FUNCTIONAL ELECTRICAL STIMULATION CYCLING IN ACUTE CARE FOR SPINAL CORD INJURY REHABILITATION: **A TOOLKIT FOR PATIENTS AND CAREGIVERS**

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> *"Well, I was going to take [FES cycling] as far as I possibly could. The difference between being in a wheelchair and walking in a walker is like flying to the moon. I mean, it's just so different. A lot of people I don't think realize that….And, of course, going from the walker to a cane, and then from dropping the cane, it's just each step is like going to a completely new planet. So, it is quite remarkable."*
>
> **- FES Cycling User**

DISCLAIMER

The toolkit has been specifically designed for the implementation of functional electrical stimulation (FES) cycling for spinal cord injury (SCI) rehabilitation using the RT 300 FES leg cycle at the University of Alberta Hospital and the Royal Alexandra Hospital located in Edmonton, Alberta with the expertise of multiple stakeholders. However, this toolkit may be used to inform FES cycling rehabilitation at other sites, settings, and for other conditions.

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1. About

Aim: To provide people living with spinal cord injury (SCI) and their loved ones with easy access to evidence-based material to help integrate functional electrical stimulation (FES) cycling into acute care for SCI rehabilitation.

FES cycling uses electrical impulses to stimulate and contract muscles. In response, cycling occurs using the legs and/or arms. Earlier studies that tested FES cycling for SCI rehabilitation in acute care showed that FES cycling can prevent the loss of muscle mass, increase muscle power, and decrease the rate of bone mineral density loss. If you start to use FES cycling as early as possible, you may have the best results. People with SCI have started FES cycling as early as two to three weeks after their injury. The people who participated in the study experienced very few side effects. Not many people dropped out of these studies. Also, people living with SCI would like to start activity-based therapy (ABT), which helps recovery, as soon as possible in their rehabilitation. FES cycling is an example of this type of therapy.

People with SCI reported that FES cycling helped them to:

- Feel happy to see the contraction of paralyzed muscles.
- Feel healthy.
- Maintain their fitness level.

2. How can FES cycling help me?

a. Benefits

Target area	Potential benefit from FES cycling
 Cardiovascular	• Improve blood flow • Decrease glucose and insulin levels in blood • Improve and maintain cardiovascular conditioning • Increase in lean muscle mass and capillary numbers
 Muscle health and movement	• Increase muscle size and strength • Improve muscle composition • Improve fatigue resistance • Improve rate of soft tissue healing • Reduce swelling • Prevent disuse atrophy
 Bone health	• Prevent loss of bone mineral density • Improve bone health in lower limbs • Improve rate of fracture healing • Increase joint range of motion
 Spasms and spasticity	• Reduce frequency and/or intensity of muscle spasms • Reduce effects of spasticity
 Cardiometabolic	• Reduce amount of adipose tissue
 Secondary complications	• Decrease chance of infections • Decrease chance of pressure injuries • Decrease chance of fractures
 Other	• Increase ISNSCI* score in lower extremity • Recovery of movement below the level of the injury

International Standards for Neurological Classification of Spinal Cord Injury

b. Is FES cycling right for me?

Functional electrical stimulation (FES) cycling should aways be performed according to established guidelines, using the right safety precautions. You should consult with a health care provider to set up the bike and FES settings at these times:

- Before you start the program
- If you want to progress (example: increase the resistance, change the stimulation settings)
- If you restart the program
- If you change from one bike model to another

These problems could happen, but with proper guidance and monitoring from your health care providers, these effects will be less likely. Some may never happen.

The potential problems related to FES cycling may be:

- **Fatigue** - this might happen because there are series of metabolic activities going on in the body during exercise that can cause tiredness, but these feelings are temporary.
- **Brief drop in blood pressure** – because the SCI disturbs the normal regulation of the blood pressure. This effect lasts only a short time.
- **Increased spasticity** - may be triggered by the leg movement.
- **Light-headedness** – make sure that you are hydrated, get enough rest, and check your blood pressure if it tends to be low. Make sure that you take your blood pressure medication if you have a prescription.
- **Skin injury or damage** - This might happen if you are not set up properly in the FES cycle. Safe transfer techniques, use of hypoallergenic electrodes, proper use of the electrodes, and control of the stimulation intensity can reduce the likelihood this will happen.
- **Incontinence** - This is unlikely if you go to the bathroom or schedule your bowel routine before cycling.
- **Leg swelling** - Proper positioning (elevating legs) and compressive stockings can help.
- **Autonomic dysreflexia** – only if your injury is at T6 or above. If you are aware of the condition and know how to manage it, it won't be a problem. It is recommended that you discuss it with your health care provider.
- **Quadriceps hematoma** – this is rare and usually happens only with vigorous exercise.
- **Bone fracture** - This is rare and might happen if you have a severe muscle spasm and/or severe osteoporosis.

