Restoring prolonged standing via functional electrical stimulation after spinal cord injury: A systematic review of control strategies

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A R T I C L E   I N F O

Article history:
Received 16 June 2018
Received in revised form 5 October 2018
Accepted 18 November 2018

Keywords:
Functional electrical stimulation
Standing
Spinal cord injury and control sensors

A B S T R A C T

Background: Functional Electrical Stimulation (FES) technologies can facilitate standing in persons with spinal cord injury (SCI), and prolonged standing elicited via FES may offer both functional and therapeutic benefits to users. However, the current attainable FES-evoked standing duration is typically short and below the threshold for clinical efficacy. To promote the objective selection of suitable control strategies to restore prolonged and higher-quality standing duration, this study summarised current and emerging approaches to FES standing.

Method: PubMed, IEEE Xplore, Web of Science and Google Scholar databases were searched for relevant studies on FES-evoked standing after SCI between the earliest return date and December 2017. Thereafter, the quality of all included studies was objectively evaluated using the Downs and Black methodological assessment checklist.

Results: Twenty-five full-length articles, with mean methodological quality score of 56%, met the inclusion criteria and were retained for analysis. Recent advancements to promote prolonged standing relied greatly on the use of voluntary upper extremities for balancing with arm engaged or disengaged. Some widely-reported constraints were issues of unpredictable postural sway, and unusual muscle responses and perturbations, such as spasm or spasticity, which diminished the reliability of the standing control sensors and algorithms.

Conclusion: Closed-loop control of FES-supported standing with arms-free modality and voluntary upper extremity balancing promoted the "longest" standing duration and "highest" efficacy among the reported methods, albeit with a limited successful transfer of the technology into the routine clinical practice or community deployment. However, open-loop control of FES standing appeared popular, particularly for its therapeutic gains, simplicity of use and other health and psychological benefits associated with weight bearing through the legs. The information from this study could stimulate useful knowledge that may promote clinically significant FES-supported standing duration.

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https://doi.org/10.1016/j.bspc.2018.11.006
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1. Introduction

Due to its significant potential for health and psychological benefits [1,2], functional electrical stimulation (FES)-elicited standing in persons with spinal cord injury (SCI) has been a significant research focus for over four decades, since the pioneering studies of Kantrowitz [3], Bajd et al [4], Kralj and Bajd [5] and Brindley et al [6] amongst others in this field. FES applies electrical current at a specific threshold to the muscle or nerve to generate purposeful muscle contraction either invasively or non-invasively depending on the stimulation electrode used [7]. Unlike some traditional passive standing methods [8], FES-evoked standing is easily deployed and potentially appealing to its users as it has a superior ability to actively re-train neuromuscular functions. Candidates for FES-supported standing must possess good upper-limb strength, which may be useful (if properly trained) to access objects from a standing posture or maneuver into places that are ordinarily inaccessible in a wheelchair [9].

Unlike some traditional standing methods such as using a passive standing frame, FES-supported standing has functional [10], physiological and therapeutic benefits [11,12]. For example, it promotes muscle trophism and cardiorespiratory fitness [13]. A functional FES-supported standing task involves a stable upright posture while the upper extremities may be used for object manipulations [10]. Conversely, when the upper extremities are mainly used for maintaining postural control and stability, an FES-supported standing technique is restricted to potential therapeutic benefits. While the latter may be of limited clinical interest, its benefits should not be underestimated [11]; standing being a simple and cost-effective therapeutic exercise for the SCI population [7]. Whether for therapeutic benefit or community functional outcomes, the advantages of standing may be fully realized if it is significantly prolonged [2]. Thus, as a requirement [14] for reaching, ambulation, as well as “equal level interaction”, standing is one of the priorities for individuals with SCI in undertaking their activities of daily living [15] for quality of life improvement [16].

Currently, the quality of FES-supported standing strategies is sub-optimal, with very high energy expenditures [17] in comparison to voluntary standing. Thus, research interest to prolong standing duration in persons with SCI has remained topical, based on the findings by Eng and colleagues [2] who reported important health benefits of a prolonged standing task. Several other prominent FES-supported standing studies, including those by Veltink and Donaldson [11], Braz et al. [18], Lau and co-workers [19] and Nataraj et al. [20], have been conducted, but few empirically compared the effectiveness of different control strategies (i.e. controller deployed and feedback mechanism used (Tables 2 and 3)). Although these studies detailed the procedures that could promote an extended FES-supported standing duration, they were either a simulation study, recruited able-bodied volunteers, non-human study participants, or were non-systematic reviews.

To our knowledge, there has not been a comprehensive and systematic synthesis of current scientific knowledge that integrates recent promising research developments, particularly in persons with SCI. The current authors set out to synthesize the available literature on prolonged FES-elicited standing strategies and to comment on the methodological quality of this work, suggesting future improvements. Specifically, the current systematic review sought to: (i) evaluate and synthesize the effectiveness of available methods and emerging concepts, with highlights on the methodological constraints for prolonging FES-supported standing in persons with spinal cord injury; and, (ii) assess the quality of these studies using Downs and Black [21] methodological checklist based on the reported quality and duration of standing and related outcomes.

2. Methods

2.1. Literature search strategy

A literature search was performed in the Pubmed, IEEE Xplore, Web of Science and Google Scholar databases from the earliest returned record until December 2017, using the following relevant search terms, keywords or phrases: “electrical stimulation”, “functional electrical stimulation”, “functional neuromuscular stimulation”, in combination with “standing”, “stance”, “spinal cord injury”, “paraplegic”, “paraplegia”, “tetraplegic”, “tetraplegia”, and other FES-supported standing related terms. A further search was conducted using the relevant reference lists of the retrieved articles. Studies reported in English language, and those that were within the eligibility criteria were retained for further analyses.

2.2. Eligibility criteria

Studies with low-cervical or thoracic spinal cord lesions participants were included and those that recruited participants with lesion levels above C4 were excluded. This is due to the contraindication of the participants’ need for “respiration assistance” during standing [2]. A prolonged standing task description by Eng and colleagues [2], with a duration of standing greater than 20 min.d−1, was included in this systematic review. Theirs was included because 20–45 min of standing duration had been previously reported to produce some significant therapeutic, functional and health benefits [22–24] accruing to standing duration [11]. Therefore, the quality of FES-supported standing, in the present review, was assessed on the following criteria: (i) duration, (ii) dexterity/ degree of freedom (DOF), and (iii) level of arm engagement. Criteria for study selection also included the stimulation type and parameters, and the muscles stimulated as
these also influenced the quality of standing. In studies where able-bodied and spinaly-injured volunteers were co-recruited, only the results of persons with SCI were analysed and reported herein. Due to probable inadequate data presentation and lack of peer-review, conference abstracts and proceedings were excluded, but in such situations a full-length article reporting the same/similar findings has been reported.

