



Response to Functional Electrical Stimulation Cycling in Women With Spinal Cord Injuries Using Dual-Energy X-ray Absorptiometry and Peripheral Quantitative Computed Tomography: A Case Series

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Abstract

Background: Loss of bone mass is common after spinal cord injury (SCI). One rehabilitation modality that has shown some promise for maintaining bone health is the functional electrical stimulation (FES) cycle ergometer. Although there has been some research investigating bone health and FES cycle ergometry, few have provided a detailed description of the changes that can occur in bone mass and soft-tissue mass.

Objective: To use 2 types of bone imaging, peripheral quantitative computed tomography (pQCT) and dual-energy X-ray absorptiometry (DXA), to provide a detailed description of bone and soft-tissue response to FES cycle ergometry training in women with SCI.

Study Design: Case series; a 6-month program of FES cycle ergometry for women with chronic motor complete (n = 2) and incomplete (n = 1) SCI.

Setting: Outpatient rehabilitation center in Canada.

Methods: Three women participated in a thrice weekly 6-month exercise program of FES cycle ergometry. We used DXA (lower extremity) and pQCT at the midshaft (50%) and distal (5%) sites of the tibia to assess bone density and soft-tissue mass before and after the exercise program.

Results: There was an increase or maintenance in bone mineral density by DXA and pQCT in the lower extremity for all 3 participants. Muscle mass by DXA increased in the lower extremity in 2 participants.

Conclusion: In this case series, we note a positive response in bone mass and soft-tissue mass in the lower extremity after a 6-month FES cycle ergometry program.

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Key Words: Spinal cord injuries; Bone density; Bone health; Bone mass; Functional electrical stimulation; Ergometry; Cycling; Exercise; Dual-energy radiographic absorptiometry; Peripheral quantitative computed tomography

INTRODUCTION

Lower extremity fractures can occur in people who sustain a spinal cord injury (SCI), and the majority of fractures take place during transfers or activities that

involve minimal or no trauma. Notable risk factors for these fractures after SCI include female gender, increasing age, and longer time since injury (1,2). A systematic review found some support for the use of pharmaceutical treatment to maintain bone mass after SCI but limited support for the use of rehabilitation modalities to maintain bone mineral density (BMD) or prevent bone loss (3). One rehabilitation modality that shows promise is functional electrical stimulation (FES) cycle ergometry, which uses surface electrodes placed in the lower extremity (hamstrings, quadriceps, and gluteal muscles)

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to simulate a cycling pattern. Previous research that tested the effect of FES cycle ergometry programs 6 months or longer in duration found limited evidence using dual-energy radiographic absorptiometry (DXA) at the hip and/or around the knee for maintaining or improving bone health in people more than 1 year after SCI (3). Most previous studies investigating the effect of FES cycle ergometry on bone health have used DXA as the imaging tool to estimate bone mass and density; however, a more advanced tool, peripheral quantitative computed tomography (pQCT), can provide a more detailed assessment of bone health at peripheral sites.

Therefore, our objective was to provide a detailed description of the effect of FES cycle ergometry on bone health and soft-tissue mass for people after SCI. Specifically, we used DXA to provide an estimate of the effect of FES cycle ergometry on lower-extremity BMD and soft-tissue mass and pQCT for an estimate of bone mass for the different tibial bone compartments.

METHODS

Participants

We recruited community-dwelling women with SCI using local advertisements. We included participants who sustained a traumatic SCI longer than 1 year in duration and were able to communicate in English. We excluded participants who had other neurologic conditions, unstable cardiovascular disease, unhealed wounds or pressure ulcers, previous low-trauma fracture(s), and/or abnormal bone formations in their lower extremity that limited hip or knee joint range of motion. All 3 participants were nonambulatory and used either power or manual wheelchairs for mobility. International standards for neurologic classification were used to describe the level and severity of SCI (4). Eligible participants gave written informed consent. The study was approved by the local hospital and university research ethics board.

FES Cycle Ergometry Training

The cycle training was performed using a computer controlled leg FES cycle ergometer (ERGYS 2, Version H.6, Therapeutic Alliances Inc, Fairborn, OH). Six surface electrodes (Uni-Patch, Wabasha, MN) provided electrical stimulation to 3 areas: hamstrings, gluteals, and quadriceps. Electrical stimulation occurred using a sinusoidal wave pulse of a 500-second duration at 60 Hz, and this was synchronized for each pair of electrodes and applied in a coordinated sequence of muscle contractions. The bike was programmed to increase the current from 0 to a preset maximum level with a preset pedaling cadence (eg, maximum cadence = 32 repetitions/min [rpm], fatigue = 18 rpm). The maximum level of electrical stimulation was determined according to each participant's sensation tolerance.