3. Indications, Contraindications and Precautions

a. What are the reasons I should try FES cycling?

Functional electrical stimulation cycling is an effective way to improve or prevent some of the problems you could experience after SCI. You can consider using FES cycling to address these conditions or problems:

- Loss of muscle mass
- Reduced leg strength or power
- Muscle or joint tightness (spasticity or contractures)
- High or unfavorable body fat percentage or body mass index
- Loss of bone mineral density
- Perceived poor quality of life, low self esteem or reduced sense of wellbeing
- Reduced physical endurance or lung function
- Poor blood sugar control
- Excessive fatigue
- Swelling Pain

b. What are the reasons I might need to avoid FES cycling?

With these conditions, you might be able to try FES cycling, but you need to ask your medical doctor first. If you have any of the conditions below, doing FES cycling could increase the chance you might get injured, make a current health condition worse, or it may mean that FES cycling is not right for you.

DO NOT engage in an FES cycling program (unless you have had clearance from your medical doctor) for these reasons. They are listed in order from the least harmful to the most harmful:

🟢	Lowest risk of harm or injury
🟡	Moderate risk of harm or injury
🟠	Special Consideration
🔴	Highest risk of harm or injury

Contraindication	Description	Severity
Complete rotator cuff tear	This applies to arm cycling only.	🟢
Pressure ulcers in buttocks or legs	This may depend on the severity of the sores and what precautions the health care providers are able to take.	🟡
Cardiac demand pacemaker (if applied to thoracic wall)	Consult your medical doctor first. Details are provided in the pop out box within the health care provider toolkit.	🟠
Fractures	It could increase the bleeding and pain around the fracture site and other complications. This applies to recent lower limb fractures or unstable fractures (past 6 months), fragility fractures, long bone, or pelvic fractures.	🔴
Pregnancy	It has not been tested in pregnant women.	🔴

> *"The effects of cycling usually lasted two, sometimes three, days after the cycling. [The] legs were more limber, [and] spasms were not so aggressive. I think it improved overall health afterwards. And the longer in between sessions, [limbs] would get stiff, and [the] spasms [would] be more aggressive and harder to control, so [I've] definitely seen that benefit there."*
>
> **- FES Cycling User**

c. With these conditions, I can try FES cycling, but proceed with caution

Proceed carefully with FES cycling if you have any of the conditions listed below, make sure that you speak with your healthcare provider and continue to closely monitor your response to FES cycling.

These are precautions to FES cycling ranked in order from least to most harmful:

Precaution	Description	Severity
Lower motor neuron involvement	Lower motor neuron injury, no spinal reflexes, degenerative neurological diseases, or total denervation, where FES will not work. Also, flaccid paralysis in response to FES.	🟢
Difficulties understanding, communicating, or symptoms of severe depression, anxiety or cognition limitations	Make sure that everyone involved with FES cycling fully understands what they need to do. If you don't feel like cycling today, you can always decrease the session time, or try something else.	🟢
Active infectious disease	This may depend on the severity and area the disease affects.	🟢
Muscle or joint stiffness that prevent you from being able to pedal the bike	Muscle or joint stiffness that allows you to pedal the bike may not be a problem.	🟢
Heterotopic ossification	This is severe joint calcification. Consult with your health care provider about the settings of the stimulation and the bike, as well as bike adjustments. FES should be away from the site of the injury.	🟢
Metal implants (screws, pins, plates, some total joint replacement hardware)	If these are newly placed	🟢
Uncontrolled pain or a diagnosis of complex regional pain syndrome	Decide if the pain is too much for you to cycle. You can consider reducing the length of the session, trying another exercise, or taking a rest day.	🟢
Bone growth plates are active		🟢
Allergic reaction, skin disease, or skin sensitivity to electrodes or FES	Do not put electrodes on over broken skin. You may need to consider changing the pads, adjusting the stimulation parameters, or something else. Consult your health care provider about how to modify the treatment.	🟢
Previous dislocations or unstable knees	You could have difficulty maintaining alignment when pedalling depending on how unstable your knees are.	🟡
Epilepsy or seizures in the past.	It could increase symptoms, in rare cases.	🟡
Less severe pressure injury	This depends on the severity of the injury and what precautions the health care providers are able to take	🟡
Diseases of bone metabolism	Some examples are osteoporosis and diseases or medications known to affect bone metabolism. Also if you have a Dual Xray absorptiometry T-score less than -2.5.	🟡