2.3. Data extraction from selected articles

An independent screening of the title and abstract of potentially eligible studies for inclusion in this review was conducted by two authors (MOI and NAH). Only full-length articles that measured FES-supported standing outcomes in persons after SCI with an incomplete or complete loss of motor function were retained and analysed. Furthermore, to be included in this review, the aim of the study and the intervention of interest was required to be only on FES-supported standing. Studies where upright stance was combined with standing-up, sit-to-stand, stepping/gaiting, were excluded as these co-interventions might independently affect the study outcomes. Studies on adolescents were also excluded due to the probable variations in their standing performance and related risks, as a result of immature musculoskeletal system responses, in comparison to those of adults with SCI [25]. As previously stated, the primary outcome of interest was the duration of standing, and secondary outcomes included; standing supports/orthotic modality, dexterity/DOF, the degree of upper limb/arm engagement. In this review, “arm free” standing referred to the situation wherein participants could use their two arms and hands for object manipulation during upright posture to execute manual tasks.

2.4. Assessment of study quality

Downs and Black [21] methodological assessment criteria were adapted to evaluate the quality of the included studies. Items 5, 9, 16, 17, 21, 22, 25, 26 and 27 were deleted from the Downs and Black (D&B) criteria as these were deemed inappropriate for the present review, being strictly applied only for randomised-controlled trials [21]. The exclusion of some items from the D&B scale for grading the quality of included studies warranted normalisation of the D&B score to 100%. As a standard measure of study quality, the D&B scale offered an assessment tool that facilitated the comparison of the methodological quality of included articles. In event of disagreement and ambiguity regarding the grading of the quality of included studies, such cases were resolved by consensus after consultation with the senior author (GMD).

3. Results

3.1. Characteristics of included studies

Initially, 17,489 articles (Fig. 1) were retrieved for possible inclusion. After the removal of duplicates and following title and abstract screening, 203 studies were retained. A further 179 studies were excluded, through failing to meet inclusion criteria after full-text assessment. Finally, twenty-five articles were included in this review (Fig. 1). Ten studies examined standing with open-loop FES techniques, and 11 investigated standing challenge tasks using closed-loop FES with arm engagement for stability to improve standing quality or duration. Four works investigated advanced standing challenge interventions using closed-loop FES with arm-free strategies including modest control of balance and posture to achieve close-to-voluntary standing outcomes.

3.2. Methodological quality

The mean of the D&B assessment (Table 5) of the included studies was 56% (range 44–63%) and these were adjudged to be satisfactory. Thus, the evidence presented in the reviewed studies was deemed of acceptable methodological quality. Most of these studies did not report “adverse effect that may be a consequence of the intervention” except references [26–29]. In most of the reviewed studies, the authors were unable to determine: “whether the study participants were asked to participate in the study representative of the entire population from which they were recruited” (Criteria 11). An exception was Bajd and colleagues [7] wherein “those study participants who were prepared to participate were representative of the entire population from which they were recruited” (Criteria 12); “an attempt was made to blind study participants to the intervention they have received” (Criteria 14); “whether study participants were randomized to intervention groups” (Criteria 23). All studies, except Kralj and co-workers [30] and Ewins et al. [31] “clearly described the characteristics of the participants included in their studies” (Criteria 3). Also, actual probability values were mostly not reported, except in Fisher et al. [32], and when these were reported, the exact significance levels were not provided (see references [33–35]).

3.3. Open-loop FES supported-standing methods

The open-loop FES control of standing strategy was characterized by a manual control of stimulation characteristics leading to fixed stimulation parameters (Table 1) throughout the contraction duration. This approach was based on user-controlled stimulation characteristics with lack of automated feedback information (particularly, that of the magnitude of muscle force/joint torque generation or joint position) of the muscle being stimulated as well as the lower limb muscles’ responses to the stimulation. Under this strategy, the knee joint range of motion is usually not within the functional limit [36]. Thus, this mode of FES standing has been characterized by instability, low standing quality and limited standing duration. For example, not more than 30-min of “hand-engaged” standing before failure has been reported, except in Rejc et al. [37,38] where a 60-min duration was targeted. The standing duration reported under this category was often characterized by “occasional seated resting periods”. In the results, we have discussed the common implementations of the open-loop control of FES-supported standing, with the characteristics and merits of the studies included in Table 1.

