Home FES: An Exploratory Review

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Abstract

This review of literature focuses on the multiple uses of Functional Electrical Stimulation (FES) and how this modality may be a valuable home-based therapy. Papers pertaining to home FES exercise were collected using the Web of Science, Google Scholar databases and collegial hints. In our opinion, the following statements summarize the results. FES may be used to induce health benefits in populations with paralysis, and in persons with musculoskeletal, cardiorespiratory and renal pathology. The EU Project Rise showed how FES could have a variety of encouraging outcomes for patients with denervated muscles following traumatic injuries. As suggested by recent literature, FES has proven to be a viable form of exercise for elderly individuals. Thus, Home FES may be an option for patients looking for an additional form of muscle and cardiopulmonary physical therapy.

Key Words: electrical stimulation; Home FES; spinal cord injury; osteoarthritis; cardiopulmonary and renal failure; elderly; muscle weakness; physical therapy.

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In 1961, Vladimir Liberson and colleagues designed a system to electrically stimulate the common peroneal nerve of a man with hemiparesis, enabling the foot to be lifted off the ground during gait when otherwise it would have dragged across the floor.[1] Indeed, if a degree of functional work is the outcome of the electrical stimulation (ES), the use of electricity to artificially activate sensory and motor nerves is known as functional electrical stimulation (FES).

In the context of spinal cord injury (SCI), it has been noted that exercise helps to reduce complications related to a sedentary lifestyle. Therefore, a FES system would allow the patient to easily adjust the type and location of their exercise on a daily basis.[2]

Home exercise using FES is an option which can help reduce the sequelae of diseases. Indeed, home FES, or “home-based (h-b) FES” as referred to by European teams looking at permanent denervated muscles,[3,4] lends itself as an exciting way for people suffering from various conditions to exercise their skeletal muscles.

While primarily used to enable those with paralysis to train, FES research has been extended with positive metabolic outcomes to persons suffering with chronic failures of heart,[5–7] lungs,[7,8] and kidneys,[7,9,10] and the elderly.[11] There has also been a large focus on the use of FES in populations with neurological diseases such as cerebral palsy, spinal cord injury, stroke and multiple sclerosis.[12]

Therefore, it would be wise to understand the potential of FES as a therapy in the home for other populations who may seek health benefits.

The home is an environment that differs markedly from a laboratory or clinical setting. Indeed, perceptions of this difference forms the basis for work performed by researchers at the University of Sydney. We previously published reviews on how compliance to prescribed home FES has been assessed across the literature. We concluded by making some recommendations for home-based FES exercise and for the compliance measurement methods.[13-15]

Reading this review of actual and potential clinical applications, we hope that the notion that FES is not an esoteric method of exercise for selected populations is convincing. Indeed, extending the use of home-based FES to elderly will tremendously increase its impact on the population at large.

Literature Retrieval

Papers pertaining to home FES exercise were collected using the Web of Science, Google Scholar databases and collegial hints. In tables 1 and 2 are summarized data from relevant papers, with information on populations utilizing ES or home-based FES.

State of the Art of Home FES

Neuromuscular Diseases

FES has characteristically been implemented in individuals with central nervous system (CNS) diseases such as spinal cord injury and cerebral palsy.[12] More generally, it has been known in the rehabilitation engineering sector for at least sixty years since Liberson's work.[1] In addition, for an even longer period of time FES has been ~~as~~ posited by authors such as Andrews,[16] who note FES use in an earlier patent by Charles Giaimo,[17] in the 1950s. The literature on FES in the home is a good reflection of the ability of FES to impart wanted benefits on individuals with neuromuscular diseases. In case studies of individuals with SCI for example, it has been demonstrated that a home FES cycling regime can increase the frequency of exercise performed by an individual, to a level much greater than that of the general population.[18,19]

In their case study, Dolbow & colleagues[18] argue that FES exercise is "feasible" on grounds of their participant having 93% compliance. The individual participated in FES cycling for nine weeks in the home. The authors also suggested that home FES cycling can help quell "barriers" to exercise by SCI patients.[2,18] As FES is capable of stimulating muscles that are otherwise not able to perform conactions, it is no surprise that home FES studies have elucidated positive effects of FES exercise for spinal cord injured subjects. Dolbow and colleagues (2012) reported that after a program of 3 sessions per week for 9 weeks, an individual showed an increase in lean mass, a decrease in percentage body fat and a decrease in seat pressures.[18] Increases in bone mineral density (BMD) and muscle volume have also been reported in a study of four children with SCI (two FES cycling protocol and two controls).[20] Subjects performed three 1-h sessions per week.