Autonomic dysreflexia	If it occurs frequently or severely, you should have someone with you. Rare or mild occurances may not be a problem depending on what your health care provider recommends. Do not engage in FES cycling if electrical stimulation triggers autonomic dysreflexia for you	🟡
Hypertension (uncontrolled)	Understand what high blood pressure is for you. This may be different than typical values. Exercise will increase your blood flow and blood pressure. If you take blood pressure medication regularly with supervison by a doctor this does not apply to you.	🟡
Regenerating nerves in the treatment area	Avoid the area.	🔴
Taking some types of steroid medications for long periods of time	Consult your medical doctor.	🔴
Clotting or bleeding disorder	Consult your medical doctor.	🔴
Severe diabetes, uncontrolled blood sugars or untreated thyroid disease	Consult your medical doctor.	🔴
Current cancer in the lower limbs, at the level of T6 and below	Consult with an oncologist.	🔴
Cardiovascular disease	Exercise will increase your blood flow and blood pressure. Some examples of this type of disease are: chronic arterial disease, unstable cardiovascular disease, uncontrolled arrhythmia, angina, or congestive heart failure.	🔴
Clot, especially in the legs	The clot could travel with increased movement and blood circulation. This includes a recent, untreated venous thromboembolism (within past 3 months) or current deep vein thrombosis or pulmonary embolism.	🔴

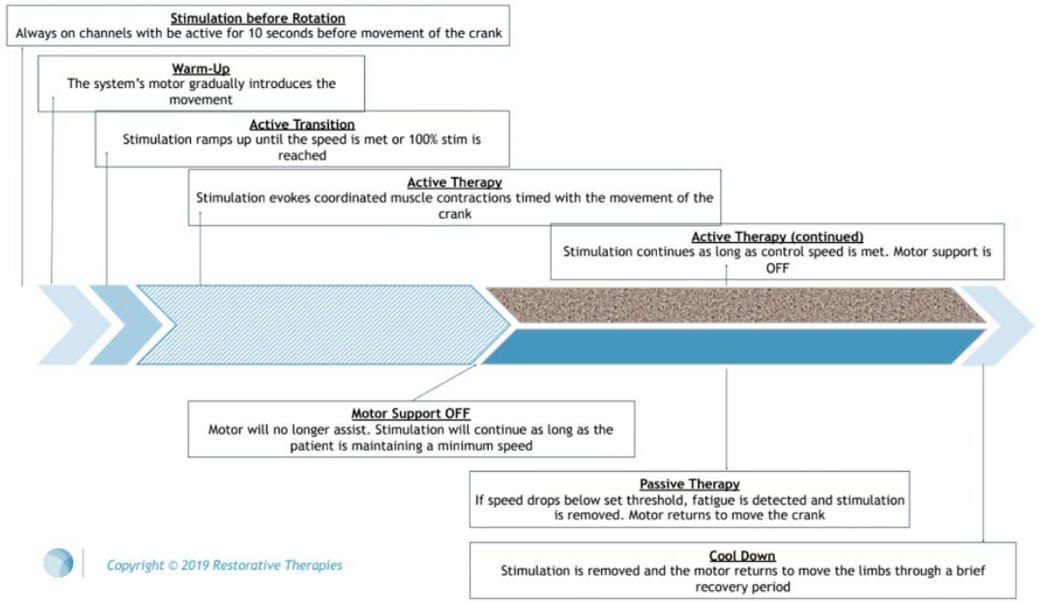
4. Before, During, and After Functional Electrical Stimulation Cycling

> *"So to me the sooner you start the better. I mean I could see in the first, you know, 2 months, how quick my legs are shrinking away and I was cycling. So, if you can cycle do it."*
>
> **- FES Cycling User**

a. Before the FES cycling session

- Bring pull on shorts (elastic waist), tank top or t-shirt and grippy footwear (i.e. crocs, slippers, or fitness shoes that are easy to put on).
- Ask nursing to help you get dressed.
- Ask nursing to get you up and ready for the day. For example: brush your teeth, wash your face or shower.
- Ask nursing to shave or trim the area where the electrodes go if you think you need it.
- Make sure you have a good meal 60-90 minutes before to avoid digestive problems, nausea, or vomiting.
- Ask nursing for pain meds 15-30 minutes before your session.
- Make sure you've gone to the bathroom and followed your bowel routine.
- Ask nursing to get you up into your seating system at least 15-30 minutes (depending on your seating and seated posture tolerance) before your cycle session. This will help to acclimate you to the position.

