FES Cycling: Clinical Justification

A review of the literature across neurological conditions

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FES Cycling: What the Evidence Shows

A review of the literature on Functional Electrical Stimulation cycling across the main neurological conditions it has been used for.

Overview

Functional Electrical Stimulation (FES) cycling is a rehabilitation modality in which low-level pulsed electrical current is applied via surface electrodes to paralysed or weakened lower-limb muscles. Stimulation is typically applied to the quadriceps, hamstrings, and gluteus maximus and synchronised with crank-angle position to produce a coordinated pedalling action. Many products will engage additional muscle groups, such as the tibialis anterior and the gastrocnemius/soleus.

The technique was first demonstrated in the early 1980s and has since been the subject of more than four decades of clinical research. The neurological conditions most extensively studied are spinal cord injury (SCI), stroke (cerebrovascular accident, CVA), multiple sclerosis (MS), cerebral palsy (CP), and Parkinson's disease (PD). The primary benefits investigated span cardiovascular fitness, musculoskeletal preservation (muscle bulk, bone mineral density, and joint range of motion), reduction in spasticity, psychological well-being, and the mitigation of secondary medical complications such as pressure sores.

Authors Note

This review synthesises evidence from landmark original studies, some systematic reviews, and meta-analyses alongside the body of engineering research represented in doctoral theses from the Centre for Rehabilitation Engineering at the University of Glasgow. A substantial proportion of that engineering work was done in collaboration with the Queen Elizabeth National Spinal Injuries Unit at the Southern General Hospital in Glasgow, and I draw on several of those doctoral theses throughout.

I'm somewhat biased to include the Glasgow studies, as this is how I got involved in this area. David Allan, at the time Clinical Director of the spinal injuries unit, and Professor Ken Hunt of the University of Glasgow were ready to commercialise some of the research they had undertaken into FES cycling. This led to a partnership between Anatomical Concepts and Hasomed GmbH, which has lasted since 2007. In the early days of working with FES Cycling in the UK, we were frequently asked for details of the research evidence to support the use of this product type. This really happens today. There is now an extensive body of research supporting the use of FES cycling across the range of conditions represented here. This review only scratches the surface.

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1. Origins of FES Cycling

1.1 The Early Work

The first published demonstration of FES cycling was reported by Petrofsky, Heaton and Phillips in 1983. They built a three-wheeled outdoor bicycle with a potentiometer on the pedal crank and a microprocessor that switched current through four channels into the quadriceps and gluteals. Paraplegic and quadriplegic volunteers were able to cycle outdoors for up to fifteen minutes. The stated aims of the work were to increase muscle strength and endurance, slow atrophy, protect bone, and provide cardiovascular training. Those aims have continued to define the field ever since.

Petrofsky's group went on to develop stationary ergometers based on modified MONARK bikes (later commercialised as the REGYS and ERGYS systems) as well as mobile tricycles. Parallel work in the 1990s and 2000s explored implanted solutions. Perkins and colleagues, for example, demonstrated FES cycling using a Lumbo-Sacral Anterior Root Stimulator Implant, with one woman who had a T9 lesion cycling over a kilometre outdoors at cadences between 25 and 85 rpm.

1.2 The Glasgow Contribution

The four doctoral theses produced at Glasgow's Centre for Rehabilitation Engineering, in partnership with the Queen Elizabeth Spinal Injuries Unit and with groups in University College London and Nottwil, represent the most substantial single body of engineering research behind modern FES cycling.

Kenneth Hunt's DSc thesis, *Control Systems for Function Restoration, Exercise, Fitness and Health in Spinal Cord Injury* (2005), describes the development of a motorised recumbent tricycle with closed-loop control of cadence and leg power. For the first time, exercise tests could be delivered in arbitrarily small increments of work rate, rather than in the six-watt steps imposed by commercial ergometers. Hunt's work explicitly addressed cardiovascular fitness, bone integrity, spasticity, muscle condition, and pressure sore risk. It is worth noting that the DSc also covered paraplegic standing and upper-limb FES in tetraplegia, so it is broader than its reputation as a "cycling thesis" suggests.

Thomas Schauer's PhD (2006) introduced isokinetic training modes and repetitive control algorithms that effectively removed the disturbances that FES-activated muscles introduce into the cycling action. Indoor cycling sessions of up to an hour became practical, and mobile outdoor cycling over useful distances was demonstrated. A one-year pilot study with three volunteers with complete SCI formed part of this work. Incidentally, Thomas, now an academic working in Berlin and a company director at SensorStim Technologies GmbH, is directly responsible for the Stim2go product brought to the market by Pajunk GmbH and marketed in the UK by Anatomical Concepts.