3.3.1. Posture switching

Posture switching is the simplest strategy for FES-supported standing and involves bilateral, open-loop stimulation of the knee extensor to keep the knee extended while maintaining the hip hyper-extended in order to facilitate the free movement of the ankle joints [30]. This technique is based on the premise that bringing the “ground reaction force in front of the knee” during stance allows the relaxation of the quadriceps muscles [30]. However, there are two major limitations of this approach: (i) rapid muscle fatigue, and (ii) engagement of upper extremities for postural stability. This standing strategy has been termed “quadrupedal standing” [39] as the hands are usually fully engaged in maintaining posture and stability during the upright stance task. Additionally, it is an important requirement that the engaged joints’ range of motion is adequate [30]. When these prerequisites are unmet, the posture switching strategy cannot be deployed as it may be catastrophic, leading to collapse [30]. By implication, this approach demands profound attention from the user and/or an assistant as it potentially predisposes the user to fall.
<table>
<thead>
<tr>
<th>Authors; country; study quality</th>
<th>Participants Mean (SD) yrs.; Duration of FES training (DFT)</th>
<th>Stimulated muscle</th>
<th>Stimulation parameters</th>
<th>DOF/ Plane</th>
<th>Standing modality/Bracing; Stimulation type</th>
<th>Duration Mean (SD)</th>
<th>Outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kralj et al. [30]; Yugoslavia &amp; USA; 44%</td>
<td>&gt;3 T4-T10 Age- NM, TSI- NM; J- NM; DFT- NM 21- C7-T11 Age-33.2(8.4) TSI-4.5(3.9); J-NM; DFT- NM</td>
<td>Quadriceps, soleus and gastrocnemius, and gluteus maximus and medius muscles</td>
<td>Freq =20Hz PW = 0.3 ms SI = NM RT = 1-2 s</td>
<td>AP</td>
<td>Crutches or walker and posture switching; Surface</td>
<td>≤ 5 hrs for “persons with good musculature and near normal ROJM”</td>
<td>Arm engaged</td>
</tr>
<tr>
<td>Jaeger et al. [26]; USA 63%</td>
<td>21- C7-T11 Age-33.2(8.4) TSI-4.5(3.9); J-NM; DFT- NM</td>
<td>Quadriceps</td>
<td>Freq = NM PW = NM SI = NM RT = NM</td>
<td>AP</td>
<td>KAFO &amp; standing frame; Surface</td>
<td>Min: 1 min Max: 30 min</td>
<td>Arm engaged</td>
</tr>
<tr>
<td>Bajd et al. [7]; Slovenia 63%</td>
<td>5- T5-T11 Age- 28.4(11.1), TSI-2.42(1.6); J- NM; DFT- Several months</td>
<td>Knee extensors</td>
<td>Freq = 20-30 Hz PW = 0.3 ms SI = NM RT = NM</td>
<td>NM</td>
<td>Walker, parallel bars or standing frame; Surface</td>
<td>~15 min- ~120 min</td>
<td>Arm engaged</td>
</tr>
<tr>
<td>Fujita et al. [40]; Japan 56%</td>
<td>2- T7 &amp; T8 Age-24(0) TSI-28&amp;3; J-NM; DFT- Several months</td>
<td>Vastus muscles and Femoral nerve trunk</td>
<td>Freq =20Hz PW = 0.2 ms SI = 15 V RT = NM</td>
<td>AP</td>
<td>Parallel bars; Percutaneous intramuscular</td>
<td>30 min</td>
<td>Arm engaged</td>
</tr>
<tr>
<td>Uhlir et al. [44]; USA 56%</td>
<td>4- T6-T4, Age-43.1(6.8) y, TSI-8-20 y; J- NM; DFT- NM</td>
<td>For implanted: (i) Vastus lateralis, vastus medialis or both and (ii) non-selective recruitment of four head of quadriceps For intramuscular: gluteus maximus, adductor magnus and hamstrings For surface: erector spinae</td>
<td>Hip extensor: Freq =20Hz PW = 0.15 ms SI = 20 mA RT = NM Erector spinae: Freq =20Hz PW =0.25 ms SI = 100 mA RT = NM</td>
<td>AP</td>
<td>Instrumented parallel bars; Implanted intramuscular and surface</td>
<td>NM</td>
<td>Arm engaged</td>
</tr>
<tr>
<td>Authors; country; study quality</td>
<td>Participants</td>
<td>Stimulated muscle</td>
<td>Stimulation parameters</td>
<td>DOF/ Plane</td>
<td>Standing modality/Bracing; Stimulation type</td>
<td>Duration Mean (SD)</td>
<td>Outcomes</td>
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<tr>
<td>Fisher et al. [32]; USA 56%</td>
<td>1-T6; Age- 53 yrs.; TSI-7; J-NM; DFT- 16wks</td>
<td>Erector spineae, semimembranosus, glutaeus maximum, vastus lateralis femoral nerves, posterior adductor magnus</td>
<td>Freq = 16Hz PW = 0.2 ms SI = 20 mA RT = NM</td>
<td>NM</td>
<td>Parallel bars; Implanted</td>
<td>Up to ~13 min</td>
<td>Arm engaged</td>
</tr>
<tr>
<td>Harkema et al. [43]; USA, Russia and Italy 56%</td>
<td>1-C7-T6; Age- 23 yrs.; TSI- 3.4 yrs.; J-NM; DFT- 80 sessions (~ 54 min per session)</td>
<td>Exposed dura’s midline</td>
<td>Freq = 15Hz PW = 0.21 or 0.45 ms SI = 8 V RT = NM</td>
<td>AP</td>
<td>Vertical and horizontal bars; Implanted for epidural stimulation</td>
<td>4.25 min</td>
<td>Arm engaged</td>
</tr>
<tr>
<td>Triolo et al. [42]; USA 56%</td>
<td>1-C6-T9; Age- NM yrs.; TSI- 6 yrs.; J-NM yrs.; DFT- 20wks</td>
<td>“L1-2 spinal roots for erector spineae activation to extend trunk, motor points on the surfaces of bilateral vastus lateralis for knee extension and glutaeus maximus and semimembranosus for hip extension”</td>
<td>Freq = 1-50Hz PW = 0.21 or 0.45 ms SI= 2, 8, 14, 20 mA RT = NM</td>
<td>NM</td>
<td>Walker, standing frame and parallel bars; Implanted</td>
<td>At discharge, 12.75(8.55) days of training resulted in 0.66(0.73) hrs of standing; and at 1 yr. follow-up 2.25(5.19) hrs of standing was recorded in 12 participants</td>
<td>Arm engaged</td>
</tr>
<tr>
<td>Rejc et al. [37]; USA 50%</td>
<td>4-C7-T4; Age- 27(3.7) yrs.; TSI-3(0.8) yrs.; J-NM yrs.; DFT- 80 sessions (5 sessions of 60 min per week)</td>
<td>Implantation at T11-L1 (vertebral level) over L1-S1 (the spinal cord segments) and at lumbosacral enlargement</td>
<td>Freq = 25 - 60Hz PW = NM SI = 1-9 V RT = NM</td>
<td>AP</td>
<td>Horizontal bars and standing frame for hip support; Implanted for epidural stimulation</td>
<td>≤ 60 min</td>
<td>Arm engaged</td>
</tr>
<tr>
<td>Rejc et al. [38]; USA 56%</td>
<td>4-C7-T4; Age- 27(3.7) yrs.; TSI-3(0.8) yrs.; J-NM yrs.; DFT- 81 sessions (5 sessions of 60 min per week)</td>
<td>Implantation at T11-L1 (vertebral level) over L1-S1 (the spinal cord segments) and at lumbosacral enlargement</td>
<td>Freq = 25 Hz PW = NM SI = 3.0 (1.2) V RT = NM</td>
<td>AP</td>
<td>Standing frame; Implanted for lumbosacral spinal cord epidural stimulation</td>
<td>≤ 63 min</td>
<td>Arm engaged and extra hip support for 2 participants</td>
</tr>
</tbody>
</table>