b. During the FES cycling session



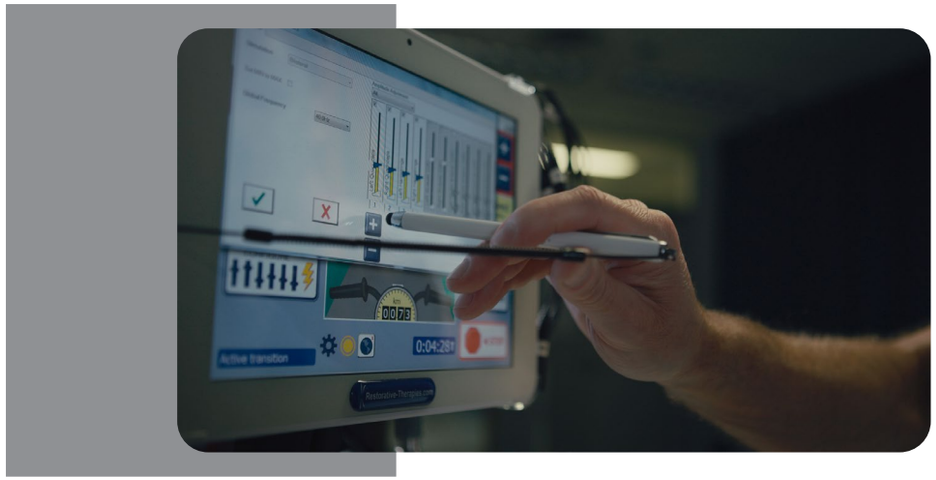
- The first session may take more time for set up. You may be tired and it's normal if you can't tolerate a long ride.
- It may take more than one try to get the electrodes in the right spot.
- Where your health care provider puts the electrodes may be slightly different for each session.
- Each therapist does things a little differently. If you remember what worked or didn't work, let them know or add it to the logbook .
- You may feel tingling, buzzing, stinging, or other sensations where the electrodes are or further down your arms or legs.
- You may have increased or decreased spasms in your arms or legs.

How to get the most out of your FES ride

- Pedal "with the bike" if you have some control over your leg muscles
- You can try to go faster in short bouts if you feel like it and then slow down again
- If you can, bike actively the whole time, or as long as you can. The therapist will set the resistance to an amount that you are comfortable with.

c. After the FES cycling session

- Check under the electrodes. If you see areas of redness that don't go away within 1-2 hours after the session – let a health care provider know.
- Look for areas of skin breakdown, tears, or redness from transferring or moving your arms or legs during cycle time.
- Ask someone to help you check for skin breakdown, tears, or redness in areas that you can't see or feel.
- Keep a logbook or notes about your session.
- Check for signs of autonomic dysreflexia.
  - » If you feel dizzy, lightheaded, sweaty, heart rate slowing, or anything different – let someone on your healthcare team know right away.
- Ask for water, electrolytes, and/or a salty snack post treatment.
- Ask for range of motion exercises or stretching if you feel tight.
- Get enough rest.



d. In general

- You may have increased or decreased sensations like tingling
- You may have increased or decreased spasms in your arms or legs
- You may be tired or sore for 1-2 days after cycling
- Some sessions may be better than others
- The more sessions you have, the more likely it is that the speed, time you ride, and/or the power (watts) you can produce will increase
- Make sure you communicate with the healthcare team if you have any questions

5. Logbook and Notes

Logbook

USER NAME, PATIENT ID

Password/PIN number	
Parameters	**Notes**
Warmup (min)	
Active cycling (backwards/ forwards) (min/min)	
Cool down (min)	
Resistance (Nm)	
Control speed (rpm)	
Motor (Nm)	
Global frequency	40Hz
Global pulse width	250 µs
Bike height	
Wheelchair height	
Distance from pedals	
Time of day	

Channel	Muscle Stimulated	Amplitude (mA)
L1		
L2		
L3		
L4		
L5		
L6		
R1		
R2		
R3		

Notes: (How did you feel before, during, after the session? How did you feel the next day? Helpful medications and dosage details. Concerns that I should talk to the healthcare providers about next time.)

> *"Oh, I attend the gym every week at the [community centre]. So, the FES cycling and the gym at the [community centre] is all in the same facility so, I try to gym and then cycle. I try to go at least 3 times a week."*
>
> **- FES Cycling User**

6. Transitions in care

> *"I found there to be some mental health benefits to doing it too. Just not only, you know, the potential for more physical recovery, but for me, just feeling like I was doing something or there was something to offer that could help with my recovery was helpful.."*
>
> **- FES Cycling User**

a. Access your FES cycling information here:

https://www.rtilink.com/datalink/login.htm

b. Community options

FES Community Options - Greater Edmonton Area

Saville Centre	Steadward Centre	YMCA - Castledowns	YMCA - Don Wheaton
Location: South Edmonton Carly Frenkel carly.frenkel@ualberta.ca 780-492-7114	Location: South Edmonton Allison Hunder infotsc@ualberta.ca 780-492-8339	Location: North Edmonton Jasmyne Pedersen jasmyne.pedersen@ymcanab.ca 780-377-3720	Location: Downtown Allison Piper allison.piper@ymcanab.ca 780-969-8946

FES Assessment - Please note that if you DO NOT have a current FES program already developed, you will need an FES assessment to build an FES bike program specific to you and your needs. Cost of this 2-hour assessment is $153.