Barry Stone's PhD (2005) took the engineering further still, introducing cascade VO_2 control. This allowed oxygen uptake to be held at a specified percentage of peak VO_2, making it possible to prescribe FES cycling exercise with the same scientific rigour that sports medicine applies to able-bodied athletes.

Helen Berry's PhD (2008) extended the physiological assessment of FES cycling outcomes in SCI, and Silvie Coupaud's 2005 PhD, less often cited, developed methods for arm-cranking exercise assisted by FES in tetraplegia, the only Glasgow thesis to address the upper limb directly. Chiara Ferrario's 2006 pilot work on incremental and step exercise testing protocols laid the groundwork for Stone's later VO_2 control studies.

The peer-reviewed engineering consolidation of all this work is Hunt and colleagues' 2004 paper in *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, which remains the clearest single reference on how motor assist and FES are integrated in the Glasgow trike.

1.3 How Stimulation Actually Produces Cycling

Three muscle groups contribute most of the useful crank torque: the quadriceps (knee extension, the dominant contributor), the hamstrings (knee flexion and hip extension), and the gluteus maximus (hip extension). Stimulation is applied through self-adhesive surface electrodes, typically with pulse widths between 150 and 300 microseconds, frequencies between 20 and 50 Hz, and amplitudes set individually to produce effective contractions without provoking uncontrolled spasms.

The limitation of surface-electrode type FES cycling is its low metabolic efficiency. Values between 3% and 14% are reported, compared with 15% to 27% for able-bodied voluntary cycling. The reasons are worth understanding. Recruitment order is reversed under electrical stimulation: fast-twitch Type II fibres fire before slow-twitch Type I, which is the opposite of what happens during voluntary effort. Coordination between muscles is less refined. Reciprocal inhibition is less effective. The practical consequence is that power outputs of 10 to 40 W are typical, against 100 to 300 W for recreational cyclists.

This is not a failure; it is a feature of the technique. The point of FES cycling is not to compete with able-bodied cycling but to bring useful mechanical and metabolic work back to muscles that would otherwise be entirely inactive.

2. Spinal Cord Injury: The Core Evidence Base

Spinal cord injury remains the condition that has generated by far the largest body of published FES cycling research. The 2021 systematic review by van der Scheer and colleagues, drawing on 92 eligible studies and 999 adults with SCI across every relevant subgroup, provides the most comprehensive overview of outcomes currently available.

2.1 Cardiovascular and Cardiopulmonary Fitness

Inactivity and lower-limb paralysis after SCI produce rapid and profound cardiovascular deconditioning. FES cycling gives a route back by bringing the large paralysed leg muscles online as a metabolic engine. Because the muscle mass mobilised is much greater than that available in arm ergometry, the cardiovascular stimulus is correspondingly greater.

Faghri and colleagues showed, as far back as the late 1980s, that twelve weeks of three sessions per week of FES cycling increased paraplegic subjects' cycling time from a few minutes to thirty minutes per session and their sustained power from around 5 W to 18 W. Barstow and colleagues reported peak VO$_2$ rising from 1.28 to 1.42 L/min after twenty-four sessions. Hooker and colleagues reported a 10% rise in VO$_2$ and a 25% rise in work rate over a nineteen-week programme on the REGYS I, and noted that the ratio of submaximal VO$_2$ to peak VO$_2$ fell from 77% to 68%, which is to say that aerobic economy improved as well as peak capacity.

The Janssen review, often cited in the Glasgow theses, concluded that FES leg cycle exercise produces "relatively high magnitudes of aerobic, metabolic and cardiopulmonary responses" that cannot be reached by arm ergometry, and that after several weeks of training, VO$_2$ levels equivalent to walking (around 1.0 L/min) are reachable. The 2021 van der Scheer review confirmed significant gains in power output and aerobic fitness in nearly every Level 3 to 4 study examined, though the GRADE rating of Low reflects study design rather than inconsistency of findings.