Moreover, encouraging results for a FES-cycling group have been reported for VO_2peak relative to a passive cycling group in a study of 30 children with SCI.[20] FES cycling in the home is thus appears capable of bestowing a range of encouraging metabolic outcomes on individuals with paralysis.

In spite of these results, it must be noted that the literature also reports a few examples of no metabolic improvements due to FES stimulation. In Johnston et al.'s study[21] for example there was no changes in VO2peak at 6 months in comparison with the baseline. The authors argue that "average percent change" was significantly different though when comparing the FES cycling with passive cycling.

In addition, some of the literature indicates no changes to lipids,[23] and minimal changes to BMD.[18,19] In light of such observations, it is apparent that improved metabolic results, due to FES training, for individuals with SCI show some inconsistent results, however the data is overwhelmingly promising. Individuals with stroke comprise another population which has been examined in the context of home FES exercise. Alon et al.[23] described a variety of improved outcomes to parameters such as spasticity, pain and lifting tests in their study looking at combined wrist/hand electrical stimulation and grasp training over a period of 5 wk. A similar study also showed several marked improvements of the same parameters.[24] In addition, some improvements in outcomes such as spasticity and movement have also been documented in a study of ten individuals with stroke using a Rehabilicare muscle stimulation system.[25] FES thus seems able to facilitate rehabilitation after stroke.

Musculoskeletal Diseases

Electrical stimulation is a useful technique in the sense that it may be used by individuals who cannot exercise, enabling them to exercise.[26] As such, it has far more uses not limited to populations with neuromuscular conditions, and has been examined by various researchers as a way of alleviating the sequelae of disease. Several groups have investigated electrical stimulation in patients suffering with osteoarthritis (OA) by various methodologies both experimental or following literature.[27–33]

Osteoarthritis is associated to a myriad of pathophysiological signs, including pain and, for joints with limited range of motion, unstability.[26] There are various goals that should be kept in mind when aiming to reduce the burden of disease with FES or by other means. Increasing muscle strength is the fundamental aim of OA treatments, to increase leg strength and prevent muscle wasting.[34] A characteristic aim of treatment in knee disorders, is to increase quadriceps strength.[35] Typically pain in the knee prevents use of the muscle, leading to its' weakness, as seen in work by Slemenda & colleagues.[36,37] Functionally this can lead to a range of biomechanical impairments, specifically preventing stair-walking.[38] Weak quadriceps muscles following OA and/or total knee arthroplasty (TKA) has been well-reported in the literature.[39,40] Through application of electricity to the quadriceps, various groups have reported attenuation in these marked deficits. When electrical stimulation was used in OA groups results included; quadriceps cross-sectional area,[39] comparable pain relief to an "education-only" regime,[28] and increased quadriceps strength when used with dedicated physiotherapy.[29] Indelibly the physiological benefits of FES may be harnessed in various times of the OA treatment spectrum. Avramidis et al. suggested that use of stimulation following a total knee arthroplasty may speed up the rehabilitation process.[3,41] However, another potential application of FES is pre-surgery, as Walls & colleagues proposed.[32] The authors investigated use of ES in a "prehabilitation" context, prior to total knee arthroplasty surgery. They noted that stimulation can increase isometric muscle strength, but this only commenced after a period of six weeks.[32]

Whether or not one performs electrical stimulation before or after surgery of course may require further investigation.[3] However, collectively these results suggest that FES is a useful therapy for muscle rehabilitation in the OA cohort. In addition, FES may be an ideal choice of therapy in this context, as it has been suggested that OA therapies are usually administered in the home.[3,41] In addition, home-based FES has been shown to reduce muscle spasms in equines and this conclusion can be easily transferred to the human population.[42] Symmetry of movement is important for pain and injury reduction and the use of FES has been also shown to improve multifidi symmetry when used bilaterally over the spine.[43] Finally, and perhaps most importantly, FES has been shown to improve mitochondria density and distribution which is an exciting benefit when evaluating the use of FES for muscle conditioning. [44]