FES Site	Cost	Baseline Level of Support	Scheduling	Extra Site Info
Saville Centre*	$18/month	- Machine set-up - Tensor wrapping - Connect pre-placed electrodes - Onsite storage of supplies	- Open Google Calendar or call 780-492-1701 - Book appointments up to 1 week in advance	- Saville fitness centre is located on 2nd floor, if low mobility we suggest a support person
Steadward Centre	2x/week = ~$175-$275 / 4 months 3x/week = ~$250-$400 / 4 months	- Full set-up and take-down support - Onsite storage of supplies	- Participant commits to a consistent schedule for 4 months at a time, 2x or 3x/week	- Electrodes available onsite for purchase - FES includes access to all other gym equipment
YMCA - Castledowns*	18-64 yr = $33 biweekly 65+ yr = $28 biweekly Plus = $58.75 biweekly	- Onsite storage of supplies	- Drop-in	- Financial assistance may be available
YMCA - Don Wheaton*	18-64 yr = $33 biweekly 65+ yr = $28 biweekly Plus = $58.75 biweekly	- Onsite storage of supplies	- Drop-in	- Financial assistance may be available

*** For Saville and YMCA sites, first year of fees (FES Assessment, FES riding fees, electrodes) will be covered by SCITCS for individuals with Spinal Cord Injury**

Glossary

Activity-based therapy (ABT): therapeutic activities that involve 'repetitive neuromuscular activation below the level of the spinal cord injury'. This repetition is usually achieved by task-specific movements with a high intensity. (Musselman 2018)

Amplitude: refers to the intensity or strength of the current being delivered. The amplitude setting controls the amount of current delivered to the nerves and muscles and can be perceived as gentle tingling to more intense electrical sensations.

American Spinal Injury Association (ASIA) Impairment Scale (AIS): The AIS is used to classify the level of severity of spinal cord injury. Classifications range from AIS A (complete injury) to AIS E (normal sensory and motor function). (https://scireproject.com/outcome/ais/)

Atrophy: degeneration or wasting of muscle tissue

Autonomic dysreflexia: a dangerous clinical syndrome that involves an overreaction of the nervous system to a stimulation and can include an increase in blood pressure, and sweating, or decrease in heart rate. Common symptoms are headache, nausea, vomiting, goosebumps, or blurred vision, among others. This can happen if your injury is at or above the T6 level.

Capillary: small hair-like blood vessels which connect small arteries and veins.

Circle of Care: person with direct responsibility for providing care for the patient. For example, health care practitioners.

Complex Regional Pain Syndrome (CRPS): form of a chronic pain that usually starts after an injury and affects an arm or a leg.

Edema: swelling in the soft tissue

Functional electrical stimulation (FES): application of an electrical stimulus to a paralyzed nerve or muscle with a goal of restoring function (Martin 2019)

Fracture: break in the bone due to trauma, stress or disease condition.

Frequency (Channel): measured in Hertz (Hz). It is the number of stimulation pulses delivered per second by one channel.

Frequency (Global): measured in Hertz (Hz). It is the number of stimulation pulses delivered per second by all channels.

Glucose: A sugar-like substance that is the main source of energy in the human body which is found in the blood. (American Heritage Medical Dictionary, 2007)

Insulin: The major fuel-regulating hormone of the body formed in the pancreas.

Hematoma: is a collection of pooled and mostly clotted blood in body tissues or space within the body. These are generally caused by damaged blood vessels due to injury or surgery, leading to blood leaking into the surrounding tissues or space.

Heterotopic ossification: the formation of bone in muscle and other soft tissues that can develop after an injury or surgery

Orthostatic hypotension: rapid decrease in blood pressure that happens when a person changes position (e.g., lying to sitting, sitting to standing) leading to fainting or dizziness

Osteoporosis: condition in which bone tissue is broken down at a faster rate than bone being replaced. It results in brittle bones that can break more easily than normal bones.

Pacemaker: device used to treat irregular heart rates and rhythms

Cardiac demand pacemaker: artificial pacemaker that activates only when it receives sensations indicating a lack of spontaneous rhythm by the heart. It attempts to avoid competing with the person's natural pacemaker

Paraplegia: impairment, loss of sensation and/or movement in the lower limbs, pelvic organs and trunk (spared upper limbs) due to damage of the neural components of spinal column

Power: the rate of energy production. It is measured in watts (W).