Abbreviations: Para – Paraplejics, AP – Antero-posterior plane (Sagittal axis), ML – Medio-lateral, J – Ankle joint moment – used to analyse postural response or ankle stiffness, PF – Plantarflexors, DOF – Degree of freedom – this describes the dexterity of a model, KAFO – Knee ankle foot orthosis, Freq- frequency, PW- pulse width, RT- ramping time, SI- stimulation intensity in amplitude or voltage, NM - Not mentioned, NA – Not applicable, Arm engaged – the upper limbs are mainly used for balancing and stabilization of the standing posture, ROJM – range of joint movement, Study quality is based on D&B methodological quality checklist [21].
<table>
<thead>
<tr>
<th>Authors; country; study quality</th>
<th>Participants</th>
<th>Controller; Feedback Mechanism; Stimulated Muscle</th>
<th>Stimulation parameters</th>
<th>DOF/ Plane</th>
<th>Standing modality or bracing; Stimulation type</th>
<th>Duration Mean (SD)</th>
<th>Outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ewins et al. [31]: UK 44%</td>
<td>Several Midthoracic, Age- NM, TSI- NM; J-NM; DFT- NM; 3-5 years, TSI- NM</td>
<td>PID; Knee angle; Quadriceps muscle</td>
<td>Freq = NM PW = 0.35 ms SI = NM RT = NM</td>
<td>AP</td>
<td>KAF and standing frame; Surface</td>
<td>10 min</td>
<td>Arm engaged</td>
</tr>
<tr>
<td>Mulder et al. [54]: The Netherlands 56%</td>
<td>1-5 T5-T7, Age- 20-29y, TSI- NM; J-NM; DFT- ≥ 18mnths</td>
<td>Finite state controller; Knee angle; Knee extensor muscles</td>
<td>Freq = 20 Hz PW = 0.3 ms SI = 0-100 mA RT = 10 s up and 10 s down</td>
<td>AP</td>
<td>Frame; Surface</td>
<td>≤ 10 min</td>
<td>Arm engaged</td>
</tr>
<tr>
<td>Munih et al. [51]: Slovenia, UK and Germany 56%</td>
<td>1-T5, Age- 35y, TSI- 13y; J-5 Kg²; FR- NM; 1-10, Age; 23, DFT- March 1994- May 1996</td>
<td>Nested-loop LQG controllers; Ankle angle Ankle angle; PF</td>
<td>Freq = NM PW = 0.05 ms SI = NM RT = NM</td>
<td>AP</td>
<td>Wobbler; Surface</td>
<td>Up to 60 secs</td>
<td>Arm immobile</td>
</tr>
<tr>
<td>Davis et al. [55]: USA, Canada and Australia 56%</td>
<td>1-10, Age-23, TSI- NM; J-NM; DFT- March 1994- May 1996</td>
<td>Rule based controller; Knee angle; Quadriceps and gluteal muscles</td>
<td>Freq = 20-50Hz PW = 0.5 ms SI = 0.4-3 mA RT = NM</td>
<td>AP</td>
<td>Andrews anterior AFO; Implanted</td>
<td>30-60 min</td>
<td>One arm free standing</td>
</tr>
<tr>
<td>Davis et al. [9]: USA, Canada and Australia 56%</td>
<td>2-10, Age-30&amp;36 y, TSI- 18y; J-NM; DFT- 1.5y</td>
<td>Microcontroller; Knee angle Quadriceps and gluteal muscles</td>
<td>Freq = 20-50Hz PW = 0.05 ms SI = 0.4-3 mA RT = NM and Freq = 600Hz PW = 0.025-0.5 ms SI = 6-8 mA RT = NM</td>
<td>AP</td>
<td>Andrews anterior AFO and standing frame; Surface and Implanted</td>
<td>30-70 min</td>
<td>One arm free standing</td>
</tr>
<tr>
<td>Davis et al. [27]: USA 63%</td>
<td>12- C6-T12 Age &gt; 18 y, TSI- &gt; 18 m; J-NA; DFT- ≥ 16 wks</td>
<td>NM; NM; Vastus lateralis, hip extensors and lumbar erector spinae PID; Ankle angle</td>
<td>Freq = NM PW = 600 Hz SI = 0.025-0.5 ms RT = 6-8 mA</td>
<td>NM</td>
<td>Walker; Implanted</td>
<td>3-40 min</td>
<td>Arm free- 5 para; Arm engage- Others</td>
</tr>
<tr>
<td>Jaime et al. [12]: UK, Denmark Germany &amp; Slovenia 56%</td>
<td>12-17y, Age- 38y, TSI- 8y; J ≤ 10Nm/deg; DFT- NM</td>
<td>H∞; Ankle moment &amp;Inclination angle; PF, DF, anterior tibialis and gastrocnemius</td>
<td>Freq = 20Hz PW = 0.05 -0.5 ms SI = 60 mA RT = 5 s</td>
<td>AP</td>
<td>MRF; Surface</td>
<td>35-42 sec</td>
<td>Arm engaged</td>
</tr>
<tr>
<td>Gollee et al. [28]: UK 63%</td>
<td>12-17y, Age-44y TSI- 4y; J=100Nms²; DFT- 12wks</td>
<td>NM</td>
<td>Freq = 20Hz PW = 0.2 ms SI = 120 mA RT = 5 s</td>
<td>AP</td>
<td>Body brace and Wobbler; Surface</td>
<td>7 min</td>
<td>Arm free</td>
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<tr>
<td>Authors; country; study quality</td>
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<td>Controller; Feedback Mechanism; Stimulated Muscle</td>
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<tr>
<td>Mihelj and Munih, [53]; Slovenia 56%</td>
<td>1-T6 Age-NM; TSI-9mths; J- NM; DFT-1mth &amp; 4-T6 Age-54 (10) TSI-9 (5); J- NM; DFT-</td>
<td>PD and double inverted pendulum structure model; Ankle angle; Coactivation of DF and PF</td>
<td>Freq = 20 Hz PW = NM SI = NM RT = NM</td>
<td>AP &amp;ML</td>
<td>MRF; Surface</td>
<td>3 min</td>
<td>Arm engaged</td>
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<tr>
<td></td>
<td>&amp;ML</td>
<td>Four miniaturised motion sensors for kinematic feedback</td>
<td>Hand-controlled: stimulation amplitude (SA) in steps of 10 mA Aut-A: 10 mA step increase for knee angle ($\theta$) &gt; 10 deg, for $\theta$ between 5-10 deg SA remained fixed, for $\theta$ &lt; 5 deg SA ramped down rate = 2.5 mA/s $^{-1}$ Aut-B: Identical to Aut A but with SA's decrements and increments rates.</td>
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<tr>
<td>Nataraj et al. [33] USA 53%</td>
<td>1-T4 Age-54 TSI- NM; J- NM; DFT- NM</td>
<td>ANN driven by proportional gain-modulated feedback; Centre of mass acceleration; Gastrocnemius/Soleus, Tibialis anterior, Quadriceps, Semimembranosus/Hamstrings, Posterior adductor magnus, Gluteus maximus and medius, and erector spinae</td>
<td>Freq = 20 Hz PW = NM SI Implanted: 2 mA for quadriceps and erector spinae; 20 mA for other muscles Surface: 100 mA RT = NM</td>
<td>AP &amp;ML</td>
<td>Harness and standing support device; Surface and Implanted</td>
<td>1-2 hrs</td>
<td>Arm engaged</td>
</tr>
</tbody>
</table>

Abbreviations: Controller – Control algorithm, PID – Proportional-integral-derivative, AP – Antero-posterior plane (Sagittal axis/plane), ML– Medio-lateral (coronal axis) plane, KAFO – Knee ankle foot orthoses, $J$ – used to analyze postural response or ankle stiffness, PF – Plantarflexors, DF – Dorsiflexors, DOF – Degree of freedom — describes the dexterity of a model, Wobbler — Modelled as an ideal single-link inverted pendulum, MRF – Multi-purpose rehabilitation frame/ mechanical rotating frame, $m$ – months, Para – Paraplegics, NM – Not mentioned, NA – Not applicable, Freq- frequency, PW- pulse width, RT- ramping time, SI- stimulation intensity in amplitude or voltage. Note that gastrocnemius muscle stimulation was used for plantar flexion and the tibialis anterior muscle for dorsiflexion, Study quality is based on D&B methodological quality scale [21].
### Table 3
Characteristics of the included studies on arm free FES-supported standing with voluntary upper extremities balancing.

