# Functional Neuromuscular Electrical Stimulation

February 19, 2019

580.435/635 Applied Bioelectrical Engineering
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Department of Biomedical Engineering
Johns Hopkins University

## What you can expect to learn today

- Functional neuromuscular electrical stimulation
- Electrode placement
- Treatment of foot drop
- Activity based restorative therapy
- Modulation of skeletal muscle contraction
- Skin impedance
- Voltage vs current stimulation

2

# Clinical Rehabilitation Using Electrical Stimulation

- Therapeutic electrical stimulation (TES)
  - Strengthening muscle, increasing motor control, decreasing pain, increasing range of motion
- Functional electrical stimulation (FES)
  - Provides or assists functional tasks
  - Functional substitute in cases of injury or disease to the central nervous system
  - E.g. with stroke, traumatic brain injury, multiple sclerosis, cerebral palsy, spinal cord injury
  - Neuromuscular electrical stimulation (NMES)
    - Improvement of motor function
    - Control of hand or arm
    - Control of standing or walking
      - Treatment of foot drop (affects ~20% stroke survivors)

3

# Research on NMES for Clinical Rehabilitation

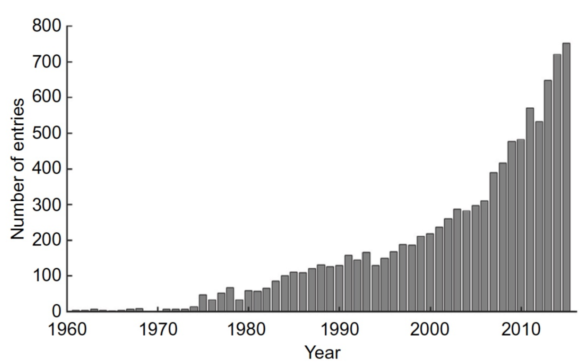
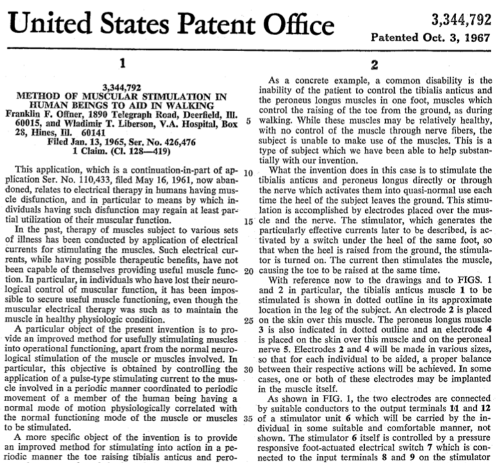



**Figure 1** Results of a PubMed (service of the US National Library of Medicine [https://www.ncbi.nlm.nih.gov/pubmed/]) search for ("electrical stimulation" OR "electrical muscle stimulation" OR "electrical nerve stimulation" OR FES OR NMES) AND (stroke OR "cerebrovascular disease" OR hemiplegic OR hemiparetic OR hemiparesis OR paralysis OR rehabilitation).
**Abbreviations:** FES, functional electrical stimulation; NMES, neuromuscular electrical stimulation.

4

# Early Patent


United States Patent Office

3,344,792
Patented Oct. 3, 1967

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3,344,792
METHOD OF MUSCULAR STIMULATION IN HUMAN BEINGS TO AID IN WALKING
Franklin F. Offner, 1890 Telegraph Road, Deerfield, Ill. 60015, and Wladimir T. Liberson, V.A. Hospital, Box 28, Hines, Ill. 60141
Filed Jan. 13, 1965, Ser. No. 426,476
1 Claim. (Cl. 128—419)

This application, which is a continuation-in-part of application Ser. No. 110,433, filed May 16, 1961, now abandoned, relates to electrical therapy in humans having muscle disfunction, and in particular to means by which individuals having such disfunction may regain at least partial utilization of their muscular function.

In the past, therapy of muscles subject to various sets of illness has been conducted by application of electrical currents for stimulating the muscles. Such electrical currents, while having possible therapeutic benefits, have not been capable of themselves providing useful muscle function. In particular, in individuals who have lost their neurological control of muscular function, it has been impossible to secure useful muscle functioning, even though the muscular electrical therapy was such as to maintain the muscle in healthy physiologic condition.