Pressure ulcer: an injury to the skin and potentially the underlying tissue, depending on severity. They are caused by sustained pressures on the skin and underlying tissue and often seen in individuals who are wheelchair or bed bound.

Pulse oximeter: estimates oxygen levels in the blood. It may not be as precise for people who have darker skin pigmentation

Pulse width: the length of time that each group of electrical pulses is delivered. It is measured in microseconds (μs) or milliseconds (ms).

Malignancy: cancer or tumor

Range of motion (ROM): the total number of degrees that a joint moves through when you actively contract your muscles, or they are moved for you (passive).

Spasticity: a condition in which there is an abnormal increase in muscle tone or stiffness after a brain and/or spinal cord injury

Spinal cord injury (complete): no sensory or motor function is preserved below the lowest sacral segments (S4-5) of the spinal cord.

Spinal cord injury (incomplete): some sensory and/or motor function is preserved below the neurological level of the injury including the lowest sacral segments (S4-5) of the spinal cord.

Tetraplegia: impairment, loss of sensation and/or movement on all the four limbs, pelvic organs, and trunk due to damage of the neural components of spinal column

Thrombosis: local clotting in the vascular system

Watt: the force times velocity that the rider is putting on the FES cycle pedals

References

1. Musselman KE, Shah M, Zariffa J. Rehabilitation technologies and interventions for individuals with spinal cord injury: translational potential of current trends. J NeuroEngineering Rehabil. 2018;15(1):40. doi:10.1186/s12984-018-0386-7

2. Demchak TJ, Linderman JK, Mysiw WJ, Jackson R, Suun J, Devor ST. Effects of functional electric stimulation cycle ergometry training on lower limb musculature in acute sci individuals. J Sports Sci Med. 2005;4(3):263-271.

3. Lai C, Chang W, Chan W, et al. Effects of functional electrical stimulation cycling exercise on bone mineral density loss in the early stages of spinal cord injury. J Rehabil Med. 2010;42(2):150-154. doi:10.2340/16501977-0499

4. Fouad K, Metz GAS, Merkler D, Dietz V, Schwab ME. Treadmill training in incomplete spinal cord injured rats. Behav Brain Res. 2000;115(1):107-113. doi:10.1016/S0166-4328(00)00244-8

5. Eser PC, Donaldson NdeN, Knecht H, Stussi E. Influence of different stimulation frequencies on power output and fatigue during FES-cycling in recently injured SCI people. IEEE Trans Neural Syst Rehabil Eng. 2003;11(3):236-240. doi:10.1109/TNSRE.2003.817677

6. Everaert DG, Okuma Y, Abdollah V, Ho C. Timing and dosage of FES cycling early after acute spinal cord injury: A case series report. J Spinal Cord Med. 2021;44(sup1):S250-S255. doi:10.1080/10790268.2021.1953323

7. Swaffield E, Cheung L, Khalili A, et al. Perspectives of people living with a spinal cord injury on activity-based therapy. Disabil Rehabil. Published online February 9, 2021:1-9. doi:10.1080/09638288.2021.1878293

8. Auchstaetter N, Luc J, Lukye S, et al. Physical Therapists' Use of Functional Electrical Stimulation for Clients With Stroke: Frequency, Barriers, and Facilitators. Phys Ther. 2016;96(7):995-1005. doi:10.2522/ptj.20150464

9. Griffin L, Decker MJ, Hwang JY, et al. Functional electrical stimulation cycling improves body composition, metabolic and neural factors in persons with spinal cord injury. J Electromyogr Kinesiol Off J Int Soc Electrophysiol Kinesiol. 2009;19(4):614-622. doi:10.1016/j.jelekin.2008.03.002

10. Johnston TE, Marino RJ, Oleson CV, et al. Musculoskeletal Effects of 2 Functional Electrical Stimulation Cycling Paradigms Conducted at Different Cadences for People With Spinal Cord Injury: A Pilot Study. Arch Phys Med Rehabil. 2016;97(9):1413-1422. doi:10.1016/j.apmr.2015.11.014

11. Martin R, Sadowsky C, Obst K, Meyer B, McDonald J. Functional electrical stimulation in spinal cord injury:: from theory to practice. Top Spinal Cord Inj Rehabil. 2012;18(1):28-33.

doi:10.1310/sci1801-28

12. van der Scheer JW, Goosey-Tolfrey VL, Valentino SE, Davis GM, Ho CH. Functional electrical stimulation cycling exercise after spinal cord injury: a systematic review of health and fitness-related outcomes. J Neuroengineering Rehabil. 2021;18(1):99. doi:10.1186/s12984-021-00882-8

