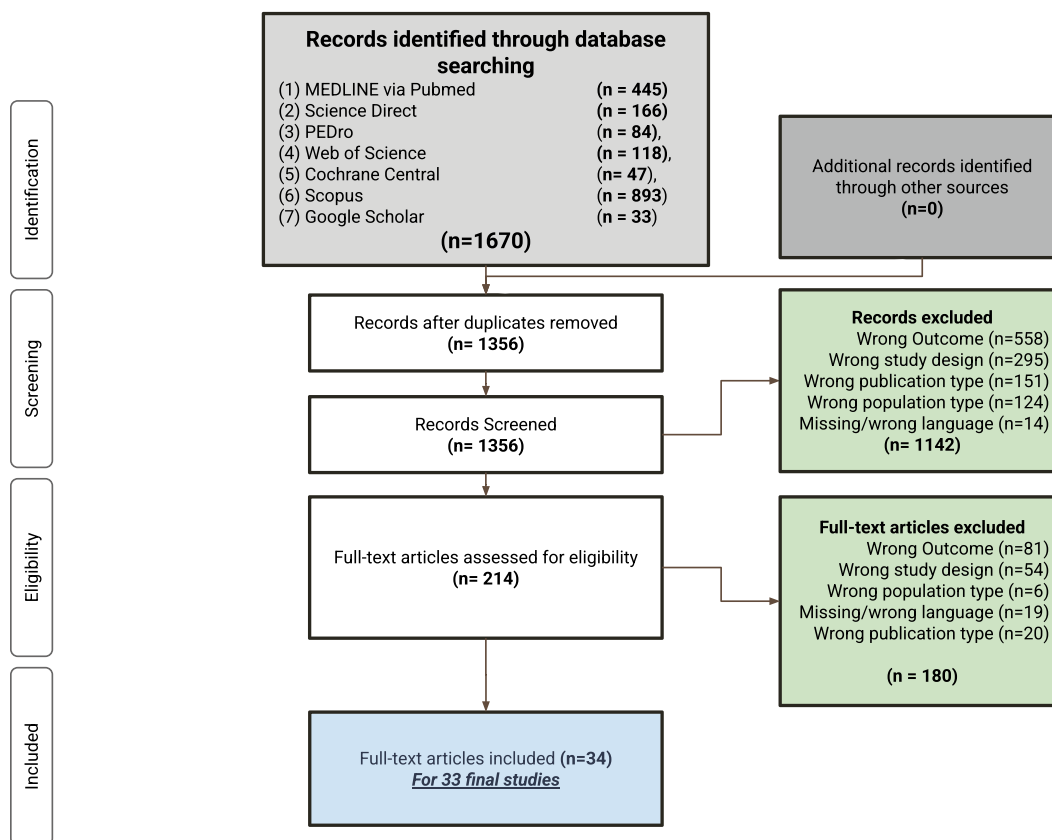


Figure 1. PRISMA flowchart showing searched databases, literature and selection process. Note that 2 articles described the performance and perception parts of a single experiment, and are here thus combined into a single study.

screened by a third reviewer (FNO) who is a qualified medical doctor. Disagreements were discussed until consensus was reached.

Search strategy & sources

Search queries were derived from a combination of keywords, referring to population, devices, and study types of interest. The following search strategy was used, using the respective keywords from Table 1. Note that “tendon transfer” was omitted, as purely surgical processes were not of interest.

- (1) Population = 1 OR 2
- (2) Devices = (3 OR 4 . . . OR 23) AND (NOT 24)
- (3) Study Types = 25 OR 26 OR . . . OR 31
- (4) Results = Population AND Devices AND Study Types

Original studies with trials published in English in journals or conferences were included. Initial search candidates were obtained through the databases: MEDLINE via (1) PubMed, (2) Science Direct, (3) PEDro, (4) Web of Science, (5) CENTRAL, (6) Scopus and (7) Google Scholar. The search strategy was defined for MEDLINE first using Medical Subject Headings (MeSH), then adapted.

Mesh terms for tetraplegia include a variety of conditions: Spinal Cord Injury (SCI) resulting in complete or incomplete tetraplegia (above C8), Amyotrophic Lateral Sclerosis (ALS), Cerebral Palsy (CP), Multiple Sclerosis (MS), Duchenne Muscular Dystrophy (DMD), Traumatic Brain Injury (TBI) and Stroke (S).

Table 1. Keyword list for searches. All items were [mesh] terms except for 26, which is a [publication type].

Population	Devices	Study Types
1. Quadriplegia	3. Self-Help Devices	25. Treatment Outcome
2. Locked-In Syndrome	4. Activities of Daily Living	26. Comparative Study
	5. Electrical Equipment and Supplies	27. Patient Satisfaction
	6. Communication Aids for Disabled	28. Surveys and Questionnaires
	7. User-Computer Interface	29. Cross-Sectional Studies
	8. Prostheses and Implants	30. Case-Control Studies
	9. Protective Devices	31. Cohort Studies
	10. Universal Design	
	11. User-Centered Design	
	12. Man-Machine Systems	
	13. Robotics	
	14. Artificial Limbs	
	15. Orthotic Devices	
	16. Sensory Aids	
	17. Exoskeleton Device	
	18. Diagnostic Equipment	
	19. Disposable Equipment	
	20. Bathroom Equipment	
	21. Ergonomics	
	22. Brain-Computer Interfaces	
	23. Dental Devices, Home Care	
	24. (NOT) tendon transfer	

Data extraction

Data extracted included (Table 2–5): authors, date and country; number of participants; condition and classification; demographic characteristics; study details (type, design, intervention, duration, and studied ADL); assistive device description; and outcome measures organized as performance metrics and measures of user perception. For the assistive devices description, technologies were considered as being composed of an *Interface strategy* serving as control methods, and an *Effector* realizing an action.

Study participants with disabilities but retaining significant control of some extremities were reported as other conditions (O). Participant outcomes without disabilities acting as controls (C) were also reported.

Methodological risk of bias

Methodological risk of bias was independently assessed using a modified version of a Downs and Black checklist (Downs & Black, 1998), accounting for the inclusion of nonintervention studies (Supplemental Material A). Two reviewers (EDNS, NZ) evaluated the methodological quality of the study in relation to the risk of bias. From the original checklist, 16 items were assessed as present or absent/unable to determine. Scores are reported as a percentage of present elements, with higher scores indicating a lower risk of bias. This quality appraisal was based on the reporting of the perception and performance outcomes assessments rather than the overall focus of the study (e.g., other outcomes). Therefore, some studies with a moderate/high risk of bias here may be considered to have a low risk of bias when rated on other criteria.

For agreement, studies scoring $\leq 35\%$ were considered low quality/high risk of bias, those scoring 35–65% medium, and over 65% as high quality. Kappa score was used to identify agreement between raters. For the final reporting, the rationale for disagreements was assessed and consensus reached. Where disagreements persisted, the lead author’s final decision (EDNS) was reported.

Results

After an initial screening of the 1670 papers, the review assessed the full text of 213 papers, of which 34 papers were included (see Figure 1). For one experiment, outcomes were described across two publications, and were thus combined as a single entry, leaving a total of 33 studies listed.

Risk of bias

After completing the bias assessment, 24 studies can be considered of high quality and 9 of medium. None were found as low. Classification agreed on 26 out of 33 studies for moderate agreement (Kappa = 0.468 (Landis & Koch, 1977)). The criteria more often unfulfilled were reaching sufficient statistical power ($n = 5$), reporting participation rate of those asked to participate ($n = 7$), and reporting representativeness of the population ($n = 17$).

Table 2. Summary of studies on computer interaction tools.