A particular object of the present invention is to provide an improved method for usefully stimulating muscles into operational functioning, apart from the normal neurological stimulation of the muscle or muscles involved. In particular, this objective is obtained by controlling the application of a pulse-type stimulating current to the muscle involved in a periodic manner coordinated to periodic movement of a member of the human being having a normal mode of motion physiologically correlated with the normal functioning mode of the muscle or muscles to be stimulated.

A more specific object of the invention is to provide an improved method for stimulating into action in a periodic manner the toe raising tibialis anticus and pero-

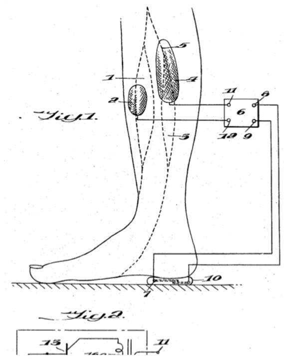
2

As a concrete example, a common disability is the inability of the patient to control the tibialis anticus and the peroneus longus muscles in one foot, muscles which control the raising of the toe from the ground, as during walking. While these muscles may be relatively healthy, with no control of the muscle through nerve fibers, the subject is unable to make use of the muscles. This is a type of subject which we have been able to help substantially with our invention.

What the invention does in this case is to stimulate the tibialis anticus and peroneus longus directly or through the nerve which activates them into quasi-normal use each time the heel of the subject leaves the ground. This stimulation is accomplished by electrodes placed over the muscle and the nerve. The stimulator, which generates the particularly effective currents later to be described, is activated by a switch under the heel of the same foot, so that when the heel is raised from the ground, the stimulator is turned on. The current then stimulates the muscle, causing the toe to be raised at the same time.

With reference now to the drawings and to FIGS. 1 and 2 in particular, the tibialis anticus muscle **1** to be stimulated is shown in dotted outline in its approximate location in the leg of the subject. An electrode **2** is placed on the skin over this muscle. The peroneus longus muscle **3** is also indicated in dotted outline and an electrode **4** is placed on the skin over this muscle and on the peroneal nerve **5**. Electrodes **2** and **4** will be made in various sizes, so that for each individual to be aided, a proper balance between their respective actions will be achieved. In some cases, one or both of these electrodes may be implanted in the muscle itself.

As shown in FIG. 1, the two electrodes are connected by suitable conductors to the output terminals **11** and **12** of a stimulator unit **6** which will be carried by the individual in some suitable and comfortable manner, not shown. The stimulator **6** itself is controlled by a pressure responsive foot-actuated electrical switch **7** which is connected to the input terminals **8** and **9** on the stimulator





# Human Gait Cycle

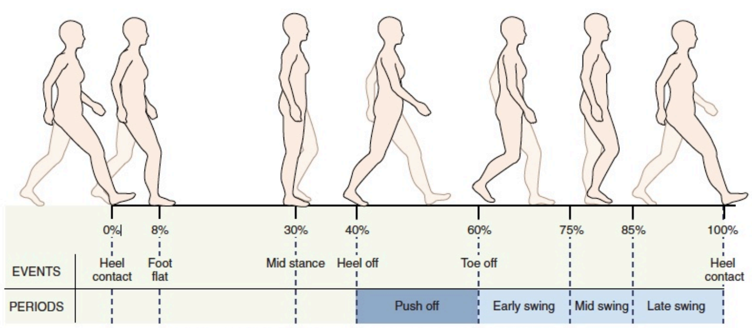



FIGURE 15-11. Traditional subdivisions of the gait cycle.

# Human Gait Cycle

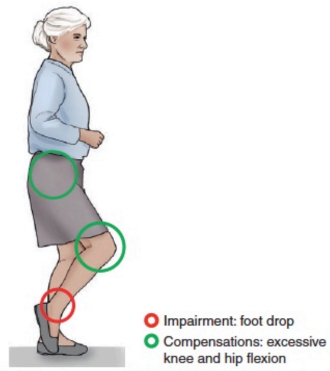
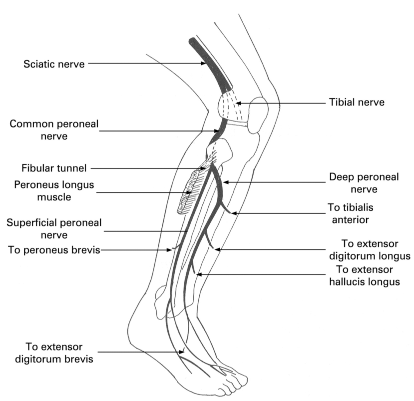
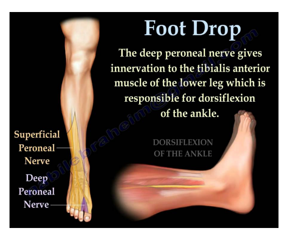