13. Hartkopp A, Murphy RJ, Mohr T, Kjaer M, Biering-Sørensen F. Bone fracture during electrical stimulation of the quadriceps in a spinal cord injured subject. Arch Phys Med Rehabil. 1998;79(9):1133-1136. doi:10.1016/s0003-9993(98)90184-8

14. Baldi JC, Jackson RD, Moraille R, Mysiw WJ. Muscle atrophy is prevented in patients with acute spinal cord injury using functional electrical stimulation. Spinal Cord. 1998;36(7):463-469. doi:10.1038/sj.sc.3100679

15. Chilibeck PD, Jeon J, Weiss C, Bell G, Burnham R. Histochemical changes in muscle of individuals with spinal cord injury following functional electrical stimulated exercise training. Spinal Cord. 1999;37(4):264-268. doi:10.1038/sj.sc.3100785

16. Corbin GN, Weaver K, Dolbow DR, Credeur D, Pattanaik S, Stokic DS. Safety and preliminary efficacy of functional electrical stimulation cycling in an individual with cervical cord injury, autonomic dysreflexia, and a pacemaker: Case report. J Spinal Cord Med. 2021;44(4):613-616. doi:10.1080/10790268.2019.1692180

17. Dolbow DR, Credeur DP. Effects of resistance-guided high intensity interval functional electrical stimulation cycling on an individual with paraplegia: A case report. J Spinal Cord Med. 2018;41(2):248-252. doi:10.1080/10790268.2017.1367358

18. Bloomfield SA, Mysiw WJ, Jackson RD. Bone mass and endocrine adaptations to training in spinal cord injured individuals. Bone. 1996;19(1):61-68. doi:10.1016/8756-3282(96)00109-3

19. Crameri RM, Cooper P, Sinclair PJ, Bryant G, Weston A. Effect of load during electrical stimulation training in spinal cord injury. Muscle Nerve. 2004;29(1):104-111. doi:10.1002/mus.10522

20. Rayegani SM, Shojaee H, Sedighipour L, Soroush MR, Baghbani M, Amirani OB. The effect of electrical passive cycling on spasticity in war veterans with spinal cord injury. Front Neurol. 2011;2:39. doi:10.3389/fneur.2011.00039

21. Dolbow DR, Gorgey AS, Cifu DX, Moore JR, Gater DR. Feasibility of home-based functional electrical stimulation cycling: case report. Spinal Cord. 2012;50(2):170-171. doi:10.1038/sc.2011.115

22. Calabrò RS, Portaro S, Tomasello P, Porcari B, Balletta T, Naro A. Paving the way for a better management of pain in patients with spinal cord injury: An exploratory study on the use of Functional Electric Stimulation(FES)-cycling. J Spinal Cord Med. 2023;46(1):107-117. doi:10.1080/10790268.2021.1961050

23. Fattal C, Sijobert B, Daubigney A, et al. Training with FES-assisted cycling in a subject with spinal cord injury: Psychological, physical and physiological considerations. J Spinal Cord Med. 2020;43(3):402-413. doi:10.1080/10790268.2018.1490098

24. Farkas GJ, Gorgey AS, Dolbow DR, Berg AS, Gater DR. Energy Expenditure, Cardiorespiratory Fitness, and Body Composition Following Arm Cycling or Functional Electrical Stimulation Exercises in Spinal Cord Injury: A 16-Week Randomized Controlled Trial. Top Spinal Cord Inj Rehabil. 2021;27(1):121-134. doi:10.46292/sci20-00065

25. Phillips CA, Danopulos D, Kezdi P, Hendershot D. Muscular, respiratory and cardiovascular responses of quadriplegic persons to an F. E. S. bicycle ergometer conditioning program. Int J Rehabil Res Int Z Rehabil Rev Int Rech Readaptation. 1989;12(2):147-157. doi:10.1097/00004356-198906000-00003

26. Duffell LD, Rowlerson AM, Donaldson NDN, Harridge SDR, Newham DJ. Effects of endurance and strength-directed electrical stimulation training on the performance and histological properties of paralyzed human muscle: a pilot study. Muscle Nerve. 2010;42(5):756-763. doi:10.1002/mus.21746

27. Tong RKY, Wang X, Leung KWC, et al. How to prepare a person with complete spinal cord injury to use surface electrodes for FES trike cycling. IEEE Int Conf Rehabil Robot Proc. 2017;2017:801-805. doi:10.1109/ICORR.2017.8009346

28. Health Canada. Active device name search results. Published online May 4, 2023. Accessed June 24, 2023. https://health-products.canada.ca/mdall-limh/information?deviceId=222878&deviceName=RT300-S%20(ADULT%20VERSION)&licenceId=70774&type=active&lang=eng