Work	Technology			Study Details			Measured Outcomes		
	Int.	Eff.	Design	Comparisons	ADL	n	Performance	Perception	
Laffont et al., (2007), France (Garches)	PD (keyboard), SS	PC Kb (Dialog Speech Synthesis)	10 training sessions (1h), evaluation, home use (2m), evaluation	Long. Freq of use. With vs without word prediction.	Communication	10T	<ul style="list-style-type: none"> Use of device and word prediction varied. 6 high-freq users. No speed difference with prediction. 	<ul style="list-style-type: none"> QUEST of 3.4 ± 1. Lower satisfaction after 2 months for low-freq users. Satisfaction at training could not predict home use. 	
Pouplin et al., (2014), France (Paris)	PD (4 joystick/trackball), HM, ET, SS	PC Kb (layouts: CVK, AZERTY, dynamic)	Long. Explanation (1h), use (2mo). Tests at start, 1mo, 2mo	Keyboard modes in order, then as preferred by the user.	Typing	10T	<ul style="list-style-type: none"> No change in input speed over time or with word prediction. Dynamic decreased speed. 	<ul style="list-style-type: none"> All 9 pointing device users preferred static. Switch user preferred dynamic. 9/10 participants preferred their previous option. 	
Pouplin et al., (2016), France	PD (Trackball), Kb, HM	PC Kb (KeyVit Onscreen Keyboard, Skippy WPS)	Cross-sectional. Explanation, training, 4 copying tasks varying predicted words (0,3,6,8, random).	Condition severity and number of predicted words	Typing	45T	<ul style="list-style-type: none"> For low lesions, text input was faster without prediction. No difference for high lesions. Control device affected speed. Number of words predicted did not affect speed. 	<ul style="list-style-type: none"> Perception of text input speed differed according to lesion level. High SCI benefits from more words. 	
Plotkin et al., (2010)	Air (Sniff controller)	PC Kb	SS. 4 proof of concepts tests. Prior practice (20min-2mo), then writing task.	None	Different writing tasks.	4T	<ul style="list-style-type: none"> 1 participant could not perform sniffing but learnt (19d). One did not after 2mo practice. 2/4 participants adopted device. 	<ul style="list-style-type: none"> One participant reported it as more comfortable and easier to use than an eye tracker. 	
Borgest et al., (2017), Sweden	ET (Tobii C12/P12), HM	PC Kb	Pre-Post. Baseline (14d), post (9–10mo), and follow-up (5–10mo).	Long.	Communication, writing, computer use, recreation, others	10Tc	<ul style="list-style-type: none"> Increased computer usage for 7/10 children. Maintained at follow-up. Increased communication with caregiver. 	<ul style="list-style-type: none"> Good parent satisfaction (QUEST 2.0) with device post-intervention 4.0/5, slightly lower in follow-up 3.5/5. 	
van Middendorp et al., (2015) UK	ET (Tobii Eyegaze C15)	PC Kb	Long. Twice per week training (1h x2), use sessions (2h x2).	Before-after	Computer use	6T	<ul style="list-style-type: none"> Small improvements in functional abilities (ATD-PA). After eight training sessions, only one participant could use eye-tracker without supervision. 	<ul style="list-style-type: none"> ET was easy to use (50%). No improvements in anxiety and depression (HADS), appraisals of disability (ADAPSS) or independence. 	
Nuyujukian et al., (2018), USA	BCI (Intracortical, Neuroport)	PC PD (point-and-click mouse), Kb (prediction)	MS (over 3 days). Decoder initialization/calibration, use of 7 apps.	Over multiple days	Typing and navigation (browsing, email, chatting, piano, text messages, etc.).	3T	<ul style="list-style-type: none"> 15.4 to 33.5 mins for 7 tasks. 12.0 to 22.8 selections per minute, 13.6 to 30.8 characters per minute with prediction. 	<ul style="list-style-type: none"> Described as intuitive, natural, easy to use (quali). Challenges with small selection regions (e.g., hyperlinks). 	
Pandarínath et al., (2017), USA	BCI (Intracortical, BrainGate2)	PC PD, Kb (cursor on keyboard)	MS. Multiple sessions (2–5) post-implant, several blockset typing tasks (2–7).	Long. Layouts (OPTI-II vs QWERTYx2 or ABDEFx1), click algorithms (Kalman, HMM)	Computer Typing on two-min evaluation blocks	3T	<ul style="list-style-type: none"> 7.8 to 2.7 words per minute from OPTI-II layout. HMM faster. 	<ul style="list-style-type: none"> Positive quali comments: Easy-to-use, better than eye-gaze (x1) and faster than head-pointing (x1). 	
Peters et al., (2016), USA (OR)	BCI (External, RSVP Keyboard)	PC Kb (with prediction)	SS. Questionnaire. At participant residence	None	Typing (copy task, 5 levels increasing in difficulty)	12T	<ul style="list-style-type: none"> Suppressing movement slowed typing rate. Mean level completed 1.3 ± 1.4. One participant completed all five levels. Area Under Curve did not guarantee use of BCI. 	<ul style="list-style-type: none"> Suppressing movement was cognitively demanding. Required "somewhat low" physical effort, but "somewhat high" mental (modified BQ). Varied quali comments. 	

(Continued)

Table 2. (Continued).

Work	Technology		Study Details			Measured Outcomes		
	Int.	Eff.	Design	Comparisons	ADL	n	Performance	Perception
Combaz et al., (2013), Belgium (Leuven)	BCI (External, 8-channel EEG w/ braincap)	PC Kb (Via SS)	MS. Preliminary test, 2 sessions, 2 free spelling (1-2h each)	SSVEP system and P3 strategies	Spelling	7T, 10C	<ul style="list-style-type: none"> Better performance with SSVEP BCI than with the P3 BCI. One participant could not use. No relationship between 4 patients did not reach 70% accuracy with P3. 	<ul style="list-style-type: none"> SSVEP led to lower mental workload (sub NASA-TLX) and higher satisfaction. No relationship between performance and quality of life (ACSA).

Participants: (T)etraplegia, (C)ontrol, (c)hildren.

Study Design: (Int)erface, (Eff)ector, Activities of Daily Living (ADL), (Long)itudinal. Multiple Sessions (MS), Single Session (SS).

Interfaces: Sipp and Puff (Air), Brain Control Interfaces (BCI), Eye Tracking (ET), Keyboard (Kb), Pointing Devices (PD).

Devices: Computer (PC).

Measures: Bates' Workload Assessment, Comfort Assessment, and Ease of Use Questionnaires (BQ), Anamnetic Comparative Self-Assessment scale (ACSA), Appraisals of Disability: Primary and Secondary Scale (ADAPSS), Assistive Technology Device Predisposition Assessment (ATD-PA), Craig Handicap Assessment and Reporting Tool (CHART), Hospital Anxiety and Depression Scale (HADS), NASA Task Load Index (NASA-TLX), Quebec User Evaluation of Satisfaction with Assistive Technology (QUEST), Upper Extremity Capabilities Questionnaire (UEC). Other: Hidden Markov model (HMM).

Table 3. Summary of studies on Power-Assisted Wheelchairs (PAW).

Work	Technology			Study Details			Measured Outcomes		
	Int.	Eff.	Design	Comparisons	ADL	n	Performance	Perception	
Ding et al., (2008), USA (PA)	RM (Pushrim-activated)	PAW	MS. Within participants. 2w trial with personal device, 2w choosing PAPA or own.	User's wheelchair vs PAPA	Driving	15T	<ul style="list-style-type: none"> Faster with PAPA. No difference in distance traveled. Chosen at similar frequency. 	<ul style="list-style-type: none"> No difference in community participation, satisfaction, or psychosocial impact (PIADS). 	
Algood et al., (2005), USA (PA)	RM (Pushrim-activated)	PAW (Yamaha JWila on Quickie 2b)	MS. Within participants. Manual vs PAPA on course (x3).	User's wheelchair vs PAPA, randomized	Driving	15T	<ul style="list-style-type: none"> Heart rate lower with PAPA for all trials. No difference in time to complete, and degree of assistance required. 	<ul style="list-style-type: none"> Survey: carpet, dimple strips, up a ramp, up the curb easier with PAPA. Easier to propel. Assistance, and ergonomics same. 	
Cooper et al., (2004), USA (WA)	PD (Joystick and buttons)	PAW (IBOT TM)	Single session: orientation (2 h), use at work env. (+4 h).	User's wheelchair vs IBOT	Driving: Office work	2T, 20	<ul style="list-style-type: none"> Enabled stair climbing, high reach, and eye-level interaction. Balance Function was used to access items and discuss at eye level. 	<ul style="list-style-type: none"> Difficulty reaching the floor, getting into car, and turning. Getting around received positively. One user missed exercise from normal chair. 	
Schmalfuß et al., (2016), Germany (Heidelberg)	EMG (Auricular Control System ACS)	PAW	MS. Activation (20 min), virtual control and games (40 min x4d), wheelchair driving (30 min, 5th day).	Virtual and real. Healthy and tetraplegia	Driving: straight corridor, obstacle course.	2T, 10C	<ul style="list-style-type: none"> Control of auricular muscles can be learned. Performance, collisions, and time improved. No fine muscle control improvement. 	<ul style="list-style-type: none"> Patients found ACS mature enough for everyday use, better than joystick. Difficulty in precise commands and driving. Low-to-mid workload (NASA TLX), can be tiring. 	
Kim et al., (2013, 2014), USA (GA, IL)	TC (piercing), Air	PAW (latched)	MS. Crossover. T had weekly TDS and PC session (6w). C had 5 trials (2.5 h over 2-10d).	Control strategies: Vs default device: SnP (54.5%) or joystick (45.5%).	Driving	11T, 23C	<ul style="list-style-type: none"> Despite familiarity with SnP, performance up to 3x better with TDS after practice. Faster and less errors with SnP at start. 	<ul style="list-style-type: none"> TDS has same usability than SnP, but more effectiveness. Cognitive load increased over 5 sessions. Unlatched strategy was easier. Good enjoyment and satisfaction. Tolerable headsets, no discomfort or irritation. Mental and effort as sources of workload (Modified NASA-TLX). 	
Floreani et al., (2022), Canada (Calgary)	BCI (Emotiv Epoc X and Flex)	PAW (PMTD)	MS. Feasibility Test. Calibration, driving, questions (x2)	None	Driving: over a specified distance	8Tc	<ul style="list-style-type: none"> Only straight line and stopping on cue. Easier to move than to stop on cue (Correct 53.1 ± 23.3% of the time). 		