<table>
<thead>
<tr>
<th>Authors; country; study quality</th>
<th>Participant Mean (SD) yrs.; Duration of FES training (DFT)</th>
<th>Controller; Feedback Mechanism; Stimulated Muscle</th>
<th>Stimulation parameter</th>
<th>DOF/Plane</th>
<th>Standing Modality/Bracing; Stimulation type</th>
<th>Duration Mean (SD)</th>
<th>Outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abbas et al. [34]; USA 53%</td>
<td>2-T7&amp;8, Age-32&amp;42y, TSI- 3 &amp; 5y; J- NM; DFT- 7mth and 4y</td>
<td>PID: Coronal plane hip angle; Quadriceps vasti, gluteus maximus, gluteus medius and adductor magnus and erector spinae</td>
<td>Freq = NA PW = NM SI = 20 mA RT = NM</td>
<td>ML</td>
<td>Standing frame; Implanted and surface</td>
<td>NM</td>
<td>The reduction in RMS error, steady-state error and compliance are 41%, 52% and 22%, respectively. Arm engaged Arm free</td>
</tr>
<tr>
<td>Hunt et al. [29]; UK 63%</td>
<td>1-T7/8, Age- 44y, TSI- 4y; J - 8 &amp; 10 Nm/deg; DFT-12 mths</td>
<td>Single linear controller; Ankle angle; Midline of soleus and tibialis anterior</td>
<td>Freq = 20 Hz PW = NM SI = 120 mA RT = NM</td>
<td>AP</td>
<td>Wobbler; Surface</td>
<td>NM</td>
<td>Arm free</td>
</tr>
<tr>
<td>Kobravi and Erfanian, [58]; Iran 56%</td>
<td>3-T6/7, T7 and T7/8, Age-29.3(4.2) y, TSI- 4.7,13y; J- NM; DFT- 0.5,0.5&amp;85y</td>
<td>Adaptive fuzzy robust control; Ankle angle; DF and PF</td>
<td>Freq = 25 Hz PW = 0-0.7 ms SI= For flexor muscle 40, 70, and 32 mA For extensor muscle 32, 80 and 35 mA RT = NM</td>
<td>AP</td>
<td>Body brace; Surface</td>
<td>5.67- 11.67 min</td>
<td>Arm free</td>
</tr>
<tr>
<td>Audu et al. [35]; USA 53%</td>
<td>2-T4 &amp; T5/T6 Age- 60&amp;61, TSI- NM; J- NM; DFT- ≤ 5y</td>
<td>PID: Center of pressure; Hip extensors, hip abductors, hip flexors, hip adductors, knee extensors, ankle plantar/ and dorsiflexors, and trunk extensors, back extensors,</td>
<td>Participant 1 Freq = 20 Hz PW = 0-0.25 ms SI = 100 mA for surface stimulation and 0-20 mA for implanted stimulation RT = NM Participant 2 Freq = 20 Hz PW = 0-0.25 ms SI = 0-20 mA RT = NM</td>
<td>AP &amp;ML</td>
<td>Walker; Implanted and surface</td>
<td>NM'</td>
<td>Arm engaged</td>
</tr>
</tbody>
</table>

Abbreviations: PID – Proportional-integral-derivative, DOF – Degree of freedom — describes the dexterity of a model, J – used to analyze postural response or ankle stiffness, COP – Centre of Pressure, AP – Antero-posterior plane (Sagittal axis), ML – Medio-lateral (Coronal/frontal axis), NM – Not mentioned, Wobbler – Modelled as an ideal single-link inverted pendulum, DF – Dorsiflexor, PF – Planterflexor, MRF – Multipurpose Rehabilitation Frame/ Mechanical Rotating Frame, LQG – Linear Quadratic Gaussian, Study quality is based on D&B methodological quality scale [21].
Kralj and colleagues [30] originally demonstrated posture switching that could prolong FES standing in paraplegia. The authors showed that a cyclic stimulation pattern of 10–20 s (on/off) duty cycle promoted a longer standing duration [30]. Specifically, they noted that standing with different postures allowed neuromuscular stimulation of only the muscles necessary to sustain upright stance at that posture, through a cyclic pattern of muscle activation. This approach was designed to allow a particular muscle some period of recovery during stimulation of the other muscles. A variant of this approach to FES standing was promoted by Bajd and co-workers [7]. They recommended the use of transcutaneous stimulation of the knee extensors in combination with “compliant shoes” (to enhance the frictional force between the ground and the feet to improve postural stability) to prolong the FES standing duration. Also, Fujita and colleagues [40], had used this approach with thoracic-level spinally injured persons with percutaneous FES electrodes. Similarly, Pournezam et al. [41], recommended cyclic stimulation of multiple heads of major muscles involved in standing. Their method was implemented in combination with an orthosis [41] (i.e. a “hybrid system”), whereby the orthosis was meant to augment the outcome of electrically stimulated muscle contractions. These studies adopted an external mechanism to biomechanically stabilize the lower limbs and thus the body posture, passively. To assess the long-term effect of an implanted standing stimulation device, Triolo and colleagues [42], reported the “longitudinal performance” of the device following its one year of home use to facilitate standing in persons with low cervical or thoracic level injuries. Their study revealed no significant different in standing duration between initial discharge and approximately one-year follow-up period. In their effort to improve the upright standing stability, Harkema and co-workers [43], originally demonstrated the use of epidural spinal cord stimulation in combination with “activity-based training” to facilitate standing in one person with paraplegia. This success has also been effectively demonstrated in four persons with paraplegia [37,38]. Collectively, these studies revealed the viability of epidural stimulation for arm-support upright standing restoration, especially in persons with paraplegia.

In general, paraplegics and some persons with low-level tetraplegia have benefited from an open-loop FES standing strat-
ergy because of its easier and faster” setup. However, a low quality of standing and a limited standing duration has been widely reported using this approach. This is due to the fixed stimulation sequence and the inherent muscle fatigue associated with this method, as well as postural support or control by upper extremities [39]. Additionally, in this approach to standing, there is usually no special consideration for ankle stabilization and stiffness except by using shoes or walkers. Thus, this standing strategy is not very useful for functional activities [12]. In an isolated extended standing trial using posture switching [30], the meticulous requirement of a good truncal strength and joint range of motion [30], which are often absent in most potential users, have stimulated research interests in the development of improved alternative modalities in recent years. Although the open-loop control of FES standing has limited benefits, it is still widely used in many clinics and centres for therapeutic gains. However, to realize the full benefits of an upright stance, a closed-loop FES-supported standing strategy has been recommended [18].