The 2006 EPSRC Final Report from the Glasgow, London and Nottwil collaboration (Hunt and Donaldson) put concrete numbers on what a year of serious home training achieves. Eleven volunteers with chronic complete SCI, training for about 5 hours per week on recumbent tricycles, increased peak power from 8.5 ± 3.3 W to 18.2 ± 8.8 W, a gain of 129%. Peak VO$_2$ rose from 543 to 820 ml/min, a 56% relative increase. Peak heart rate rose from 82 to 92 bpm. VO$_2$ at the ventilatory threshold rose by about 109 ml/min in the first six months. The Cardiff 2006 FES Sports Festival, which grew out of this programme, set the first world records in FES cycling over 100 m and 1 km.

Sipski and colleagues' questionnaire study of 47 patients on a clinical FES ergometer programme found that 62% of paraplegic and 65% of quadriplegic participants reported improved endurance after the programme. A 2025 systematic review confirmed that FES-assisted cycling improves muscle strength, power, and neuromuscular efficiency in hospitalised patients, with ambulation capacity improving threefold compared with controls. ### 2.2 Muscle Health and the Reversal of Disuse Atrophy

Paralysis produces atrophy quickly. Within six months of a complete SCI, muscle cross-sectional area falls substantially and the fibre-type mix shifts from slow-oxidative Type I toward fast-glycolytic Type II. FES cycling pushes both of those changes in the opposite direction.

The Janssen review concluded that FES leg cycle exercise "appeared to reverse or retard disuse atrophy of the paralysed muscle" and that the "bulk and appearance of the lower limbs had greatly improved." The 2021 van der Scheer review rated this evidence GRADE High, the strongest rating in the analysis, based on 3 of 4 Level 1 to 2 studies and 27 of 32 Level 3 to 4 studies showing significant improvements.

Frotzler and colleagues' 2008 study, which measured thigh muscle cross-sectional area using peripheral quantitative computed tomography in 11 chronic complete SCI volunteers after 12 months of high-volume training, remains the landmark result. Thigh muscle CSA rose by a mean of 35.5 ± 18.3%, while fat CSA at the shank fell by 16.7 ± 12.3%. Sadowsky and colleagues (2013) reported comparable findings: 36% greater quadriceps mass and 44% less lower-limb fat mass, along with 30 to 35% greater hamstring and quadriceps strength, in FES cycling participants than in controls who received only range-of-motion exercises.

A useful counterpoint comes from Duffell, Newham, Kakebeeke and colleagues (2008), reporting on the same multicentre programme that produced the Frotzler bone paper. Eleven volunteers, training for around one hour a day, five days a week, for a year, showed a fivefold increase in maximal electrically stimulated quadriceps torque, improved fatigue resistance, and an unchanged relaxation rate. Interestingly, the cycling power gains, though real, were proportionally smaller than the isolated muscle gains. This matters clinically: it is a reminder that strength adaptations in the stimulated muscle outrun the coordinated cycling action they support, and that patient expectations around "cycling power" should be calibrated accordingly.

The metabolic implications are not cosmetic. Greater muscle mass improves insulin sensitivity and reduces body fat accumulation and cardiovascular risk, all of which are elevated in the SCI population, for obvious reasons: most conventional exercise is no longer available to them. ### 2.3 Bone Mineral Density

Neurogenic osteoporosis is among the most clinically significant secondary complications of SCI. Bone loss is most rapid in the first two years after injury, and it concentrates at the distal femur and proximal tibia. Minor trauma, particularly in transfers, can produce fractures that carry a heavy morbidity burden.

The evidence on FES cycling and bone density is more nuanced than the evidence on muscle, and the nuance is almost entirely about dose.

The early studies were disappointing. BeDell and colleagues (1996) reported a positive but non-significant trend at the lumbar spine and no significant change at femoral sites after a three-phase FES programme in twelve male SCI volunteers. Eser and colleagues (2003), who began cycling an average of 4.5 weeks after injury (the earliest reported intervention), found no significant attenuation of tibial bone loss over 6 months despite three weekly sessions.

The turning point was Frotzler et al. (2008). Eleven chronic complete SCI volunteers, with an average of 11 years post-injury, cycled 3.7 times per week for 58 minutes per session for a full year. After twelve months, trabecular BMD at the distal femoral epiphysis had risen by 14.4 ± 21.1%, total BMD by 7.0 ± 10.8%, and total cross-sectional area by 1.2 ± 1.5%. The authors concluded that high-volume FES cycling has clinical relevance because it can partially reverse bone loss at a fracture-prone site. The effect was site-specific: bones loaded directly by FES contractions responded, and passively loaded sites did not.