Participants: (T)Tetraplegia, (C)children, (C)ontrol, (O)ther.

Study Design: (Int)erface, (Eff)ector, Activities of Daily Living (ADL), Multiple Sessions (MS).

Interfaces: Sipp and Puff (Air), Brain Control Interfaces (BCI), Electromyography (EMG), NO Residual Motion (RM), Tongue Control (TC).

Devices: Power-Assisted Wheelchair (PAW), Pushrim-activated PAW (PAPA), Computer (PC).

Measures: NASA Task Load Index (NASA-TLX), Psychosocial Impact of Assistive Devices Scale (PIADS).

Table 4. Summary of studies on Functional Electrical Stimulation (FES).

Work	Technology			Study Details			Measured Outcomes	
	Int.	Eff.	Design	Comparisons	ADL	n	Performance	Perception
Mulcahey et al., (2004), USA (PA)	MT (shoulder shrug)	FES (Implanted)	Implantation, soft dressing (2–4d), assessment (3–8w)	Pre-Post. W/O	Feeding, grooming, bladder function	4†	<ul style="list-style-type: none"> • 3/4 improved UEC performance. All increased independence (QIF). • Can improve hand function during initial rehab after injury. 	<ul style="list-style-type: none"> • Performance and satisfaction all improved (COPM). • Desire to continue using and difficulties.
Thorsen et al., (2020), Italy	EMG (Surface electrodes)	FES (External)	2 sessions (2 h)	Pre-Post. W/O	Writing, Dressing, Pick-up, Cooking, Feeding, Care (Participant Selected)	27†	<ul style="list-style-type: none"> • 3 continued using. • Improvement of hand function. • Describes some completed activities. • 14 continued using. 	<ul style="list-style-type: none"> • Good satisfaction (QUEST 3.1 ± 0.6), facilitated problematic tasks, positive comments. • Reduction in IPPA (17.0, to 11.8).
Kilgore et al., (2006), USA (OH)	EMG (implanted), Sip and puff	FES (implanted)	Conditioning, implantation, cast (3w), training (2–3mo), assessment (1y)	Long.	Object manipulation, ADLAT	3†	<ul style="list-style-type: none"> • Improvement in 5+ ADLAT activities, pinch force, and grasp. • Success in feeding, grooming, and picking. • 50% to daily use. 	<ul style="list-style-type: none"> • Increased physical independence (subscale of CHART). • More community participation (NP Usage Survey).

Participants: (†)Tetraplegia.
 Study Design: (Int)erface, (Eff)ector, Activities of Daily Living (ADL), (Long)itudinal. With-without (W/O).
 Interfaces: Brain Control Interfaces (BCI). Electromyography (EMG), Motion Tracking (MT).
 Devices: Functional Electrical Stimulation (FES).
 ADLs: Activities of Daily Living Abilities Test (ADLAT).
 Measures: Craig Handicap Assessment and Reporting Tool (CHART), Canadian Occupational Performance Measure (COPM), Individually Prioritized Problem Assessment (IPPA), NeuroProsthesis (NP) usage survey, Quadriplegia Index of Function (QIF), Quebec User Evaluation of Satisfaction with Assistive Technology (QUEST), Upper Extremity Capabilities Questionnaire (UEC).

Table 5. Summary of studies on Robot Arms (RA) and Mobile Robot Arms (MRA).

Work	Technology			Study Details			Measured Outcomes		
	Int.	Eff.	Design	Comparisons	ADL	n	Performance	Perception	
Laffont et al., (2009), France (Multicenter)	PD (Mouse, Switch Contactor, GUI)	RA (Manus arm)	SS. Training period (15 min), grasping task (3x, 15 tasks per user).	Vs Controls	Grasping everyday items.	20T, 24C	<ul style="list-style-type: none"> Success of 81.1%. Failures mostly from system malfunction. Task duration higher for T than C (71.6s vs 39.1s). 	<ul style="list-style-type: none"> High satisfaction and ease of learning. Not-to-slightly tiring. 	
Chung et al., (2017), USA (PA)	PD (Touchscreen x7 or joystick x1)	RA	SS. Training on 2 UIs. Chose one to perform ARMET 3 tasks	Interfaces	ARMET tool test: toggling switch, pushing door handle, turning knob	7T, 10	<ul style="list-style-type: none"> TS GUI led to faster movement speed and completion time than single joystick participant. All T chose GUI. 72.2% completed both task. 60% of non-completions due to depth issues. High gesture non-detection for T. 	<ul style="list-style-type: none"> 18C/20 prefer robot on a separate platform. Touchscreen chosen because of ease of use and lower physical effort. 	
Rudigkeit & Gebhard, (2019), Germany (Hamburg)	MT (Head, AMICUS)	RA (URS)	SS. Feasibility study, one trial each participant.	Vs Controls	2 Pick and place tasks, 1 requiring stacking	12T, 10, 13C	<ul style="list-style-type: none"> 2/3 completed all tasks. T had issues performing nodding down gesture. No difference in completion time for predefined. 3/7 completed the robot control phase. 	<ul style="list-style-type: none"> Intuitive, high user acceptance. GUI and menus received positively. Gestures easy and fast, but switching slow. Rotation control given lowest score. GUI received positively. Gestures were easy and fast. Rotation control was worst received. 	
Jackowski et al., (2018), Germany (Bremen)	MT (Head, AMICUS)	RA (URS)	SS. Feasibility study on 3 stages: trial, predefined and complex stacking.	Vs Controls	2 Pick and place tasks, 1 requiring stacking	6T, 24C	<ul style="list-style-type: none"> 2/3 completed all tasks. T had issues performing nodding down gesture. No difference in completion time for predefined. 3/7 completed the robot control phase. 	<ul style="list-style-type: none"> Control reported from good to less than cursor. 	
Onose et al., (2012), Romania (Bucharest)	BCI (EEG), ET (View Point)	PD, RA	SS. 1–2 training sessions, trial for PD, trial for RA, post-trial follow-up (Up to 14mo after)	W/O.	Robot grasping (3D). Mouse control (1D)	3T	<ul style="list-style-type: none"> 3/7 completed the robot control phase. 	<ul style="list-style-type: none"> Control reported from good to less than cursor. 	
Ranganen et al., (2023), USA (Remote)	PD (trackpad/ ball, mouse, stylus), HM	MRA (Stretch RE1)	SS. Mixed methods. Overview, practice, tasks with different action and control combinations.	Vs Controls. Action (base, press-release, step action) and control modes (base and custom settings)	Navigation, pick, then drop	10T, 13C	<ul style="list-style-type: none"> Better performance with custom settings for navigation, not for manipulation. Faster with custom. 	<ul style="list-style-type: none"> No interface satisfies all users. For small movements; most preferred press-release. Step mode led to fatigue. Similar NASA-TLX between all settings. Most satisfied with control and ease to learn. Split on (50%) confidence, desire to use, and utility to caregivers' time. 	
Fattal et al., (2018), France (Multicenter)	PD (mouse, trackball, joystick)	MRA (RobuLAB 10TM and Jaco arm)	SS. Single session (2 h)	Three control scenarios	Navigation with exploration (teleop.), pick-up, return.	17T	<ul style="list-style-type: none"> Better performance at navigation than grasping. Best for navigation, less success with grasping. 	<ul style="list-style-type: none"> Overall positive satisfaction, easy to learn and not fatiguing. Only 25% reported they would like to adopt the robot. 3/4 T judged the system easy-to-use and comfortable. Modified QCM: all T were interested and positive of BCI tech. No group differences. 	
Coignard et al., (2013), France (Multicenter)	Kb, PD, HM, Kb	MR (MP470, and Manus arm)	SS. Presentation, practice session, test	Vs Controls. Three control scenarios.	Navigation with exploration (teleoperation), item pick-up and return.	29T, 34C	<ul style="list-style-type: none"> Took longer to select room and object than C. Same number of failures as C. 	<ul style="list-style-type: none"> Overall positive satisfaction, easy to learn and not fatiguing. Only 25% reported they would like to adopt the robot. 3/4 T judged the system easy-to-use and comfortable. Modified QCM: all T were interested and positive of BCI tech. No group differences. 	
Spataro et al., (2015)	BCI (P300-based)	MRA (NAO)	SS. Calibration, online practice and robot sessions (2 h, 3T/4 teleop).	Vs Controls	Navigation and grab a glass of water	4T, 4C	<ul style="list-style-type: none"> 3/4 T and all C performed the task. 78.32% success in T against 100% in C. 3/4 T performed properly. 	<ul style="list-style-type: none"> Overall positive satisfaction, easy to learn and not fatiguing. Only 25% reported they would like to adopt the robot. 3/4 T judged the system easy-to-use and comfortable. Modified QCM: all T were interested and positive of BCI tech. No group differences. 	