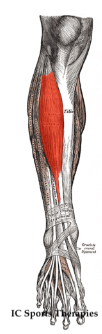

**FIGURE 15-46.** Weak ankle dorsiflexors may result in a foot drop during swing phase, requiring excessive hip and knee flexion for the toes to clear the ground as the limb is advanced forward during swing.

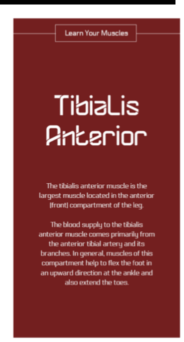
7

# Foot Drop and Loss of Gait Function




8

# WalkAide




# WalkAide (Innovative Neurotronics, Reno, NV)


**Figure 3** WalkAide system.
**Notes:** Surface electrode pads (red arrows) are fixed by a cuff to the leg below the knee. The stimulator is also tied to the cuff. Initially, a clinician connects a hand switch device (black arrow head) to the stimulator to dorsiflex the ankle manually during the swing phase of the patient's gait. The specific stimulation timing is then programmed, so that the electrical stimulation can be accurately performed consequently with the stimulator alone. A heel sensor under the insole of shoe or a tilt sensor built in the stimulator is used as a measure of the patient's gait. Image courtesy of Innovative Neurotronics, Inc., Austin, TX, USA.

# NESS L300 (Bioness, Valencia, CA)


**Figure 4** Commercial FES devices.
**Notes:** (**A**) NESS L300 and wireless foot switch for gait and (**B**) NESS H200, which is worn over the paralyzed arm and hand. Image courtesy of Bioness Inc., Valencia, CA, USA.
**Abbreviation:** FES, functional electrical stimulation.

11

# Axelgaard ValuTrode® electrodes

- Reusable, self-adhering, OTC neurostimulation electrode
- 4 basic components
  - Cloth cover material
  - Lead wire with insulation on female connector
  - Conductive carbon film
  - Conductive MultiStick® hydrogel: 4-layer glycerin, water and poly(acrylate) co-polymer hydrogel

12

## Ankle Dorsiflexion


13

## Ankle Dorsiflexion (inappropriate)


14

# Transcutaneous (surface) Electrodes

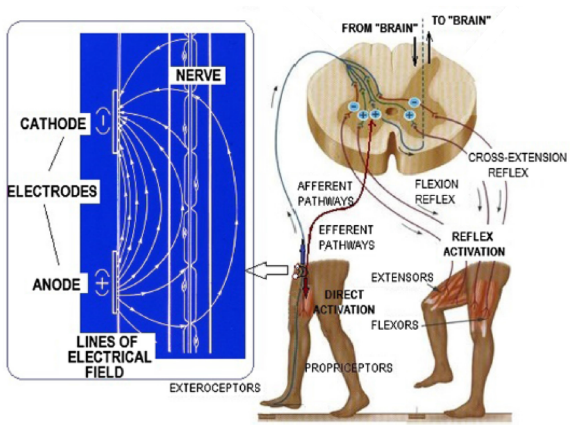



**Fig. 1.** Model of the effects of peripheral electrical stimulation. The stimulator generates a voltage that creates a pulsatile electrical field that activates afferent and efferent neurons, resulting in direct activation of the muscles that are innervated by the stimulated nerve and several reflex responses.