The 6-month program was divided into 2 phases: habituation and training. In phase 1, participants were asked to train for 3 sessions per week without any

resistance to become familiar with the bike (habituation). When participants were able to complete 30 minutes of continuous cycling for 2 consecutive sessions, the maximum speed was increased. When the participant was able to cycle for 30 minutes continuously between 49 rpm (maximum speed) and 35 rpm (fatigue), resistance was added (phase 2). During phase 2 (training), if the participant was able to maintain 90% of the preset pedal resistance for 30 minutes on 2 consecutive training sessions, resistance was increased with an increment of 1/8 kilopond (kp; corresponding to 6.1 watts at 50 rpm) at the next training session. When the pedaling rate dropped below 45 rpm and the maximum stimulation reached 100% of the preset level, the resistance was reduced automatically (eg, from 1/8 kp to 50% of 1/8 kp). At the end of each training session, the ERGYS 2 summarized the maximum and average resistance. Participants were asked to use the FES cycle ergometer thrice weekly for the habituation and training phases, which resulted in a 6-month cumulative training program.

Imaging

We used DXA (Hologic 4500, Bedford, MA) to obtain a whole body scan. We used the standard whole body analyses provided by the manufacturer. The outcomes from DXA leg scans were pre-post differences in BMD (g/cm^2), lean mass (g), and fat mass (g). We also used pQCT (Stratec Medizintechnik XCT 2000, software version 5.50; Pforzheim, Germany) to obtain bone images before and after the FES cycle ergometry training program. We obtained a 2.5-mm image of the tibia at the distal 5% and midshaft 50% site for each leg. These sites are commonly assessed using pQCT to provide an estimate of bone health in the trabecular (5% of the tibial length from the medial malleolus or just proximal to the ankle joint) and cortical (50% of the midshaft) compartments of the tibia. The outcomes from the tibial pQCT measurements were pre-post differences in total content (gm/mm) and total density (mg/cm^3) at the 5% site and cortical density (mg/cm^3) at the 50% site.

Statistical Analysis

Characteristics of the participants were reported as mean \pm SD. Within each participant, we compared differences in bone outcomes as a percent difference over time $[(\text{time } 2 - \text{time } 1)/\text{time } 1 \times 100]$. We considered maintenance of bone mass and muscle mass as $\pm 2\%$ and an increase as $\pm 3.9\%$ [$1.96 \times$ least significant change (2%)]. We used SPSS version 15 (SPSS, Chicago, IL).

RESULTS

Table 1 outlines characteristics of the 3 participants and their training regimen. Our 3 participants ranged in age from 19 to 51 years. Participant 3 had some nonfunc-

Table 1. Description of Participants in the Functional Electrical Stimulation Cycle Ergometry Case Series

	Participant 1	Participant 2	Participant 3
Age (y)	29	19	51
Level of injury	T4	C4	T7
Time since injury (y)	14	2.5	16
AIS classification			
Right leg motor score	A0	B0	C10
Left leg motor score	0	0	20
Total AIS leg motor score	0	0	30
Performance and Adherence to the Program			
Phase 1: habituation period (sessions)	15	25	13
Phase 2: training period (sessions)	36	36	34
Total FES cycle ergometry sessions	51	61	47
Total duration of program (weeks)	24	30	27
Mean number of sessions/week	2.1	2.4	1.7
Resistance at end of training sessions (kp ^a)	2/8	2/8	1/8

^a This is a unit of force equal to the gravitational force on a mass of 1 kg. AIS, ASIA Impairment Scale grade (4); FES, functional electrical stimulation.

tional motor activity on both legs (left > right). Overall, participant 2 (C4 level complete lesion) had the longest habituation phase (25 vs 13–15 sessions); however, she was able to reach 2/8th kilopond for resistance.

Soft-Tissue Mass (DXA)

Participants 1 and 2 increased lean mass in both legs after the 6-month program (12–37%), and participant 3 maintained lean mass. The fat mass of participants 1 and 3 remained the same, whereas participant 2 had 16 to 32% reduction in fat mass in the legs (Table 2).

Bone Mass (DXA and pQCT)

The 3 participants had a percent change in BMD by DXA in both legs that ranged from –1 to 16% (Table 2). With pQCT, there was maintenance of cortical bone density at the 50% site of the tibia for all participants that ranged from 0.51 to 1.24% (data not shown). At the predominantly trabecular distal site of the tibia, participants responded differently. At this site, participant 1 had maintenance of BMD in both legs, participant 2 had

gains in BMD for both legs (Table 3), and participant 3 only experienced an increase in BMD on the left leg.