The 2023 de Gruyter systematic review confirmed that FES combined with frame-supported leg exercise is superior to frame-assisted exercise alone for bone preservation, and specified the dose that matters: intervention started within three months of injury, at least thirty minutes per session, at least three times a week, continued for up to two years. Chang and colleagues' 2013 meta-analysis concluded that FES can reduce bone loss in newly injured patients and increase BMD by up to 10% after twelve months in established injuries, while emphasising that the training has to continue if the gains are to be kept. Lauer and colleagues (2011) reported non-significant yet promising trends in hip BMD among children with SCI.

The honest summary is that FES cycling can move bone density in the right direction at clinically relevant sites, but only at doses that most casual programmes do not reach. Three hour-long sessions a week for months, sustained for a year or longer, is the territory where bone responds. ### 2.4 Spasticity

Spasticity, characterised by hypertonia and velocity-dependent hyperreflexia, affects a substantial proportion of people living with SCI. It disrupts sleep, impairs transfers, complicates positioning, and contributes to the development of contractures. The rhythmic, bilateral leg movement of FES cycling engages reciprocal inhibition pathways and provides afferent sensory input, and both mechanisms plausibly contribute to the reductions in tone that patients consistently report.

Janssen and colleagues concluded that "most FES users experience a temporary reduction in spasticity on the day of exercise," and that increased muscle bulk from training tends to lower the overall frequency of spasms, even when individual spasms remain forceful. Two systematic reviews published in 2021 and 2022 confirmed a significant spasticity-reducing effect of FES cycling in SCI: Alashram and colleagues (2022) reported significant reductions across multiple studies, and Fang and colleagues (2021) showed dose-dependent effects in their meta-analysis. Kuhn and colleagues (2014) reported significant reductions in spasticity across several muscle groups after only four weeks of training, alongside quadriceps mass gains of 15 to 25%.

It is worth saying clearly that spasms during cycling are a recognised clinical reality, not a rare event. In the Glasgow exercise-testing work, one volunteer had to stop an incremental test because of persistent spasm. With appropriate stimulation design and a gradual warm-up, most users manage the issue without difficulty. ### 2.5 Range of Motion

Immobility and spasticity progressively restrict joint range of motion, with obvious consequences for transfers, positioning, and the practicalities of daily life. FES cycling, because it drives the hips, knees, and ankles through repeated full arcs of flexion and extension, directly counteracts these restrictions. Janssen and colleagues documented that "SCI can limit the ROM and may hinder activities, such as transfers," and that "there is evidence in the literature that FES can increase the ROM." The coordinated agonist-antagonist activation of cycling does what passive stretching on its own cannot: it provides both mechanical stretch and neuromuscular facilitation around each joint. ### 2.6 Pressure Injuries and Skin Integrity

Pressure injury is a potentially life-threatening complication of SCI, arising from a combination of impaired sensation, reduced tissue perfusion, and the sustained load of sitting. Hunt's DSc programme explicitly included research on factors relating to skin breakdown. The underlying hypothesis is that FES cycling improves local tissue perfusion by increasing blood flow and reducing sustained pressure, and that the additional muscle bulk beneath insensate skin provides a mechanical cushion. Direct evidence on pressure sore *rates* is harder to find than evidence on proxy measures such as transcutaneous oxygen tension. The EPSRC Final Report noted MRI trends toward increased gluteal thickness and reduced subcutaneous fat after a year of training, though no clear change in seating pressure or $TcpO_2$. The mechanism is plausible; the long-term clinical translation is still being worked out. ### 2.7 Psychological Well-Being and Quality of Life

Janssen and colleagues reported that FES cycling participants experienced "an improved self-image, they felt stronger and more energetic, less fatigued, and they had an increased feeling of overall wellbeing," and that mood disturbance, common in the SCI population, was often improved. Sipski and colleagues' questionnaire study found that 62% of paraplegic and 56% of quadriplegic participants reported improved self-image, and between 54% and 77% felt that their appearance had improved.

Dolbow and colleagues (2013) specifically studied home-based FES cycling in SCI and reported significant gains in pain, energy, fatigue, physical health, sleep, and work capacity after three weekly sessions. The 2024 systematic review and meta-analysis by Ponzano and colleagues, drawing on 19 randomised trials and 797 participants, found that exercise in adults with SCI improved overall well-being (d = 0.494), subjective well-being (d = 0.543), psychological well-being (d = 0.499), social well-being (d = 0.452), and health-related quality of life (d = 0.323), all statistically significant. FES cycling is one of several modalities in that analysis, but it is a well-evidenced route into exercise for those whose mobility options are limited.