Participants: (T)tetraplegia, (C)control.

Study Design: (Int)erface, (Eff)ector, Activities of Daily Living (ADL), With-without (W/O).

Interfaces: Brain Control Interfaces (BCI), Eye Tracking (ET), Motion Tracking (MT), Keyboard (Kb), Pointing Devices (PD).

Devices: Robot Arm (RA), Mobile RA (MRA).

ADLs: Standardized assistive robotic manipulators evaluation tool (ARMET).

Measures: NASA Task Load Index (NASA-TLX), Questionnaire of Current Motivation (QCM).

Table 6. Summary of studies on wearables (Wa).

Work	Technology			Study Details			Measured Outcomes		
	Int.	Eff.	Design	Comparisons	ADL	n	Performance	Perception	
Dittli et al., (2023), Switzerland	SS	Wa (Robotic hand orthosis)	Mixed Methods. Exposure and test (1 h), completing ARAT (2 h)	W/O	ARAT: Grasp, Grip, Pinch, Gross movement	16T	<ul style="list-style-type: none"> Immediate improvement of ARAT performance (5.8 points). Avg donning time of 5 mins. 	<ul style="list-style-type: none"> SUS rating of 60.6. Needs more customization to improve usability. Donning times considered long, ergonomics good. 	
Correia et al., (2020), USA (Multicentre at MA)	Sw	Wa (Soft robotic glove)	SS. Max 3 hours	W/O	JHFT, Gross motor tasks: scooping, lifting light and heavy items.	13T	<ul style="list-style-type: none"> Completed 50% more JHFT tasks with glove, no changes in completion time. Lower motor function benefited more. 	<ul style="list-style-type: none"> Custom Usability Quest: satisfaction with glove, comfort, and reported wanting to continue its use. 	
Mohammadi et al., (2023), Denmark (Viborg)	TC (iTongue)	Wa (EXOTIC Upper Limb Exo.)	MS. Within subjects. Simulation, real exo 2d after (Total 7 h)	Long.	Drinking or snacking task (first trial in simulation)	10T	<ul style="list-style-type: none"> Reduction in execution and pause time with sessions. Snacking took longer than drinking due to rotation. 	<ul style="list-style-type: none"> INTUI of 5.4. NASA TLX score of 40, with Mental Demand and Effort highest, Physical demand lowest. 	
Thøgersen et al., (2022)	TC (iTongue)	Wa (EXOTIC Upper Limb Exo)	MS. Within subjects. Simulation (1.5 h), training (1.5 h), semi-autonomous control (2.5 h).	Vs Controls. Tasks.	Drinking, eating, scratching, depressing switch	3T, 10C	<ul style="list-style-type: none"> All completed task, T slower than C. Sometimes users could not apply enough force to grasp. Some users memorized tongue interface during practice. 	<ul style="list-style-type: none"> Glove doesn't have enough grasp force. Exo should be more rigid for contractures and less flexibility. 	
Bengtson et al., (2022)	TC (modified iTongue)	Wa (EXOTIC Upper Limb Exo)	MS. Within subjects. Simulation, real exoskeleton, different schemes, and test (3d).	3 control schemes: Non-autonomous, fixed semi-auto., adaptive semi-auto.	Object grasp and lift as instructed (food or drink)	7T, 10C	<ul style="list-style-type: none"> Both semi-auto. strategies outperformed non-auto. 	<ul style="list-style-type: none"> Better INTUI and NASA-TLX for fixed-auto., followed by adaptive. 	

Participants: (T)etraplegia, (C)ontrol.

Study Design: (Int)erface, (Eff)ector, Activities of Daily Living (ADL), (Long)itudinal. With-without (W/O).

Interfaces: Single Switch (SSw) Tongue Control (TC).

Devices: Wearable (Wa).

ADLs: Action Research Arm Test (ARAT) The Jebsen Taylor Hand Function Test (JHFT).

Measures: Intuitive Task-oriented User Interface (INTUI), NASA Task Load Index (NASA-TLX), System Usability Scale (SUS).

Synthesis

The following sections synthesize the main findings on the literature based on the type of effector technology used: Computers, Power-Assisted Wheelchairs, Functional Electrical Stimulation, Robotic Arms, and Wearables. The included studies have been summarized in Table 2–6.

Computer interaction (PC)

Ten studies covered different interfaces for computer interaction, assisting in typing, communication, and general use. Note that here, keyboard (Kb) can serve as either the control interface or the controlled effector.

Three studies investigated the use of residual movement for typing and communication (Laffont et al., 2007; Pouplin et al., 2014, 2016) as part of the same research series. These examined text prediction on keyboard typing speed and user experience, allowing participants to select their preferred method from Kb, various screen Pointing Devices (PD), head Motion Tracking (MT), and Singlescan Switches (SSw). Studies explored user trends based on condition (Laffont et al., 2007), effect of dynamical customization of layout (Pouplin et al., 2014), and the influence of the number of predicted words (Pouplin et al., 2016). Typing using PD did not benefit from prediction, but one participant using SSw scanning showed improvement. Individuals with severe impairments had greater improvements, while those with greater independence found them disruptive.

Plotkin et al. (2010) presented a device to detect nasal pressure, enabling three of four participants with Locked-in Syndrome (LIS) to type. One participant regained sniffing ability after dedicated practice. Participants responded positively, one preferring it to eye tracking, and two continued using it afterward.

Two studies examined Eye Tracking (ET) devices for typing and computer interaction. Borgestig et al. (2017) included children with Cerebral Palsy (CP) and no speech ability. Parent satisfaction was included in place of the children, reporting improvements in computer use, satisfaction, goal achievement, and communication. In contrast, Van Middendorp et al. (2015) included adults with recent Spinal Cord Injury (SCI). Most users prioritized physical recovery over adopting assistive technology. The logistical challenges in conducting high-powered studies with this population were also highlighted. Both studies criticized needing support to use or set up ET.

Four studies used Brain-Computer Interfaces (BCIs) for computer interaction. Two related studies used invasive intracortical electrodes to classify motor cortex signals (Nuyujukian et al., 2018; Pandarinath et al., 2017). Imagined hand movement was used to control a cursor to type or interact with applications. In Pandarinath et al. (2017), participants were discouraged from actually moving, which was found cognitively demanding and to reduce typing rates. For noninvasive evaluations, Combaz et al. (2013) compared two canonical BCI spelling paradigms, where their strategy led to higher accuracy, lower mental workload, and satisfaction. Peters et al. (2016) used an EEG-based commercial system with language model prediction. Some participants' typing rates benefited from

optimized keyboard layout (Pandarinath et al., 2017) and word prediction (Nuyujukian et al., 2018). In general, BCIs allow intuitive computer use while benefiting from prediction, but often require long training times and invasive procedures.