29. Duffell LD, Donaldson N de N. A Comparison of FES and SCS for Neuroplastic Recovery After SCI: Historical Perspectives and Future Directions. Front Neurol. 2020;11:607. doi:10.3389/fneur.2020.00607

30. Chilibeck PD, Bell G, Jeon J, et al. Functional electrical stimulation exercise increases GLUT-1 and GLUT-4 in paralyzed skeletal muscle. Metabolism. 1999;48(11):1409-1413. doi:10.1016/s0026-0495(99)90151-8

31. Gerrits HL, de Haan A, Sargeant AJ, Dallmeijer A, Hopman MT. Altered contractile properties of the quadriceps muscle in people with spinal cord injury following functional electrical stimulated cycle training. Spinal Cord. 2000;38(4):214-223. doi:10.1038/sj.sc.3100974

32. Sijobert B, Fattal C, Daubigney A, Azevedo-Coste C. Participation to the first Cybathlon: an overview of the FREEWHEELS team FES-cycling solution. Eur J Transl Myol. 2017;27(4):7120. doi:10.4081/ejtm.2017.7120

33. Allison DJ, Chapman B, Wolfe D, Sequeira K, Hayes K, Ditor DS. Effects of a Functional Electrical Stimulation-Assisted Cycling Program on Immune and Cardiovascular

Health in Persons with Spinal Cord Injury. Top Spinal Cord Inj Rehabil. 2016;22(1):71-78. doi:10.1310/sci2201-71

34. Scremin AM, Kurta L, Gentili A, et al. Increasing muscle mass in spinal cord injured persons with a functional electrical stimulation exercise program. Arch Phys Med Rehabil. 1999;80(12):1531-1536. doi:10.1016/s0003-9993(99)90326-x

35. Jeon JY, Weiss CB, Steadward RD, et al. Improved glucose tolerance and insulin sensitivity after electrical stimulation-assisted cycling in people with spinal cord injury. Spinal Cord. 2002;40(3):110-117. doi:10.1038/sj.sc.3101260

36. Gurney AB, Robergs RA, Aisenbrey J, Cordova JC, McClanahan L. Detraining from total body exercise ergometry in individuals with spinal cord injury. Spinal Cord. 1998;36(11):782-789. doi:10.1038/sj.sc.3100698

37. Dolbow DR, Gorgey AS, Moore JR, Gater DR. Report of practicability of a 6-month home-based functional electrical stimulation cycling program in an individual with tetraplegia. J Spinal Cord Med. 2012;35(3):182-186. doi:10.1179/2045772312Y.0000000007

38. Mazzoleni S, Battini E, Rustici A, Stampacchia G. An integrated gait rehabilitation training based on Functional Electrical Stimulation cycling and overground robotic exoskeleton in complete spinal cord injury patients: Preliminary results. IEEE Int Conf Rehabil Robot Proc. 2017;2017:289-293. doi:10.1109/ICORR.2017.8009261

39. Gorgey AS, Graham ZA, Bauman WA, Cardozo C, Gater DR. Abundance in proteins expressed after functional electrical stimulation cycling or arm cycling ergometry training in persons with chronic spinal cord injury. J Spinal Cord Med. 2017;40(4):439-448. doi:10.1080/10790268.2016.1229397

40. Rennie S. Contraindications and precautions: an evidence-based approach to clinical decision making in physical therapy. In: Electrophysical Agents. ; 2010:1-3.

41. Burri H, Piguet V. UninTENSional pacemaker interactions with transcutaneous electrical nerve stimulation. Eur Eur Pacing Arrhythm Card Electrophysiol J Work Groups Card Pacing Arrhythm Card Cell Electrophysiol Eur Soc Cardiol. 2009;11(3):283-284. doi:10.1093/europace/eup008

42. Carlson T, Andréll P, Ekre O, et al. Interference of transcutaneous electrical nerve stimulation with permanent ventricular stimulation: a new clinical problem? Eur Eur Pacing Arrhythm Card Electrophysiol J Work Groups Card Pacing Arrhythm Card Cell Electrophysiol Eur Soc Cardiol. 2009;11(3):364-369. doi:10.1093/europace/eun351

43. Pyatt JR, Trenbath D, Chester M, Connelly DT. The simultaneous use of a biventricular implantable cardioverter defibrillator (ICD) and transcutaneous electrical nerve stimulation (TENS) unit: implications for device interaction. Eur Eur Pacing Arrhythm Card Electrophysiol J Work Groups Card Pacing Arrhythm Card Cell Electrophysiol Eur Soc Cardiol. 2003;5(1):91-93. doi:10.1053/eupc.2002.0277