3.4. Closed-loop FES-supported standing methods

To improve the quality and duration of the open-loop standing strategy, automatic modulation of electrical stimulation parameters [31] and selective recruitment of the involved muscle’s motor units [45] have been trialled. This practice reduces the human intervention in the control of upright stance, whereby the modulation of the stimulation parameters are titrated based on the muscle response feedback signals derived from biopotential signals of muscle origin [46]. These type of signals have gained recent popularity in the implementation of a closed-loop FES-supported standing, whereby the muscle stimulation strategy has been automated based on the lower limb neuromuscular information and changes in joint position or angle [18]. Other than the crucial need for reliable sensors to acquire these signals, a closed-loop system requires efficient control algorithms for its best implementation. For example, the proportional-integral-derivative (PID) feedback controller titrates the neuro-stimulation characteristics (current or voltage) [31]. PID computes the difference, termed ‘error value’, between a desired value/output and the current or instantaneous value which it corrects using PID-driven feedback [47]

Also, a general-purpose microcontroller, which is a special case of PID, has equally been implemented in closed-loop FES systems. For an improved performance, particularly for its parameter tuning [48]. PID implementation on the H∞ theory has also been reported in closed-loop FES systems [48, 49]. However, the limitations imposed by the complication of sensor fixation on the body for capturing neuromuscular information, joint stabilization during standing [9, 50], the complexity of the control algorithms and hardware limitations have continued to draw research attention for improvement (and simplification) of this type of FES standing strategy. A detailed discussion on this mode of standing with specific emphasis on the major implemented control strategies is described in Table 2.

3.4.1. Arm free standing

To realize a functional stance, whereby arms are available for object manipulation in order to derive the full benefits of upright stance [10], Jaeger [36] originally developed a theoretical model of an arm free standing (i.e., “single link inverted pendulum model”) with only one degree of freedom at the ankle joint. The model was implemented through a simple Proportional-Derivative (PD) closed-loop FES stimulation of calf muscles and dorsiflexors [36]. Subsequently, Munih and co-authors [51] reported the experimental application, based on the advancement of this controller, to implement an arm free standing whereby only the plantarfлексors were stimulated with the upper body braced for a balanced standing. In their study, the postural control mainly relied on nested-loop Linear Quadratic Gaussian FES controller [51]. Therefore, a practical implementation of an artificial postural control requirement is beyond the scope of PD controller, since the measurement of the body inclination angle typically introduced noise into the PD-based feedback loop [30], Davis et al. [39], presented the hybrid application of FES and Andrews Ankle-Foot Orthosis to promote a prolonged standing duration. With the use of a microcontroller for the stimulation parameter modulation, the authors demonstrated modest standing duration of about 30–70 min with partial availability of the arm for object manipulation.

Essentially, arm free standing demands that the ankle stiffness is stabilized and kept at approximately “10 Nm.deg⁻¹” [12, 29, 52]. The ankle stiffness could be sufficiently controlled by FES depending on the muscle strength around the joint [29]. Nevertheless, to improve the accuracy of such control and due to the inherent muscle fatigue associated with the FES-evoked contractions, researchers [12] have also recommended the use of an hydraulic actuator for the ankle stiffness control. Unfortunately, due to the issue of acceptable cosmosis, especially for applications in daily use, and impracticability for implantation, the conventional hydraulic actuator has a limited usage for ankle stiffness control [12]. Therefore, an FES system has been consistently investigated as a flexible and viable ankle stiffness control mechanism with or without upper body contribution [12, 53]. Another important inference that could be drawn from the literature is that the integration of residual sensorimotor and voluntary upper body with the FES control of paralyzed lower body muscle is required to stabilize the standing posture. This is needed to promote the arm availability for object manipulation. However, poor thoraco–lumbar neuromuscular control may preclude arms-free standing even with the deployment of available technologies [12]. Although improved standing quality has been shown with the deployment of innovative standing strategies for arms–free standing techniques, the reported duration of stance could be considered of only experimental interest with a limited clinical significance. These limitations have highlighted the need for a better method to extend the duration of FES-supported arm free standing.

3.4.2. Arm free standing with voluntary upper extremity balancing

Arm free standing with voluntary upper extremity balancing is an improved functional mode of arms-free standing. It involves the integration of neurologically intact upper body voluntary musculature, in persons with a good thoraco–lumbar strength, with the artificial activation of the poorly innervated lower body muscles to prolong upright stance [52]. Matjačić and Bajd [57] originally showed the feasibility of this strategy of upright stance and balancing for paraplegics with retained trunk muscles. However, a stable stance, but of limited duration in the range of 6–12 minutes, could only be sustained using this approach. Also, it was reported that the method was limited [11] to participants with neurological lesions between T4 and T12 with a good control of upper extremities and without medical conditions that may inadvertently interfere with FES-supported standing. This method promoted a balanced support during arms-free standing and was implemented with the integration of upper body voluntary control with FES control of the lower body [28].

The effective and robust control of upright standing stability in individuals with SCI is summarily based on the biomechanical representation that the upright human body represents a double-link inverted pendulum, whereby the trunk is represented by the upper link – under voluntary control at the hip-joint. The legs are assumed to be the lower link that can rotate at the ankle joint – controlled by the artificial electrical stimulation [28]. The ankle stiffness has been normally controlled by the electrical stimulation whereby the
upper “able” body could move freely [12]. In this case, the knees are locked, either by an arrangement of a mechanical bracing or by electrical stimulation of the thigh muscles [28].

Simple PID may have limited application in practical FES-supported standing as its derivative action might amplify high-frequency system dynamics and lead to system’s instability [39]. However, Audu and colleagues [35] implemented a modified version of the conventional PID controller and showed that such controllers not only have the potential of prolonging standing duration, but could also improve the quality of standing for balance and manoeuvring purposes.

Therefore, there is increased research interest in the implementation of a closed-loop FES for controlling upright stance. This mode of standing has been shown to potentially promote a prolonged standing duration because; (i) the stimulation pattern is not pre-determined, but rather based on the muscle response’s modulation of stimulation parameters as revealed by the state of the musculature in real-time, (ii) it promotes independence during FES-supported standing, and, (iii) the facilitation of an optimal coordination and integration of the upper body with the upright FES-supported standing of the denervated lower body are equally vital [39]. The postural sway, especially in the Medio-Lateral, – which could be used to quantify the stability of standing as well as the control’s model dexterity, was reported in few studies [33–35,59]. Issues of sensor reliability and control models in the face of intermittent muscle spasms, spasticity, muscle paresis, rapid muscle fatigue and other biological sequelae after SCI continue to impede the growth of this strategy.

Within the context of the studies reviewed herein and in comparison with the open-loop approaches to FES-supported standing, closed-loop FES-supported standing duration was not necessarily or significantly longer, but the standing quality [30] was better particularly with the functional application of upper extremities for maneuvering and resistance to external perturbations. Table 4 summarizes the performance of all included studies pertaining to the main objectives of assessing the study participants’ standing duration and stability (Table 5).