Power Assisted Wheelchair (PAW)

Six studies were found on interfaces for driving Power Assisted Wheelchairs (PAWs). Two compared manual against push-rim-activated power-assist wheelchairs (PAPAWs), evaluating simulated driving activities (Algood et al., 2005) and home/community impact (Ding et al., 2008). Some moderate improvements were found in the objective metrics. However, no significant differences were found in perception metrics, including assistance needed (Algood et al., 2005), community participation, satisfaction, and psychosocial impacts (Ding et al., 2008). Cooper et al. (2004) explored the use of the IBOT, a joystick-controlled powered wheelchair with self-balancing capability. Features like climbing stairs and maintaining eye-level conversations were well received, but users criticized difficulties reaching the floor and making smooth turns. The utility of PAPAWs was concluded to depend on users' preference, lifestyle, physical conditions, transportation, and environmental factors.

Schmalfuß et al. (2016) introduced control via “ear-wiggling,” using electromyography (EMG) to measure auricular muscle contractions to control a PAW over an obstacle course. After practice, 2 participants learned to use the device. It was found mature enough for use, but workload scores and effectiveness varied.

Over multiple studies, the Tongue Drive System (TDS) (Huo et al., 2008) was explored for controlling wheelchairs. The TDS uses a tongue piercing with a magnetic element tracked by headset sensors to capture movement and translate it to control commands for the wheelchair (Kim et al., 2013). The “unlatched” control strategy was preferred by most users, requiring them to hold a command to keep driving, in contrast to “latched” - continuing actions until the tongue interacted again. Qualitative assessment (Kim et al., 2014) showed most users preferred TDS over existing devices, particularly sip-and-puff systems. The tongue piercing procedure received mostly positive feedback (Laumann et al., 2015), though issues like fatigue, pain, and discomfort were reported.

Floreani et al. (2022) explored BCIs for wheelchair control, where children with Cerebral Palsy (CP) used a BCI interface to navigate a set distance. Participants were instructed to visualize two personalized cues representing commands for moving forward and stopping, classified by a proprietary service. Participants reliably activated commands on cue and reported positive experience, but struggled to maintain a neutral (stop) state.

Functional Electric Stimulation (FES)

Three studies demonstrated the use of FES for arms, which applies electric signals to stimulate muscle contractions. Different degrees of invasiveness were shown: implanted electromyography (EMG) with a sip-and-puff device requiring chest and arm incisions (Kilgore et al., 2006), intramuscular electrodes with minimally invasive incisions controlled via position sensors (Mulcahey et al., 2004), and superficial FES via external EMG sensors (Thorsen et al., 2020). The activities focused on object

manipulation and everyday tasks. Despite similarities, the different objective performance outcomes make direct comparison difficult. A common finding was that a subset of participants used the systems extensively on their own (Kilgore et al., 2006), even after the test was concluded (Mulcahey et al., 2004; Thorsen et al., 2020), indicating real-world utility.

Robotic Arms (RA)

Nine studies focused on Robotic Arms: six on individual Robotic Arms (RA) (Chung et al., 2017; Jackowski et al., 2018; Laffont et al., 2009; Onose et al., 2012; Rudigkeit & Gebhard, 2019), and 3 on Mobile Robotic Arms (MRA) (Coignard et al., 2013; Fattal et al., 2018; Ranganeni et al., 2023; Spataro et al., 2015),

Two studies allowed participants to select from different control methods for RA control, including different PD, MT and ET devices. Laffont et al., (2009) expanded planar control with automatic item retrieval when positioned near the object, receiving positive feedback from users. However, users found panoramic webcams for additional awareness limited. Chung et al., (2017) compared inputs for a RA, using its standard 3D joystick or a tablet to complete the ISO 9241–9 test. All participants with tetraplegia opted for the tablet, perceived as easier to understand and use, and requiring less physical effort.

Three studies evaluated robots on a mobile base (MRA) for teleoperation. Two used a GUI with PD or Kb for Cartesian position and rotation control. Coignard et al., (2013); Fattal et al., (2018) tested multiple-teleoperation scenarios to fetch items: objects in the user's view, in the camera view only, or outside both. Similarly, Ranganeni et al., (2023) provided multiple interfaces, including overlaying buttons onto the camera feed and tracing the desired path. Three "Action Modes" – discrete steps, continuous movement while pressing, or toggle – were compared along with customizable settings, leading to increased speed. Significant differences in user perception support that control strategy and customization majorly influence user acceptance.

Two studies utilized the AMiCUS (Rudigkeit & Gebhard, 2019; Rudigkeit et al., 2014), a head-worn IMU-based sensor system to control RA via head orientation and displacement. Slow head movements managed positioning and grasping. In (Jackowski et al., 2018), fast nodding switched between four control strategies, supported by a GUI displaying status and options. In the follow-up (Rudigkeit & Gebhard, 2019) gestures accessed a mode selection menu, switching between control modes via a virtual mouse. Both studies tested block-stacking tasks in 3D, where movement was positively received but rotation found more difficult. Gestures were found quick but difficult to perform. Thanks to easier customization, the virtual mouse was recommended by the authors for reduced mobility (Rudigkeit & Gebhard, 2019).

Two systems used BCI to control robots: EEG capturing using counting-based potentials (Spataro et al., 2015), and EEG capturing motor imagery with 3D ET (Onose et al., 2012). Both used external EEG caps, with the latter using 3D gaze to estimate item position, and required prior calibration and training. Successful completions varied from 3/4 (Spataro et al., 2015) to 3/9 (Onose et al., 2012), all reporting positive experience and sense of control. The technology thus allows control of complex systems, but the failure rate establishes it as less widely applicable than other systems.

Wearable devices (Wa)

Five studies focused on wearable devices (Bengtson et al., 2022; Correia et al., 2020; Dittli et al., 2023; Mohammadi et al., 2023; Thøgersen et al., 2022). Two of the wearable systems consisted of soft orthoses activated by residual motion. These used a single switch to open and close the participant's hand (Correia et al., 2020; Dittli et al., 2023). Performance in ADLs was measured using the ARAT and JHFT standardized tests, respectively. Participants were found to perform significantly better in both with little practice. The soft gloves were received positively by users, reporting mid-to-high usability. Some reported wanting to continue to use (Correia et al., 2020), but the extensive support to don the device independently was criticized (Dittli et al., 2023).

Three studies examined tongue-based control of an exoskeleton, all using the iTongue, a dental retainer with inductive sensors activated by a metal tongue piercing. Users then controlled movements, rotation, and grasping with their tongue (Mohammadi et al., 2023). Later studies introduced autonomous grasping (Thøgersen et al., 2022) and blended adaptive control based on hand position (Bengtson et al., 2022). Participants practiced in simulation, learning controls quickly. Positive experience and low physical task load were reported, but also concerns over the need for a custom mouthpiece, aesthetic appearance, and the need for a piercing.

Population

In total, 366 participants were included across all studies (see Table 7). Of the total participants, SCI was most prevalent (71%, $n = 260$), encompassing various injury levels (C3 to C8). This aligns with the inclusion criteria, with some studies explicitly excluding conditions different from SCI or individuals with comorbidities. Several studies reported time since injury (Algood et al., 2005; Ding et al., 2008; Fattal et al., 2018; Kilgore et al., 2006; Kim et al., 2013; Mulcahey et al., 2004; Onose et al., 2012; Schmalfuß et al., 2016; Thøgersen et al., 2022; van Middendorp et al., 2015), ranging from 6 weeks (Mulcahey et al., 2004) to 28 years (van Middendorp et al., 2015). Chung et al., (2017) was the only to involve participants with upper limb impairments – not limited to tetraplegia. The majority of the studies ($n = 27$) reported conditions using at least one standardized classification metric, either assessed by medical professionals or self-reported. Two studies broadly identified participants as having "tetraplegia" without specifying the etiology (Bengtson et al., 2022; Dittli et al., 2023), and three did for "LIS" (Laffont et al., 2007; Peters et al., 2016; Pouplin et al., 2014). The studies predominantly sought individuals with SCI and without comorbidities. Some sought participants capable of using traditional wheelchairs (Algood et al., 2005; Ding et al., 2008), computers (Coignard et al., 2013; Nuyujukian et al., 2018; Pandarinath et al., 2017; Pouplin et al., 2016), or regular users of PD excluding SSw (Coignard et al., 2013).