FES Goal Setting Activities

The FES exercise may be carried out in a variety of modalities such as, cycling,[45] rowing,[46] or walking.[47] Recently there was great interest in motivating SCI patients to perform FES cycling by organising competitions among FES Cycling SCI athletes, such as the First Cybathlon Competition in 2016. This was achieved after a long training performed at home after careful instructions in clinics or outpatient services.[48]

Permanent Denervated Muscle and the EU Project Rise

Since the late 1980's, it was put forward that FES may be used for SCI patients whom have intact lower motor neurons.[12] On the other hand, the European Project RISE is an example of how patients with permanent denervated muscles may benefit from home-based FES protocol up to perform standing and in-place-stepping trainings.[3] Initially, there were several challenges to the implementation of FES for denervated muscles. Mayr and colleagues (2002) at the Medical University of Vienna discuss how FES devices at the time were unable to provide the appropriate stimulation required for permanently denervated muscle activation.[49] In particular, permanent denervation of skeletal muscles poses many challenges that are not seen in stimulation of normal "innervated" muscles.

The problems even worsen, when an increased amount of adipocytes and collagen replaces atrophing muscle tissue after years of persistent denervation.[3] Another important fact in stimulating permanently denervated muscle is that the FES stimulation parameters differ substantially from those for innervated muscles (e.g., those of thoracic level SCI). Denervated muscle that has not been activated for years requires a waveform hundreds of milliseconds longer than normal innervated muscle. Kern and colleagues implemented pulse widths in the range of 120-150ms in their study of 25 patients with "complete conus/cauda equina lesion".[3,4] Indeed, they found that after only three months of denervation, the functional and histopathological state of muscles differs substantially from normal innervated muscle. A likely explanation for the need of this unusually large pulse width is that there is poor excitability, and thus contractility, of muscle fibres when they are denervated for several months. Another important consideration is the lower or much lower excitability (dependent on the length of time from SCI) of denervated muscle as opposed to motor and sensory nerves.[3] Long-term denervated muscle fibers (typically after six-twelve month after motor denervation) have a low excitability (10-150 ms pulse width is required to initiate contraction), compared with nerves that have a much higher excitability (0.1 – 1 ms pulse width) at an equivalent stimulus amplitude.[3]The literature on the EU Project Rise offers insights into the use of FES for denervated muscle training in the home. Five main original results (some of them, unexpected) were obtained while training a group of complete SCI patients with permanent lower motor neuron denervation of leg muscles (i.e, complete and permanent *Conus and Cauda Equina* Syndrome).

These promising findings are:

1. *Time course of muscle atrophy*: Progression of muscle atrophy in complete denervated human muscles takes several years (five to ten years) to reach the final tage of muscle fibro-fatty degeneration. This is in contrast with the process in rodents, that was described to be from six to nine months.[3,4]
2. *Stimulation parameters required for long-term denervated muscles:* The permanently denervated muscle responds to electrical stimulation, but requires long bidirectional stimuli (5-10 ms if FES starts from three to six months of denervation, and to up to 150-300 ms if FES starts between two to six years post-SCI).[3,4]
3. *Contractility changes during two years of home FES:* Atrophying muscles were rescued by 2 years of home-based functional electrical stimulation (hbFES) when a purpose developed electrical stimulator,[50] now commercially available at the Company Schuhfried, Wien (Austria),[51] provided the needed high currents to large anatomically-shaped surface electrodes that need to completely cover the permanent denervated quadriceps muscles.[3,4] The progressive rehabilitation strategy may start with single twitch contractions during the first three to six months of hbFES. Then moves to sustained tetanic contractions when excitation/contraction improved, so that FES may be provided in train of impulses at 20 Hz. These changes in parameters are due to the recovered excitability/contractility of the long-term trained denervated muscle, usually occurring after three to six months of hbFES.[3,4]
4. *Functional outcomes of home stimulation:* Many trained SCI patients reached a stage of muscle recovery by hbFES that improved the contractile properties of the quadriceps muscles to a level that allowed them to stand