3. Stroke

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4. Multiple Sclerosis

MS is characterised by progressive demyelination and neurological dysfunction that can produce significant lower-limb weakness, fatigue, and spasticity. Exercise is well established [illegible]

5. Cerebral Palsy

CP is the most common motor disability in children. It is characterised by spasticity, reduced muscle strength, impaired coordination, and secondary musculoskeletal change. Conventional cycling often fails to achieve adequate exercise intensity in children with CP because the effort required to overcome spasticity and weakness exceeds their voluntary capacity. FES-assisted cycling closes the gap. ### 5.1 Gross Motor Function

Armstrong and colleagues' 2020 randomised controlled trial enrolled 21 children with CP (mean age 10 years 3 months, GMFCS II to IV) in an eight-week programme combining FES cycling, goal-directed training, and adapted cycling. The intervention group showed significantly better outcomes than usual care on GMFM-88 (mean difference +7.4, 95% CI 2.3 to 12.6, $p = 0.007$), GMFM-66 (mean difference +5.9, 95% CI 3.1 to 8.8, $p < 0.001$), and the COPM Performance score (mean difference +4.4, $p < 0.001$). Those are clinically meaningful gains in a population where gross motor change is hard to win.

A 2025 systematic review of five studies published between 2005 and 2025 reported gait speed improvements of 12 to 20%, stride length increases of up to 15%, and GMFM gains of 8 to 10 points, with the greatest functional mobility gains observed in studies that used FES during walking or cycling. ### 5.2 Cardiovascular and Aerobic Responses

Cycling with FES assistance can bring children with CP into the aerobic intensity range needed for cardiorespiratory benefit, an intensity that voluntary cycling alone often cannot reach. A 2021 randomised study in 39 children compared FES-assisted cycling, volitional cycling, and a no-intervention control and confirmed the aerobic benefit specifically attributable to FES assistance. An updated 2022 review of stationary cycling in CP reported promising results for muscle strength and endurance, though heterogeneity across studies made firm conclusions about functional activity outcomes more difficult. ### 5.3 Spasticity Management

Harrington and colleagues (2012) evaluated FES cycling in four adolescents with spastic CP, reporting increases in cadence (2 to 43 rpm above baseline) and power output (1 to 70%), with heart rate rising 4 to 5%. Two of the four participants needed an auxiliary hub motor to maintain cadence, underscoring that device selection matters in CP as much as stimulation parameters. The same afferent inhibitory mechanisms that reduce spasticity in SCI appear to operate here, though multimodal approaches (cycling plus goal-directed training, as in the Armstrong trial) are where the evidence points.

6. Parkinson’s Disease

Parkinson’s disease is a progressive neurodegenerative disorder characterised by tremor, bradykinesia, rigidity, and postural instability, driven by dopaminergic cell loss in the substantia nigra: [illegible]

7. Benefits and Evidence Strength: A Cross-Condition View

Benefit Domain	SCI	Stroke	MS	Cerebral Palsy	Parkinson's Disease
Cardiovascular / VO_2	Strong (92 studies; van der Scheer 2021)	Moderate (RCT evidence; Heeren 2024)	Moderate (Ratchford 2010)	Moderate (RCT; Howcroft 2021)	Moderate (MOTOmed SR 2022)
Muscle Strength / Mass	Strong (GRADE High; van der Scheer 2021; Duffell 2008)	Moderate (Ambrosini, Ferrante 2008)	Limited (Ratchford 2010)	Moderate (Armstrong RCT 2020)	Moderate (MOTOmed SR 2022)
Bone Mineral Density	Moderate, dose-dependent (Frotzler 2008)	Insufficient data	Insufficient data	Limited (Lauer 2011)	Not specifically studied
Spasticity Reduction	Strong (Alashram 2022, Fang 2021)	Moderate	Moderate (Backus 2017)	Moderate	Not specifically studied
Range of Motion	Moderate (Janssen review)	Moderate	Limited	Limited	Limited
Gait / Motor Function	Emerging for incomplete SCI (Duffell 2019)	Moderate to Strong (Heeren 2024)	Moderate (Ratchford 2010)	Strong (Armstrong RCT 2020)	Strong (Ridgel, Cleveland Clinic)
Psychological / QoL	Moderate (Ponzano 2024)	Limited	Moderate (Backus 2017)	Limited	Limited
Fatigue Reduction	Moderate (Dolbow 2013)	Limited	Strong (Backus 2017)	Not specifically studied	Limited
Safety	Established across all conditions	Established	Established (no AEs in studies)	Established	Established