Participants were predominantly male (68%, $n = 248$), with 19% female ($n = 69$) and 13% ($n = 49$) not reported. Ages ranged from 1 year (Borgestig et al., 2017) to 81 years (Dittli et al., 2023). Two studies focused on children with cerebral palsy (CP) and other comorbidities, including some who were non-verbal. Geographic representation was limited, with only one study situated in the global south (Chhikara et al., 2023). No studies

Table 7. User demographics across included studies.

Ref	Group	n=	Measurement	Interface	Effector
Laffont et al. (2007)	CP	5		Kb, SSw	PC
	ALS	3			
	LIS	1			
	ABD	1			
Pouplin et al. (2014)	LIS	4		PD, HT, SSw, ET	
	MS	4			
	SCI	2			
Pouplin et al., (2016)	SCI	15	C4-C5 ASIA A or B	Kb, PD, HT	
	SCI	30	C6-C8 ASIA A or B		
Plotkin et al. (2010)	S	2	LIS	Sn	
	SCI	1	LIS		
	MS	1			
Borgestig et al. ¹	SCI	1	High	ET	
	CP	4	Dyskinesia, GMFCS 4-5, MACS 4-5		
	CP	2	Spastic GMFCS 5, MACS 4-5		
	O-CP	3	Spastic Dipl. GMFCS 4-5, MACS 5		
van Middendorp et al. (2015)	SCI	3	C2-C4, AIS A		
	SCI	3	Incomplete C4-C5, AIS C-D		
Nuyujukian et al. (2018)	ALS	2		BCI	
	SCI	1	C4, ASIA C		
Nuyujukian et al. (2018)	ALS	2	ALSFRS-R		
	SCI	1	C4, ASIA C		
Nuyujukian et al. (2018)	LIS	1	With some movement		
	ALS	7			
	CP	2			
	DMD	1			
	SCA	1			
Combaz et al. (2013)	S	6	LSFRS-R and Patterson		
	TBI	1			
Ding et al. (2008)	SCI	15	C3 to C7	PD	PAW
Algood et al. (2005)	SCI	15			
Cooper et al. (2004)	SCI	2	Tetraplegia		
	O-SCI	2	Paraplegia		
Schmalfuß et al. (2016)	SCI	2	ASIA A-C	EMG	
	C	10			
Kim et al. 2013 and 2014	SCI	11		TC, Air	
	C ₂	23			
Floreani	CP	8	GMFCS of 5, MACS of 4-5	BCI	
Mulcahey et al. (2004)	SCI	4	ASIA C4-C5, ICSHT 0	MT	FES
Thorsen et al. (2020)	SCI	27	C5-C7	EMG	
Kilgore et al. (2006)	SCI	3	ICSHT O/Cu 0-2		
Laffont et al., (2009)	SCI	13	C4-C6	PD	RA
	MD	3	C4-C6		
	GBS	2	C4-C6		
	SMA	2	C4-C6		
	C	24			
Chung et al. (2017)	SCI	2	QD 59.1-38.6		
	SCI	3	C5-C7, QD 65.9-31.8		
	MD	1	QD 25		
	Unk.	1	QD50		
	O-S	1	Hemiplegia QD 70.5		
Rudigkeit et al. (2019)	SCI	6	C4-C7	MT (Head)	
	C	13			
Jackowski et al. (2018)	SCI	6	C3-C4		
	C	24			
Onose et al. (2012)	SCI	9	C4-C8	BCI	

(Continued)

Table 7. (Continued).

Ranganeni et al. (2023)	SCI	8	C3-C6	PD, SSw, MT	MRA
	TM	1			
	CMT	1	Type 2A		
	C	13			
Fattal et al. (2018)	SCI	12	7x C6 and 5x C5	PD	
	Unk.	1	Other C6		
	Unk.	4	Neurological		
Coignard et al. (2013)*	SCI	23		PD, Kb, MT	
	LIS	2	Post-S		
	Unk.	1	Arthrogryposis		
	O.	1	Quadruple amputee		
	CP	1			
	SMA	1			
	C	34	16 carers, 18 not		
Spataro et al. (2015)	ALS	4	LIS, ALSFRS-R 0-6	BCI	
	C	4			
Dittli et al. (2023)	SCI	11	Complete C6-C7, AIS A	SSw	Wa
	SCI	3	Incomplete C3-C8, AIS C-D		
	Unk.	1			
Correia et al. (2020)	SCI	13	C4-C7, ISNCSCI		
Mohammadi et al. (2023)	SCI	10	ISNCSCI	TC	
Thøgersen et al. (2022)	SCI	3	ASIA A to D		
	C	10			
Bengtson et al. (2022)	Unk	7			
	C	10			

Conditions: Anoxic Brain Damage (ABD), Amyotrophic Lateral Sclerosis (ALS), Charcot – Marie – Tooth disease (CMT), Cerebral Palsy (CP), Duchenne Muscular Dystrophy (DMD), Guillain-Barré Syndrome (GBS), Locked-in Syndrome (LIS), Myopathy (M), Muscular Dystrophy (MD), Multiple Sclerosis (MS), Transverse Myelitis (TM), Traumatic Brain Injury (TBI), Stroke (S), Spinocerebellar Ataxia (SCA), Spinal Cord Injury (SCI), Spinal Muscular Atrophy (SMA), Unknown (Unk), Other non-tetraplegia condition (O), Control (C).

Classification strategy: AIS, ALSFRS, GMFCS, Injury level (C1 to C8), ICSSHT, ISNCSCI, MACS, Patterson, Plum and Posner, QuickDASH (QD).

Interfaces: Brain Control Interfaces (BCI) Electromyography (EMG), Eye Tracking (ET), Inertial Measurement Unit (IMU), Joystick (JS), Keyboard (Kb), Pointing Devices (PD), Residual Mption (RM), Sniff (Sn), Switch (Sw), Tongue Control (TC), TouchScreen (TS).

Devices: Functional Electrical Stimulation (FES), Power Assisted Wheelchair (PAW), PC, Robot Arm (RA) and Mobile RA (MRA), Spline (Sp) Wearable (Wa).

1. All children, some with unspecified cognitive impairment. 2. Control participants only on qualitative part.

reported participants' ethnicity or education levels, but one (Kim et al., 2012, 2013) included it in follow-up publications (Laumann et al., 2015). One hundred and seventy-seven control participants were included (60 males, 60 females, 57 not specified), and only one study explicitly involved caregivers (Coignard et al., 2013).

Trial abandonment was a common challenge, with several studies reporting 40% or more of the recruited participants not completing the study (Kim et al., 2013; Laffont et al., 2007; van Middendorp et al., 2015), and in some cases up to two-thirds dropping out (Dittli et al., 2023; Onose et al., 2012). Cited reasons included finding the device heavy, preference for other devices, separate visual impairments (Laffont et al., 2007), unmet expectations, technical difficulties, early discharge (van Middendorp et al., 2015), scheduling or caregiver issues, and disqualification due to medical conditions (Kim et al., 2013). Non-participation reasons included prioritizing recovery, preference for other devices, and lack of interest (van Middendorp et al., 2015).

Discussion

The aim of this review was to assess new assistive technologies and their utility in supporting the independence of individuals with tetraplegia, focusing on experimental studies with both performance and perception metrics.

Impact on quality of life and adoption

While device effectiveness was generally reported positively, few studies investigated whether these devices measurably affected QoL (Combaz et al., 2013; Ding et al., 2008; van Middendorp et al., 2015), an underexplored topic in assistive technology research (Baldassin et al., 2018). Several studies reported that their systems functioned as intended, but few provided evidence regarding long-term adoption or real-world usability. The fluctuating health and priorities of individuals with tetraplegia reduces participation rates and limits statistical power (van Middendorp et al., 2015). Opting for participants with stabilized conditions and prioritizing independence was suggested (Ding et al., 2008; van Middendorp et al., 2015) to increase research impact. This aligns with findings from Motahar et al. (2024) where assistive technology was not recommended soon after injury or for emotionally unprepared participants.

Notably, some studies reported participant adoption of devices (e.g., FES devices (Mulcahey et al., 2004; Thorsen et al., 2020) and sniff-controlled communication tools (Plotkin et al., 2010)), respectively, suggesting demand for technologies that drastically improve abilities, enable previously inaccessible activities, or provide alternatives to disliked options. Furthermore, some works reported user conditions affecting responses, as those with severe impairments may benefit greatly, but more independent users

Table 8. Cross comparison of control interfaces against effectors.