DISCUSSION

In this case series, we noted a positive response in lean mass and bone density in the lower extremity in 3 women after a 6-month FES cycle ergometry program. To our knowledge, no previous studies have reported these detailed responses. Our participants had maintenance or an increase in soft-tissue mass and/or bone mass depending on the participant, site measured, and imaging technology. For 2 participants, there was a large increase in total BMD at the distal site of the tibia as measured by pQCT. The distal tibia is composed of predominantly trabecular bone surrounded by a thin cortical shell; because trabecular bone generally has a faster bone turnover cycle, it may therefore respond sooner to stimulation, such as an exercise intervention. It is possible that participants in previous studies had a similar response, but site-specific changes were not reported due to limitations in earlier imaging technology.

Table 2. Change in Bone Mineral Density, Lean Mass, and Percent Fat By Dual Energy Radiographic Absorptiometry

	Percent Change ^a	Participant 1	Participant 2	Participant 3
Left leg	Bone mineral density	15.63	–1.38	4.79
	Lean mass	12.25	36.9	–2.04
	Percent fat	–1.9	–31.82	1.03
Right leg	Bone mineral density	7.35	0.83	0.2
	Lean mass	17.97	23.43	0.01
	Percent fat	–2.44	–16.23	0.51

^a (Time 2 – Time 1)/Time 1 × 100.

Results are the percent difference of the legs for all participants at baseline and after the 6-month exercise program.

Table 3. Peripheral Quantitative Computed Tomography Results at the Distal 5% of the Tibia

	Percent Change ^a	Participant 1	Participant 2	Participant 3
Left leg	BMC	-5.6	10.8	38.1
	vBMD	-1.6	12.5	16.5
Right leg	BMC	-0.4	15.1	2.8
	vBMD	-1.1	13.5	-0.5

^a (Time 2 – Time 1)/Time 1 × 100.

BMC, bone mineral content; vBMD, volumetric bone mineral density.

The table represents total bone mineral content and total volumetric bone mineral density percent differences of the 5% site of the tibia before and after the 6-month exercise program.

There are 2 possible mechanisms by which these adaptations may have occurred. Because our participants were nonambulatory and reported that they did not change their physical activity patterns outside of the study, the exercise program may have contributed to the observed changes. Specifically, the FES cycle ergometry may have increased blood flow to the lower limbs with an increase to the trabecular bone compartment. Previous literature suggests that increased perfusion to bone could improve bone tissue (5). There is also the possibility that there was compression to the feet/lower limbs as the bike pedals moved through the range of motion. In particular, we note that participant 3 had a greater increase in bone density on her left leg that had some (nonfunctional) motor activity. This cyclic “loading” of the limb could be responsible for the observed increase in trabecular bone mineral content for this participant.

The differences in the observed changes among the 3 participants were an interesting finding. In participant 1, an increase in bone density and muscle mass by DXA was accompanied by maintenance in the distal tibia using pQCT. In contrast, participant 2 maintained leg BMD by DXA but increased in BMD at the distal tibia using pQCT. Participant 3 had a variable response: the leg with some motor activity experienced an increase in BMD. There was no change in bone density in any participant at the cortical midshaft site, where bone turnover is generally slower. Age, hormonal status, level of impairment, and time since injury may have contributed to the different responses observed. Interestingly, the largest bone changes occurred in the tibia of the participant who was the oldest and in whom the most years had passed since injury. This participant, however, had a motor incomplete injury, and the larger bone changes were observed on the side with some motor function. Perhaps these bone changes were a result of the interaction of the FES and innervated muscle.

In this case series, we used DXA and pQCT to observe changes in muscle and bone mass. There are notable differences between these 2 technologies. Dual-energy radiographic absorptiometry is considered by the World Health Organization to be the standard for the diagnosis of osteoporosis and can also provide a measure of body composition. Despite its many strengths, DXA provides a

2-dimensional view and therefore may be influenced by overall body size and/or soft-tissue mass. In contrast, pQCT can provide a more detailed view of bone geometry; however, it is not able to provide an estimate at the hip. In this case series, both imaging methods were useful in providing a more global view of bone health, as well as a more detailed look at bone compartments in response to the FES cycle ergometry.

CONCLUSIONS

We acknowledge that our results have limited generalizability due to our small sample size and the differences between our volunteers; however, the protocol described extends previous literature about the feasibility of using FES cycle ergometry for people with SCI. It is also possible that maintenance of bone mass was not a positive finding but, rather, the expected outcome. Evidence highlights a rapid loss of bone mass early after SCI. However, less is known about the long-term bone response to SCI. Recent literature suggests that a stabilization of bone mass in the lower extremity was not achieved within 3 years (6). Finally, we note that despite the potential benefits of FES cycle ergometry, possible barriers for some people are the cost, potential adverse effects, and time commitment. Despite these limitations, FES cycle ergometry has the potential to have a positive effect on bone density and muscle mass for people who have sustained an SCI. Further investigation is warranted.

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