8. Dose, Timing, and Practical Considerations

8.1 Dose

The magnitude of benefit depends on dose, and the evidence is consistent on this point. For bone density in SCI, Frotzler's 2008 study (the only one to demonstrate partial reversal of BMD loss) required 3.7 sessions a week of around 58 minutes each for a full year. The de Gruyter 2023 systematic review specified at least 30 minutes a day, at least three times a week, for up to two years, as the minimum threshold for skeletal benefit. Cardiovascular and muscle gains appear at more modest doses, usually 2 to 3 sessions a week over 4 to 12 weeks. ### 8.2 Timing

For bone preservation in SCI, starting within three months of injury is more effective than delayed intervention. For stroke, FES cycling can be started early in the subacute phase, when gait-based work is not yet feasible. For MS, a four-week programme is already enough to produce significant fatigue and quality-of-life benefits, and the safety profile supports use in patients with advanced disability for whom other exercise options are impractical. ### 8.3 Hybrid Approaches

Combining FES lower-limb cycling with simultaneous voluntary arm cranking consistently produces higher VO_2 responses than either modality alone, reaching 1.5 to 2.0 L/min against around 1.0 L/min for FES cycling on its own. The BerkelBike, which integrates a hand-crank mechanism, achieved peak VO_2 of 25.7 to 28.1 ml/min/kg after a four-week training period in SCI volunteers. For individuals with complete SCI who can use their arms, hybrid exercise is the most effective way to maximise the cardiovascular stimulus. ### 8.4 Home Versus Clinic

The arrival of motorised ergometers that can be accessed from the wheelchair without transferring has made home-based FES cycling practical. The training consistency that produces lasting physiological adaptation is much easier to achieve at home than in a clinic, simply because more sessions can be fitted into a week. Several products are commercially available for home use. ### 8.5 Incomplete Injury, Neuroplasticity, and the Future of the Evidence Base

For people with incomplete SCI, FES cycling is increasingly being framed as a tool for neuroplastic recovery rather than only for maintenance. Duffell and Donaldson's 2020 review in *Frontiers in Neurology* makes the case directly, arguing that FES, by providing peripheral input in time with voluntary effort, may drive recovery in descending pathways faster than activity-based therapy alone and at lower cost than implanted spinal cord stimulation. The authors suggest that AISA A and B injuries are likely to need ongoing stimulation or implants, whereas AISA C and D injuries may benefit from a defined course of therapy followed by recovery that persists beyond the intervention.

Duffell and colleagues' 2019 iCycle pilot supports this. Eleven participants with incomplete SCI (C1 to T12) completed twelve sessions of FES cycling with a VR racing biofeedback system. Median improvements in the International Standards for Neurological Classification of SCI (ISNCSCI) motor score were 3.5 points in chronic participants and 8.0 points in sub-acute participants. Four of five sub-acute and two of six chronic participants improved their motor score by more than 8 points. Five of eleven showed moderate improvements in voluntary cycling power ($R^2 = 0.50$, $p < 0.05$). These are small numbers, but the direction of travel is genuinely interesting for a population that has historically been told that functional recovery has a ceiling. ### 8.6 Limitations and Precautions

Absolute contraindications to FES cycling include implanted electronic devices (pacemakers, defibrillators), active lower-limb fractures, severe osteoporosis at fracture threshold, uncontrolled cardiovascular disease, and the inability to elicit adequate muscle contractions in lower motor neuron lesions.

A subset of SCI patients with neurogenic pain may find that FES provokes pain rather than relieving it. Sipski and colleagues reported that six of nine such patients withdrew from a programme for this reason. Autonomic dysreflexia risk needs careful consideration in complete injuries at or above T6. Rapid muscle fatigue, driven by the reversed motor-unit recruitment order under electrical stimulation, limits session duration and achievable power, and it is the fundamental technical limitation of surface FES that the engineering literature has been trying to address for four decades. The Duffell and Donaldson review helpfully catalogues the six main limitations of surface FES (rapid fatigue, skin variability, pain, antagonist co-activation, limited selectivity, and cable inconvenience), all of which are live targets for further work.

9. Where the Field Is Heading

Conclusion

More than forty years of research have established FES cycling as an effective, safe, and versatile rehabilitation modality across a range of neurological conditions. The evidence base

The engineering ad-

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