Effector	Interface									
	Kb	PD	SSw	MT	EMG	TC	Air	ET	BCI	
AR	-	Chung et al., (2017), Laffont et al., (2009), Ranganeni et al., (2023)	-	Jackowski et al., (2018), Ranganeni et al., (2023), Rudigkeit & Gebhard, (2019) Coignard et al., (2013)	-	-	-	-	Onose et al., (2012)	
MAR	Coignard et al., (2013), Fattal et al., (2018)	-	-	-	-	-	-	-	Spataro et al., (2015)	
Wa	-	Correia et al., (2020), Dittli et al., (2023)	-	-	-	Bengtson et al., (2022), Mohammadi et al., (2023), Thøgersen et al., (2022)	-	-	-	-
FES	-	-	Mulcahey et al., (2004)	-	Kilgore et al., (2006), Thorsen et al., (2020)	-	Kilgore et al., (2006)	-	-	-
PC	Laffont et al., (2007), Pouplin et al., (2016) et al., (2016)	Pouplin et al., (2014, 2016)	Laffont et al., (2007), Pouplin et al., (2014)	Kim et al., (2012), Kim et al., (2014), Kim et al., (2013), Venkatesh al., (2003)	-	-	Plotkin et al., (2010)	Borgestig et al., (2017), Pouplin et al., (2014), van Middendorp et al., (2015)	Combaz et al., (2013); Nuyujukian et al., (2018); Pandarinath et al., (2017); Peters et al., (2016)	
PAW	-	-	Algood et al., (2005), Cooper et al., (2004), Ding et al., (2008)	-	Schmalfuß et al., (2016)	Kim et al., (2014)	-	-	Floreani et al., (2022)	

Interfaces: Keyboard (Kb), Pointing Devices (PD), Single Switch (SSw) Motion Tracking (MT), Electromyography (EMG), Tongue Control (TC), Sipp and Puff (Air), Eye Tracking (ET), Brain Control Interfaces (BCI).
Effector: Assistive Robot (AR), Mobile AR (MAR) Wearable (Wa), Functional Electrical Stimulation (FES), Computer (PC), Power-Assisted Wheelchair (PAW).

may find new systems disruptive (Pouplin et al., 2014, 2016). In contrast, studies that presented incremental improvements to existing technology, such as wheelchairs (Algood et al., 2005; Ding et al., 2008) or screen control (Laffont et al., 2007; Pouplin et al., 2014, 2016) showed minor improvements. This suggests that, for technology to be worth its cost of entry and adaptation efforts, its payoff must be large. Future research should prioritize substantial usability improvements or activities that participants are unable to perform.

Device characteristics

The combinations of interfaces and effectors are illustrated in Table 8, showing current research interests and potential research gaps. Compared to traditional assistive technology (Kb, PD and SSw), experimental interfaces such as tongue control (TC), air-based devices (Air), and ET remain relatively unexplored, particularly in applications involving RA and PAWs.

Several systems allowed only limited information transfer (e.g., Sw, Air, and EMG), restricting their applicability without modifications. Consistent with Myburg *et al.* (2017), control of complex effectors via SSw was reported to be poor and slow (Laffont et al., 2007). However, these proved effective for devices with binary operation, such as FES (Kilgore et al., 2006; Thorsen et al., 2020). When used in pairs, inner-ear EMG was also successful in wheelchair control (Schmalfuß et al., 2016). The utility and success of some devices depended on other factors such as need for supervision/support in ET (van Middendorp et al., 2015), and invasiveness in BCI (Nuyujukian et al., 2018; Pandarinath et al., 2017), and fast head mobility for MT (Jackowski et al., 2018; Rudigkeit & Gebhard, 2019). Furthermore, two studies feature devices that participants could not use initially and learned after practice (Plotkin et al., 2010; Schmalfuß et al., 2016). Difficulty in an independent setup was another barrier noted (Dittli et al., 2023; Motahar & Wiese, 2024). Exploring and comparing multiple options against each other was recommended (van Middendorp et al., 2015). Finally, to support the diversity of conditions and to maximize potential adoption (Orejuela-Zapata et al., 2019), customization was received positively (Ranganeni et al., 2023), requested (Dittli et al., 2023) and identified as essential (Rudigkeit & Gebhard, 2019). Exploring novel interface-effector combinations, allowing customization and experimentation, could lead to more effective interface systems.

Invasive devices like the Tongue Drive System (Kim et al., 2013), implanted FES (Kilgore et al., 2006; Mulcahey et al., 2004) and intracortical BCI systems (Nuyujukian et al., 2018; Pandarinath et al., 2017) were well received by participants, delivering notable long-term benefits. Their relative rarity contrasts with findings from Blabe *et al.* (2015), where participants with tetraplegia expressed willingness to undergo invasive procedures if these could deliver effective control and natural appearance. While most participants in (Kim et al., 2013) were satisfied with the appearance of the headset and piercing, the aesthetics of the iTongue were identified as a concern in (Thøgersen et al., 2022), supporting the importance of aesthetic acceptability, sometimes over invasiveness.

Demographic considerations & study applicability

Several studies specifically recruited individuals with residual motion, capable of using some assistive devices, or excluded additional comorbidities or conditions beyond SCI. This may introduce significant bias and limit applicability, particularly as tetraplegia needs are known to change over time depending on condition (Alizadeh et al., 2019; Schnetzer et al., 2023), meaning that those who might benefit the most are under-represented. The demographic representation across studies showed a predominance of male participants. This aligns with the incidence of some conditions such as SCI and MD but may also indicate participant selection or participation bias. Expanding beyond SCI would also improve sample sizes and better reflect real-world user diversity. Reporting of etiology varied notably across studies, and no study reported participant demographics comprehensively. Notably, only one study included participants from the global south (Chhikara et al., 2023), highlighting a significant research gap in geographic diversity. Similarly, only one included carers, who act as key stakeholders and sometimes users of the technology.

Furthermore, two studies feature devices that participants could not use initially and learned after practice (Plotkin et al., 2010; Schmalfuß et al., 2016). Difficulty in independent setup was another barrier noted (Dittli et al., 2023; Motahar & Wiese, 2024). Exploring and comparing multiple options against each other was recommended (van Middendorp et al., 2015).

Methodological approaches & standardization

High heterogeneity in study methodologies was found, including different performance metrics, evaluation environments, and participant criteria. This makes establishing meaningful comparisons between assistive devices challenging – even for similar devices – limiting the ability to establish evidence-based recommendations.

Some studies, particularly those involving FES (Mulcahey et al., 2004; Thorsen et al., 2020), reported only high-level task completion, while technically complex devices often provided results broken down into component steps (Coignard et al., 2013; Fattal et al., 2018; Ranganeni et al., 2023). Several papers emphasized the need for standardized outcome measures, though standardized assessment tools (ISO 9241–9 protocol (Chung et al., 2017), ARAT (Dittli et al., 2023), JHFT (Correia et al., 2020), ADLAT (Kilgore et al., 2006)) were the exception rather than the norm. This evaluation heterogeneity limits cross-study comparisons, potentially hindering informed clinical decisions. This may partly explain why most systems in this review were uni-modal, as the potential advantages of more complex approaches may be obfuscated.

In terms of perception, the NASA-TLX was the most frequently used (six studies) (Bengtson et al., 2022; Combaz et al., 2013; Floreani et al., 2022; Mohammadi et al., 2023; Ranganeni et al., 2023; Schmalfuß et al., 2016), followed by the QUEST (five) (Borgestig et al., 2017; Coignard et al., 2013; Laffont et al., 2007; Spataro et al., 2015; Thorsen et al., 2020), and the INTUI (two) (Bengtson et al., 2022; Mohammadi et al., 2023). Other standardized outcomes appeared once. NASA-TLX over-use was criticized by Peters et al (2016),

pointing out that it's not always the correct tool for the job. Furthermore, there was a lack of user-centered evaluation frameworks. While some studies iteratively assessed technology at different stages as part of longer projects (Coignard et al., 2013; Ding et al., 2008; Kim et al., 2016; Pandarinath et al., 2017; Rudigkeit & Gebhard, 2019), the role and extent of user involvement in shaping the devices was not always clear. For successful adoption, technology needs to be matched to user needs (Venkatesh et al., 2003). Current development practices frequently do not support a user-guided design and evaluation process.

For data collection, the distinction between prompted qualitative feedback and anecdotal evidence was not always clear, confounding interpretation of user experiences. Several studies compared the performance of individuals with disabilities against healthy control groups. While this approach provides an upper-bound performance benchmark, it does not directly evaluate the efficacy of the assistive device itself, and is better suited for initial exploration of the device. It is also recommended for future experiments to report non-completions and their reasons transparently.