Table 1. *State of the Art: Home Electrical Stimulation Studies*

Condition	References
Stroke	• **Alon et al., 2003[23]** • **Alon & Ring, 2003[24]** • **Chan et al. 2015[66] (TENS)** • **Sullivan & Hedman, 2007[25] (arm hemiparesis)**
Foot drop	• **Prenton et al., 2014[67]**
Posterior tibial tendon dysfunction	• **Bek et al., 2012[68] [counter-example as argue for in-centre FES]**
Spinal cord injury, paraplegia, tetraplegia	• **Berry et al., 2008[69]** • **Berry et al., 2012[70]** • **Bremner et al., 1992[19]** • **Dolbow et al., 2012[2]** • **Dolbow et al., 2012[18]** • **Dolbow et al., 2012[19] (veterans)** • **Donaldson et al., 2000[71]** • **Johnston et al., 2008[20]** • **Johnston et al., 2009[21] (children);** • **Mödlin et al., 2005[72] (with quadriceps denervation);** • **Moynahan et al., 1996[73] (adolescents);** • **Sipski et al., 1993[74]**
Permanent muscle denervation and complete conus cauda syndrome	• **Kern, 1995[75]** • **Kern et al., 2009[76]** • **Kern et al., 2010[4]** • **Kern et al. 2010[3]** • **Kern, 2014[3]** • **Kern & Carraro, 2014[3]** • **Zanato et al., 2010[53]** • **Zanato et al., 2011[54]** • **Zanato et al., 2013[55]**
Multiple sclerosis	• **Coote et al., 2015[77]**
Knee osteoarthritis	• **Avramidis et al., 2011[78]** • **Beswick et al. 2019[41]** • **Bruce-Brand et al., 2012[39]** • **Burch et al., 2008[27]** • **Gaines et al., 2004[28]** • **Talbot et al., 2003[79] (elderly)** • **Stevens-Lapsley et al., 2012[30] (post-TKA)** • **Stevens-Lapsley et al., 2012[31] (post-TKA)** • **Walls et al., 2010[32] (pre-TKA)**

and perform steps-in-place training. Further, some SCI persons could walk up to 100-200 m.[3,4]

5. *CT and biopsy results:* The improvement in functional outcomes were correlated to the increased muscle mass of both quadriceps and hamstrings muscles documented by Muscle Color Computed Tomography Imaging.[3,4] In addition, after 2 years of FES training, the results of microscopic and ultramicroscopic analyses of the quadriceps muscles biopsied before and after two years of home-based FES training showed an improvement in muscle fiber size and ultrastructure, that fully explain the recovered contractility of the permanent denervated muscles.[3,4] Interestingly, it was also recently demonstrated that the skin exposed to two years of hbFES (to induce contractions of the denervated quadriceps muscles) showed an improvement in epidermis thickness.[52] In a similar fashion, the Italian branch of the RISE project (Rise2-Italy) also offers similar prospects. For example, in their case studies of leg denervated muscles, Zanato et al.[53] found that hyperaemia of muscle may be sustained upon cessation of electrical stimulation. Moreover, FES stimulation for six months has resulted in an increase in tibialis anterior thickness documented by ultrasound analyses.[54,55]

Table 2. *State of the Art: Home Electrical Stimulation Studies [Continued]*

Condition	References
Elderly Muscle Training	• Barberi et al., 2015[3] • Carraro et al., 2017[63] • Carraro et al., 2018[3] • Caulfield et al., 2013[11] (healthy) • Cvecka et al., 2015[3] • Hendling et al., 2013[80] • Kern et al., 2014[60] • Mangione et al., 2010[81] (post-hip fracture) • Mayr, 2015[3] • Protasi, 2015[3] • Sarabon et al., 2015[3] • Tezze et al., 2018[64] • Zampieri et al., 2015[81] • Zampieri et al., 2015[82] • Zampieri et al., 2016[62]
Chronic heart failure	• Harris et al., 2003[5] • Jones et al, 2016[7] • Soska et al., 2014[6]
Chronic obstructive pulmonary disease	• Neder et al., 2002[8] • Jones et al., 2016[7]
Chronic kidney failure	• Brüggemann et al., 2017[9] • Jones et al., 2016[7] • McGregor et al., 2018[10]
Cancer	• Coletti et al., 2016[3] • Hiroux et al., 20166[3] • Windholz et al., 2014[83]
Bilateral patellofemoral pain syndrome	• Bily et al., 2008[84] • Sajer, 2017[3]
Sciatic nerve injury	• Zanato et al., 2010[53] • Zanato et al., 2011[54] • Zanato et al., 2013[55]
Peripheral nerve lesion	• Rossato et al., 2009[85]
Spastic diplegic cerebral palsy	• Johnston & Wainwright, 2011[86]
Equine muscle training	• Schils & Turner, 2014[44] • Schils et al, 2015[42] • Isbell et al, 2017[43]

Other Diseases

The literature in Tables 1 and 2 also indicates that electrical stimulation has been used for cardiopulmonary conditions such as chronic obstructive pulmonary disease (COPD)[8] and chronic heart failure (CHF).[5,6] Neder et al.[8] for example, proposed that electrical stimulation can lead to user-specified alleviation of dyspnoea, as assessed by a questionnaire. In their study of NMES for heart failure, Harris et al.[5] showed that exercise parameters can increase with NMES comparable to standard cycling.