4. Discussion

There is a consensus that prolonged FES-evoked standing after spinal cord injury has the potential to confer to the user some health benefits and arguably promote an improved quality of life [36,53]. The built environment is predominantly constructed for bipedal humans, with steps, ramps, kerbs and enclosures suitable for upright gait. These barriers can be significant limitations for wheelchair users, so if some degree of standing can be regained via FES activated muscle contractions, then there may be significant benefits accruing to these individuals. Based on the available scientific evidence, some techniques for prolonged FES-supported standing, from rigorous experimental trials, have been described in the present study. Many of these strategies for upright stance have not been introduced into routine clinical practice, yet hold potential and are amenable to further improvements. For example, no studies could be located in the available literature referencing a widely-accepted instrument for grading the quality of functional upright stance. Although open-loop FES-supported standing remains fairly common, its impact on health promotion has been limited as the upper limbs are still required to maintain postural stability. Closed-loop FES-supported standing remains at a rudimentary stage and is complicated by inherent biological variability after SCI. Furthermore, it is not only in early experimental deployment, but also mainly exists in a few advanced laboratories. However, the potential of closed-loop FES-supported standing has somewhat outperformed that of open-loop controlled FES based on the functional limitations of the former. In some studies, closed-loop approaches have been reported to have addressed the inherent problems of prolonged FES–supported standing, but most of those studies have failed to report how such limitations [60] affected functional standing test such as often requiring dexterity in object.

### Table 4

Summary of all included studies.

<table>
<thead>
<tr>
<th>Study</th>
<th>No of subjects</th>
<th>Range of Standing time (min)</th>
<th>Balance / Stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Included studies on open-loop control of FES-supported standing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kralj et al., 1986</td>
<td>&gt;3</td>
<td>≤ 300</td>
<td>AP</td>
</tr>
<tr>
<td>Jaeger et al., 1989</td>
<td>21</td>
<td>1-30</td>
<td>AP</td>
</tr>
<tr>
<td>Bajd et al., 1999</td>
<td>5</td>
<td>15-120</td>
<td>NM</td>
</tr>
<tr>
<td>Fujita et al., 1999</td>
<td>2</td>
<td>30</td>
<td>AP</td>
</tr>
<tr>
<td>Uhlir et al., 2000</td>
<td>4</td>
<td>∼13</td>
<td>NM</td>
</tr>
<tr>
<td>Fisher et al., 2008</td>
<td>1</td>
<td>4.25</td>
<td>AP</td>
</tr>
<tr>
<td>Harkema et al., 2011</td>
<td>15</td>
<td>0.66 &amp; 2.25*</td>
<td>NM</td>
</tr>
<tr>
<td>Rej et al., 2015</td>
<td>4</td>
<td>≤ 60*</td>
<td>AP</td>
</tr>
<tr>
<td>Rej et al., 2017</td>
<td>4</td>
<td>≤ 63*</td>
<td>AP</td>
</tr>
<tr>
<td>Included studies on partial arm free FES-supported standing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ewins et al., 1988</td>
<td>Several</td>
<td>10</td>
<td>AP</td>
</tr>
<tr>
<td>Mulder et al., 1992</td>
<td>3</td>
<td>≤ 10</td>
<td>AP</td>
</tr>
<tr>
<td>Munihi et al., 1997</td>
<td>1</td>
<td>≤ 1</td>
<td>AP</td>
</tr>
<tr>
<td>Davis et al., 1997</td>
<td>1</td>
<td>30-60</td>
<td>AP</td>
</tr>
<tr>
<td>Davis et al., 1999</td>
<td>2</td>
<td>30-70</td>
<td>AP</td>
</tr>
<tr>
<td>Davis et al., 2001</td>
<td>12</td>
<td>3-40</td>
<td>NM</td>
</tr>
<tr>
<td>Jaime et al., 2002</td>
<td>1</td>
<td>&lt; 1</td>
<td>AP</td>
</tr>
<tr>
<td>Golley et al., 2001</td>
<td>1</td>
<td>3</td>
<td>AP</td>
</tr>
<tr>
<td>Mitcheh and Munich, 2004</td>
<td>1</td>
<td>7</td>
<td>AP</td>
</tr>
<tr>
<td>Braz et al., 2009</td>
<td>4</td>
<td>∼ 7-20</td>
<td>AP &amp; ML</td>
</tr>
<tr>
<td>Nataraj et al., 2013</td>
<td>1</td>
<td>60-120</td>
<td>AP &amp; ML</td>
</tr>
<tr>
<td>Included studies on arm free FES-supported standing with voluntary upper extremities balancing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Abbas et al., 1991</td>
<td>2</td>
<td>–</td>
<td>ML</td>
</tr>
<tr>
<td>Hunt et al., 2001</td>
<td>1</td>
<td>–</td>
<td>AP</td>
</tr>
<tr>
<td>Kobravi and Erfanian, 2012</td>
<td>3</td>
<td>5.67-11.67</td>
<td>AP</td>
</tr>
<tr>
<td>Audu et al., 2017</td>
<td>2</td>
<td>–</td>
<td>AP &amp; ML</td>
</tr>
<tr>
<td>Total</td>
<td>&gt; 95</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: AP – Antero-posterior plane (Sagittal axis), ML – Medio-lateral (Coronal/frontal axis), NM – Not mentioned, *Mean of total standing duration at discharge and at 1 year follow-up evaluation respectively, Mean of total standing duration.
manipulation and lifting [61]. If it were available, this information could be used to grade the clinical efficacy of any “functional gains” claimed during closed-loop FES-supported standing.

Furthermore, most studies investigated the degree of freedom (DOF) of standing in AP plane – which is the greatest direction for postural instability [36]. Yet, for manoeuvring, other directions to improve DOF have not been sufficiently investigated. Depending on the number of DOF and the truncal strength, better postural stability during upright stance could be attained by stimulating knee extensor muscles, gastrocnemius and tibialis anterior muscles, adductor magnus, erector spinae and glutei muscle groups, but such a multi-muscle approach would add increased complexity and processing time to any closed-loop FES system. It has also been highlighted that in order to improve stability and increase the range of motion, the stiffness of both the knee and ankle must be ensured [31]. That is why the feedback mechanisms, on which the feedback controller mainly relied are knee and/or ankle angles. Additionally, improved postural stability may be achieved with the stimulation of additional muscle groups (i.e. hip extensors) and/or by wearing special thoracoacumbular orthosis to reinforce hip stability. However, this method has drawbacks for standing since orthosis-stabilised hip flexion may warrant unnecessary arm support for standing stability [44]. In addition, some authors such as Munih and colleagues [51] have promoted the idea of planteflexors stimulation only and relied on the bracing of the upper body. This approach seemed to have been predominant in earlier standing strategies and used to prevent the unnecessary influence of the intact upper body neuromusculature [51].