Limitations of this review

A limitation of this review is the omission of papers with Quality of Life measures but without performance metrics, or measuring adoption, which could have revealed additional impactful devices. For instance, Corallo *et al.* (2017) establishes a link between head MT devices and QoL, but was excluded as it lacked performance outcomes. This could expand on existing works reviewing QoL (Baldassin et al., 2018).

Splints were included in the search terms to broaden our results. However, due to their purely passive nature, two studies that appeared to meet the rest of the criteria were not included (Chhikara et al., 2023; Kim et al., 2022). Future work could include both passive and active criteria to consider multiple assistive options.

Recommendations

Based on this review's findings, we present the following targeted recommendations to advance assistive technology for individuals with tetraplegia.

Design and development

- **Break the Device Adoption Threshold:** Marginal improvements were shown unlikely to be adopted by users (Pouplin et al., 2014, 2016). Development should focus on substantial improvements – enabling previously inaccessible activities or providing significant functional improvements (Mulcahey et al., 2004; Plotkin et al., 2010; Thorsen et al., 2020) – to justify adaptation effort, cost and setup.
- **Explore Multimodal Interfaces:** Most works in this review focused on control with a single input type. Interfaces with limited information transfer were capable

of controlling complex systems intuitively when combined (Schmalfuß et al., 2016). Interface-effector combinations, particularly tongue control, air-based devices, and eye-tracking, could offer promising and underexplored research avenues.

- **Invasiveness can be Justified:** Literature explores how users with tetraplegia can accept invasive setups when these provide good performance, simple setups, and a non-disruptive appearance (Blabe et al., 2015). While explored by some works here (BCI (Nuyujukian et al., 2018; Pandarinath et al., 2017), FES (Kilgore et al., 2006; Mulcahey et al., 2004), and to a lesser extent tongue (Kim et al., 2016)), sensors, particularly EMG, stand to benefit from more invasive approaches.
- **Appearance Matters:** Aesthetic considerations can outweigh invasiveness concerns (Kim et al., 2016), consistent with the literature (Blabe et al., 2015; Jafar & Nagesh, 2023; Wielandt et al., 2006). Devices should be functional and aesthetically acceptable, ideally involving users in the design (Wielandt et al., 2006).
- **Build for Customization:** Beyond users and conditions, devices must adapt to changes of an individual over time (Alizadeh et al., 2019; Schnetzer et al., 2023). Personalization is thus essential to increase usability and acceptance (Rudigkeit & Gebhard, 2019), and such measures should be reported transparently in studies.
- **Involve Caregivers and Clinicians:** Despite their role as stakeholders and technology users (Orejuela-Zapata et al., 2019), few studies involved caregiver(s) or health-care staff, whose presence is crucial for deployment. The setup process must be considered as devices can be rejected if they need extensive support or supervision during use (van Middendorp et al., 2015).

Research and evaluation

- **Prioritize Functional Outcomes Over Condition:** Most studies lacked etiology diversity (SCI-dominated) and focused on diagnostic categories rather than functional capacity. Recruiting based on functional metrics rather than specific conditions would improve cross-study comparisons and broader applicability of findings. For longitudinal studies, functional status should be reported at multiple time points.
- **Improve Reporting Transparency:** Reasons for trial abandonment should be clearly explained following standard guidelines (Downs & Black, 1998). Report individuals contacted, agreement to participate, losses to follow-up, and separately, non-completions. Similarly, demographic reporting should expand beyond age and gender to include other factors that may impact participation and acceptance, such as education, socioeconomic status, and ethnicity. We encourage researchers in the Global South to conduct similar studies to improve global Representation
- **User Perception and Adoption as Proxies for Success:** Measuring device impact on QoL remains underexplored (Baldassin et al., 2018), but longitudinal testing is challenging (van Middendorp et al., 2015).

Experimental studies should include user perception outcomes alongside performance metrics (Wielandt et al., 2006). Desire for adoption could be useful metric, particularly when comparing new devices against the currently used technology. Qualitative comments should be included, but experimenters should distinguish when prompted.

- **Standardize Measures with Flexibility:** High methodological heterogeneity necessitates standardized outcome measures for cross-study comparison and present evidence-based recommendations. Due to the difficulty in conducting powerful longitudinal and RCT experiments (van Middendorp et al., 2015), flexible study designs with standard measurements might offer the best compromise. In addition, adopting co-design methodologies that involve users early on and include comprehensive user-centered evaluation is key for adoption (Wielandt et al., 2006).

Clinical implementation

- **Enable Exploration and Learning:** Clinicians should facilitate opportunities to explore multiple options (van Middendorp et al., 2015) and recognize learning curves, incorporating adequate training time and support (Fattal et al., 2018; Plotkin et al., 2010; Schmalfuß et al., 2016). Clinician should be collected and fed back into successful User-Centered Design protocols.
- **Optimize Introduction Timing:** Technology should be introduced to participants with stabilized conditions who are emotionally prepared and independence-focused (Ding et al., 2008; van Middendorp et al., 2015), avoiding early post-injury periods (Motahar & Wiese, 2024).

Conclusion

Assistive technologies offer significant potential to improve the quality of life for individuals with tetraplegia. However, their real-world impact remains limited due to usability challenges, lack of customization, and insufficient participant diversity in research. Their benefit must be significant to offset their monetary and time investments and lead to successful adoption. Further exploring the emotional and psychological dimensions of technology is vital to long-term use and user satisfaction.

Author contributions

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Appendix A. Risk of Bias

Results for modified Downs and Black (Table A1) including questions on basic reporting (8 questions), external validity (3), internal validity (3), confounding (1), and statistical power (1). Final results have been included in Table A2.

Authors

Table A1. Risk of bias category for the included studies.

Authors	Risk of Bias
Laffont et al., (2007)	Low
Pouplin et al., (2014)	Low
Pouplin et al., (2016)	Low
Plotkin et al., (2010)	Low
Borgestig et al., (2017)	Low
van Middendorp et al., (2015)	Low
Pandarinath et al., (2017)	Mid
Nuyujukian et al., (2018)	Low
Combaz et al., (2013)	Low
Peters et al., (2016)	Low
Algood et al., (2005)	Low
Ding et al., (2008)	Low
Cooper et al., (2004)	Mid
Schmalfuß et al., (2016)	Low
Kim et al., (2013, 2014)	Low
Floreani et al., (2022)	Low
Mulcahey et al., (2004)	Mid
Thorsen et al., (2020)	Low
Kilgore et al., (2006)	Mid
Laffont et al., (2009)	Low
Chung et al., (2017)	Low
Rudigkeit & Gebhard, (2019)	Mid
Jackowski et al., (2018)	Low
Onose et al., ((2012)	Mid
Ranganeni et al., (2023)	Mid
Fattal et al., (2018)	Low
Coignard et al., (2013)	Low
Spataro et al., (2015)	Mid
Dittli et al., (2023)	Low
Correia et al., (2020)	Low
Mohammadi et al., (2023)	Low
Thøgersen et al., (2022)	Low
Bengtson et al., (2022)	Low

Table A2. Modified Downs and Black Risk of Bias Questionnaire.

Study Design
1. Is the hypothesis/aim/objective of the study clearly described?
2. Are the main outcomes to be measured clearly described in the Introduction or Methods section?
3. Are the characteristics of the patients included in the study clearly described?
4. Are the interventions of interest clearly described? Treatments and placebo (where relevant) that are to be compared should be clearly described.
5. Are the main findings of the study clearly described?
6. Does the study provide estimates of the random variability in the data for the main outcomes?
7. Have the characteristics of patients lost to follow-up been described? 8. Have actual probability values been reported (e.g. 0.035 rather than <0.05) for the main outcomes except where the probability value is less than 0.001?
External Validity
9. Is the participation Rate clearly defined?
10. Were the subjects asked to participate in the study representative of the entire population from which they were recruited?
11. Were those subjects who were prepared to participate representative of the entire population from which they were recruited?
Internal validity – bias
12. If any of the results of the study were based on “data dredging” , was this made clear?
13. Were the statistical tests used to assess the main outcomes appropriate?
14. Were the main outcome measures used accurate (valid and reliable)?
Internal validity “confounding (selection bias)
15. Was there adequate adjustment for confounding in the analyses from which the main findings were drawn?
Power
16. Did the study have sufficient power to detect a clinically important effect where the probability value for a difference being due to chance is less than 5%?
Total score: X/16