A similar result was obtained in another study that demonstrated addition of EMS, or EMS by itself, had no added benefit to changing oxygen uptake or power generation in comparison with standard "aerobic training".[6]

These studies offer initial insight into potential use of FES exercise in these populations, but to confirm those results further investigations are needed. On the other hand, recent literature provides strong evidence of the efficacy of FES (and hbFES) in the cases of "Intradialytic Neuromuscular Electrical Stimulation on Strength and Muscle Architecture in Patients suffering with Chronic Kidney Failure,[9,10,56] and many other chronic diseases.[7]

Anyhow, these studies illustrate some important concepts regarding the practical use and purpose of home-based

FES. Firstly, concomitant electrical stimulation and standard best practice may not yield added therapeutic benefits.[6] However, the fact that ES may be comparable with such best practice,[5] may suggest it is a way in which chronic heart failure patients can perform "useful" exercise. Harris et al.[5] highlighted that FES is particularly useful for use in populations where normal exercise may be difficult to perform, as it may be done so while individuals are "sedentary" or even bed-ridden. Further investigations into the added utility of FES over other forms of exercise in these populations is at least justified.

Aging

We list here some of the literature data that provide promising results on the effects of home FES in "normal" (that is, over 65 years persons without any, or at least stable, pharmacological therapy) aging persons.[57]

Heartened by the strong evidence of the efficacy of hbFES for recovery of denervated muscles in complete SCI persons (see above)[3,4] and of the value of a life-long amateur sport activity in delaying aging decay,[58,59] Helmut Kern and his group of Austrian and Italian collaborators, designed and implemented a series of trials demonstrating that: i) long-term high level exercise delays age-associated skeletal muscle decline[3,60-63] and ii) that home FES at least mimics volitional exercise in elderly persons.[64,65]

Conclusions

This review provide a general directive for those who are considering FES as an alternative form of training/rehabilitation for their patients. The European Project RISE has been a successful example of home based FES, that can be adapted for other populations in the home leading to physiological changes beneficial for patients. Together with the literature presented, this review showed that FES is not confined to treating those with neurological diseases, but offers potential in populations suffering with musculoskeletal, cardiopulmonary and kidney pathologies and in sedentary or bed-ridden elderly. There is still much more work required to implement electrical stimulation in home, but premises are heartening. In summary, this review shows that: i) home FES may be used to induce health benefits in populations with paralysis, and in persons with musculoskeletal, cardiorespiratory and renal pathology; ii) The EU Project Rise showed how FES can have a variety of encouraging outcomes for patients with permanent denervated muscles following traumatic injuries; iii) Recent literature suggests that FES is a viable form of exercise for elderly individuals. Thus, home FES may be a sensible option for patients looking for an additional form of cardiopulmonary and muscle training/rehabilitation.

List of acronyms

BMD – bone mineral density
CHF – chronic heart failure
CNS – central nervous system
COPD – chronic obstructive pulmonary disease
EMS – electrical muscle stimulation/ electromyostimulation
ES – electrical stimulation
FES – functional electrical stimulation
hbFES – home-based FES
NMES – neuromuscular electrical stimulation
OA – osteoarthritis
SCI – spinal cord injury
TKA – total knee arthroplasty
VO_2 (peak) – oxygen uptake (peak)

Authors contributions

MJT drafted the manuscript and was responsible for literature review and critical synthesis and analysis of literature, SS was responsible for review of the equine literature and assisted with reformatting and organisation of the work, AJR was the primary supervisor of related thesis work.

MJT is a former PhD student at the University of Sydney, Australia. He is currently a Researcher: Learning, Technology and Innovation at the University of Sydney Business School.

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Conflict of Interest

The authors have no conflicts to disclose.

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We confirm that we have read the Journal's position on issues involved in ethical publication and affirm that this report is consistent with those guidelines.

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