# Nerve Cuff Electrodes

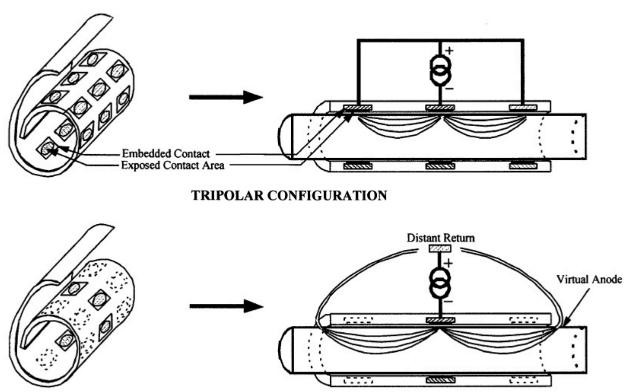



Fig. 1. Monopolar and tripolar cuff electrode configurations (*left*). Schematics of the resultant current flow (*right*).

# Percutaneous Electrodes

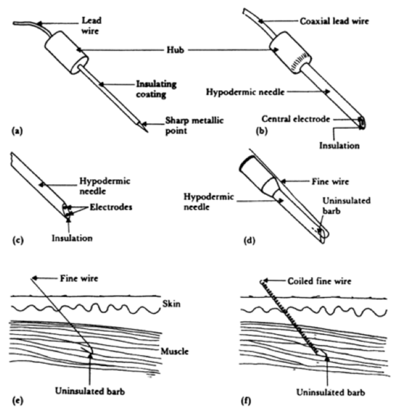



**Figure 5.19 Needle and wire electrodes for percutaneous measurement of biopotentials** (a) Insulated needle electrode. (b) Coaxial needle electrode. (c) Bipolar coaxial electrode. (d) Fine-wire electrode connected to hypodermic needle, before being inserted. (e) Cross-sectional view of skin and muscle, showing fine-wire electrode in place. (f) Cross-sectional view of skin and muscle, showing coiled fine-wire electrode in place.

17

# Percutaneous Electrodes

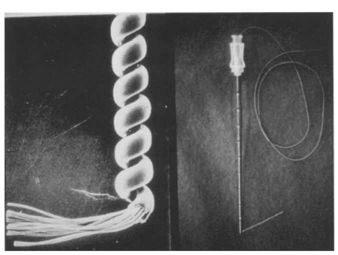


**Fig. 2.** Percutaneous intramuscular electrode

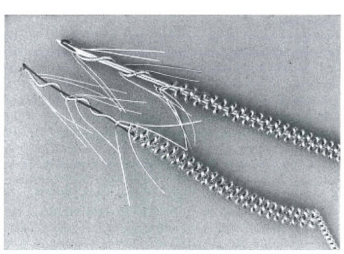


**Figure 1.** Double-helix intramuscular electrode used for FES. The top electrode is mounted on a 26-gauge needle for implantation.

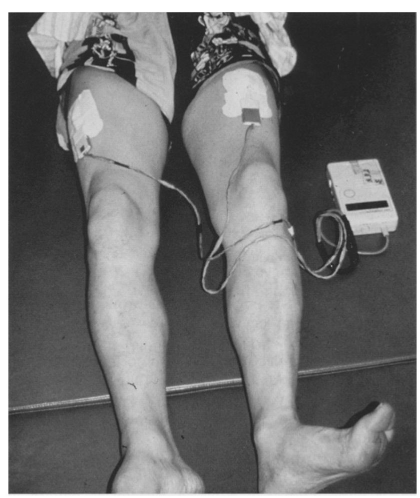


**Fig. 4.** Entry points of electrodes at anterior thighs

18

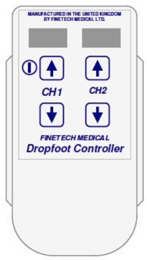
# STIMuSTEP (Finetech Medical, Hertfordshire, UK)

(no longer marketed)

Finetech Medical

*SPECIALISTS IN THE MANUFACTURE AND DESIGN OF ACTIVE SURGICAL IMPLANTS*

***THE STIMuSTEP® SYSTEM***



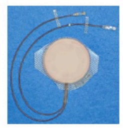

CE 0086

*Helping to Correct the Dropped Foot Condition*

***WHAT IS THE STIMuSTEP® SYSTEM?***

The system is designed to assist people with the correction of the dropped foot condition in patient who have had a stroke or got Multiple Sclerosis (MS). The system comprises of two main parts:

- The **Implanted Stimulator.**
- The **External Components**, include the Controller, Leg strap, Footswitch and Battery charger.