The findings [34] in this review revealed limited success for the maintenance of upright stance and posture. The factors that often dictated the short duration and poor quality of standing other than the mode of stimulation were: (i) the degree of muscle conditioning, (ii) the extent of muscle atrophy or potency of post-acute care exercise, (iii) the level of injury and strength of the trunk musculature. Although these factors were not specifically investigated in relation to their influence on standing quality, future studies must address these knowledge gaps. Fundamental outcome measures to grade the ‘quality’ of standing was not reported in most articles, thus, we were unable to compare the outcome of the available closed-loop FES-supported standing strategies. Ultimately, human factors and not available technologies may limit standing duration in this population, but clearly further research is warranted if this is so. An interesting question is if “human factors” currently limit standing duration and quality, can future machine-learning approaches ever overcome these?

Further, the extant literature revealed different closed-loop control strategies and there is yet to be any widely accepted closed-loop control of FES supported standing method. Therefore, there is a need for a multidisciplinary research to link patients’ voluntary control of their remaining innervated musculature with artificial muscle activation and control systems for a wider application of the technology particularly in a routine clinical practice. For example, the ability to reliably quantify the muscle response to FES-evoked contractions prior to knee buckling [56], as an indication of knee extensor fatigue, has been recommended to prolong standing duration by modulating the stimulation parameter based on the information of the muscle instantaneous state during FES-evoked contractions. This is due primarily to the fact that most control strategies relied on using the variation in joint angle from its initial locked position to regulate standing posture [62]. FES users require high stimulation intensities, sometimes often more than necessary, to perform a standing challenge [63] being an antigravity task [36]. Although the high intensity stimulation amplitude is meant to generate stiffer leg during standing, it also promotes rapid muscle fatigue by occluding the blood supply to the leg musculature [63]. Regulation of the stimulation level for modest standing response warrants the application of an efficient control algorithm which may rely on the muscle activity as measured by muscle...
contraction signals. A realistic control algorithm that is free from over-simplification of the human musculature response is therefore clearly warranted.

FES-supported standing is most effectively applied to a certain population of SCI individuals, particularly those with “low tetraplegia (C5–C8) and thoracic level paraplegia (approximately T4–T11)” [64]. Furthermore, user’s musculoskeletal and joint (ankle and knee) range of motion have been shown to be a strong factor in determining the duration of FES standing. For “those with lesions at the high thoracic level, or above, generally, have poor truncal control and impaired upper extremity function and are not good candidates for lower extremity FES-supported standing” [64]. Otherwise, the whole standing task will be unrealistic and frustrating. Furthermore, in order to avoid frustration and subvert exercise-induced injury, Bajd and colleagues [7] have recommended inclusion criteria for FES standing in paraplegia to accommodate only candidates with: upper motor neuron lesion, no or modest joint contractures or spasm, no major skin problems, adequate upper extremity function and physiological status, and the qualified candidate should be motivated and cooperative. Moreover, FES-supported standing requires adequate muscle force or power, which could be achieved through muscle training/conditioning for partial reversal of muscle atrophy secondary to SCI [45,65].

On the stimulation type, the quality of standing with percutaneous or fully implanted stimulation electrodes tended to be higher compared to transcutaneous stimulation. Such quality has not been widely reported to be significantly translated to a longer FES-supported standing in the former, except by Nataraj et al. [31]. While selective recruitment of motor units, can be better achieved via implanted stimulation, and promotes more selective muscle responses [45], the available evidence is insufficient to arrive at a definitive conclusion on the mode of stimulation that should be promoted. This is evident because 12 out of twenty-five (48%) studies employed surface FES administration versus 8 (32%) that employed implanted stimulation while the remaining five (20%) used both the implanted and surface stimulation. The probable explanation for this observation is the ease of use and the non-invasive nature of skin surface in FES administration for standing.

Although there is a consensus that prolonged FES-supported standing is feasible, ensuring an upright and a prolonged posture by mimicking the normal/voluntary standing without compromising simplicity remain a daunting task. Based on the available evidence, the FES controlled of arms-free standing, where the voluntary upper extremity is used for postural balancing, may be the most promising strategy and this may be deemed worthy of further investigation for future development. This FES-supported standing approach appeared to reduce the voluntary upper-body support, and prolong standing duration without the need for external support/ortheses [66]. Among the most reported benefits of prolonged standing duration were: improvement of joint range of motion, improvement of physiological responses such as prevention of orthostatic hypotension and circulatory hypokinesis as well as improvement of cardiorespiratory and metabolic functions [67], and, preservation of muscle integrity and overall promotion of the quality of life [13].

4.1 Limitations

Interestingly, studies with strict adherence to the effective standing protocol have not reported any adverse effects of the standing tasks. Apart from the need for habituation prior to exposure to an FES-supported standing challenge, there is generally low or no incidence of exposing the musculature to damage or any related health risks. Therefore, the emerging strategies for FES-supported standing prolongation are promising. Although several controllers including dynamic, Neural Network based, PID, H∞ and finite state have been used to facilitate the prolongation of FES upright standing duration, there is still considerable limited clinical and home care applications [48]. While certain controllers such as Linear Quadratic (LQ) [68] were only described through modelling studies, their application for controlling standing in persons with SCI remain unexplored. Furthermore, there were some promising models that were not tested on spinal cord injured participants and, therefore, could not be accommodated within this systematic review. As objective criteria for FES-supported standing assessment is unavailable, the extent of generalization of the recommendations given in this review cannot be ascertained. Also, the scope of this review is limited to paraplegia and those with lower tetraplegia (C5–C8) for which the goal of FES-supported standing is a high priority and achievable for the activities of daily living.

5. Conclusion

This study presented scientific evidence of strategies to prolong FES-supported standing to promote the health of persons with paraplegia and those with low tetraplegia for functioning and participation. Within the limitation of the available evidence and emerging trends for modest FES-supported standing duration in these populations, it is pertinent to resolve the problems of an efficient muscle activation via the type of controller deployed, the stimulation parameters employed, and mechanism of postural control used. As the desired standing is that which is reliable and dexterous, such as facilitates reaching and object manipulation, refinement of protocol should consider those methods that could promote activation of many degrees of freedom during upright stance. Although none of the available standing methods has matured for routine clinical deployment, a closed-loop control of FES-supported standing with arms-free modality and voluntary upper extremity balancing is most promising. The implementation of this standing strategy has been made simpler [28,33,35,53,58] and potentially more beneficial for clinical use as suggested by Jaeger [36]. Therefore, findings from this review may impact clinical rehabilitation practice significantly with regards to the restoration of some muscle functions for muscle integrity preservation following a prolonged FES-supported standing duration. In future studies, RCT methodology and psychological approach should be adopted to holistically assess the effectiveness of each available and emerging method. This may further make evident the specific clinical benefits of prolonged standing duration.

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