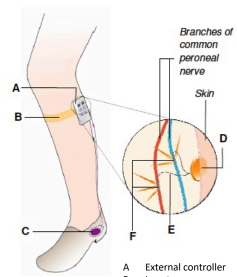


*Implant Receiver*

***HOW IT WORKS?***

The External Controller (A) is positioned over the site of the Implant Receiver (D) using the Leg Strap (B). The Footswitch (C) is placed under the heel of the foot inside the shoe and plugged into the External Controller.

While the External Controller is switched on, stimulation will start when the heel leaves the floor. While the heel is lifting, the implant stimulates the two branches of the common peroneal nerve causing the combination of muscles to contract appropriately, thus lifting and rotating the foot to the correct position for walking. Stimulation stops when the heel struck the ground.




A External controller
B Leg strap
C Footswitch
D Implant receiver
E Cooper cables
F Electrodes



# Strength-Duration Curves for Nerve and Muscle

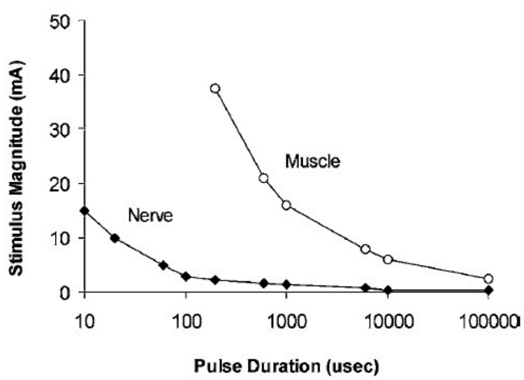



**Figure 1** Strength-duration curve for nerve and muscle tissue. Stimulus magnitude required to produce a constant muscle response in normal and pharmacologically denervated cat tibialis anterior. Modified after figure 20 in Reference 2.

# Neuroprosthesis Systems

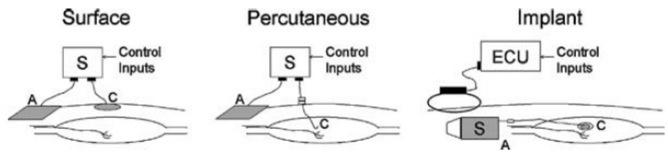



**Figure 2** Neuroprosthetic system configurations. S = stimulator, A = anode (reference electrode), C = cathode (active electrode), ECU = external control unit. Single-channel monopolar stimulation of one muscle near its motor point is shown for a surface, percutaneous, and implanted system.



# Implantable Stimulators

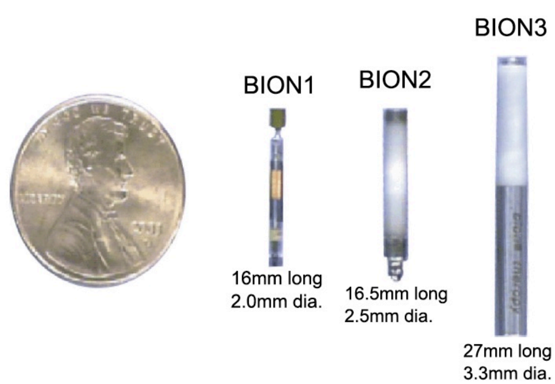



**Fig. 3.** Three generations of implantable BION microstimulator (Loeb et al., 2004, 2006). Reproduced with permission from Rockwater, Inc.

Still largely a research device.

# KKI International Center for Spinal Cord Injury Activity Based Restorative Therapy



# RT300 (Restorative Therapies, Baltimore, MD)


Closed loop control

# Components of Skeletal Muscle

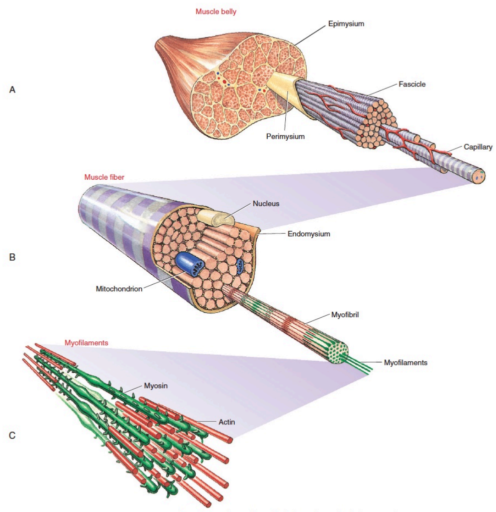



**FIGURE 3-1.** Basic components of muscle are shown, from the belly to the individual contractile, or active, proteins (myofilaments). Three sets of connective tissues are also depicted. **A,** The muscle belly is enclosed by the *epimysium;* individual fascicles (groups of fibers) are surrounded by the *perimysium*. **B,** Each muscle fiber is surrounded by the *endomysium*. Each *myofibril* within the muscle fibers contains many myofilaments. **C,** These filaments consist of the contractile proteins of actin and myosin. (Modified from Standring S: *Gray's anatomy: the anatomical basis of clinical practice*, ed 39, New York, 2005, Churchill Livingstone.)



# NMES Waveforms

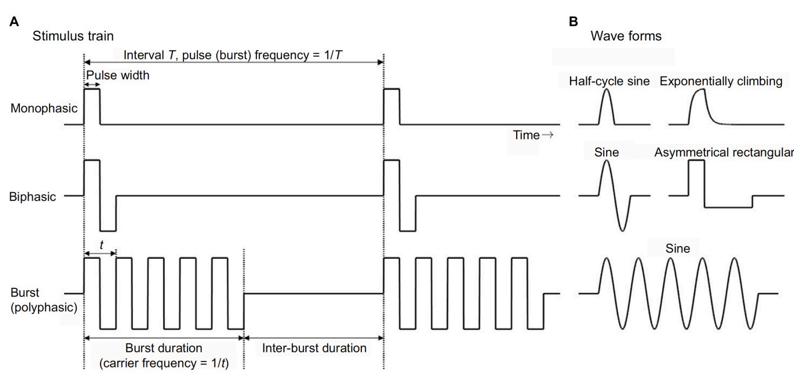



**Figure 2** Parameters of NMES.
**Notes:** (**A**) Monophasic, biphasic, and polyphasic stimulus train. (**B**) Examples of wave forms. A specific stimulus, burst sine wave of carrier frequency of 2,500 Hz and burst and inter-burst duration of 10 ms is called a Russian current.
**Abbreviation:** NMES, neuromuscular electrical stimulation.

Monophasic vs biphasic?

# Preset Stimulation (Trapezoidal Envelope)

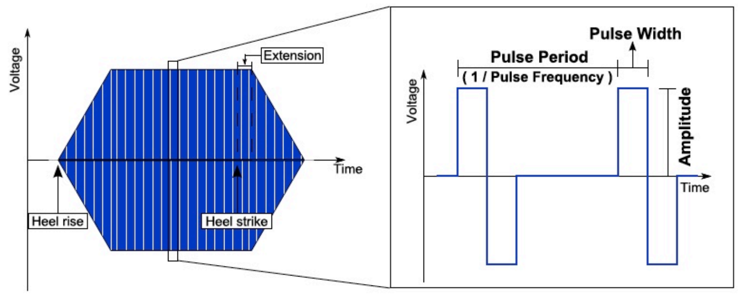



Fig. 1. Typical trapezoidal waveform used by most FES commercial systems, with balanced charges, posing no threat to tissue integrity. Note: Figure not drawn to scale.

27

# Skeletal Muscle Contraction

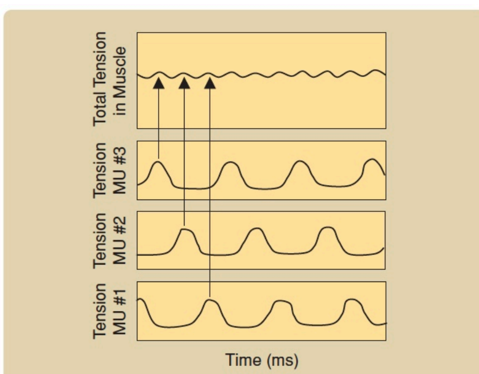



FIGURE 2 Summation of tension in motor units. The production of tension in skeletal muscle is accomplished by sequentially stimulating adjacent motor units, abbreviated "MU" in the figure. The stimulation is timed by the intact neurological system so that each motor unit contracts before the previously stimulated motor unit relaxes completely. The tension in the overall muscle is the sum of the tensions in the individual motor units. (Adapted from [22].)

Asynchronous spatial summation occurs physiologically

28

## Skeletal Muscle Contraction

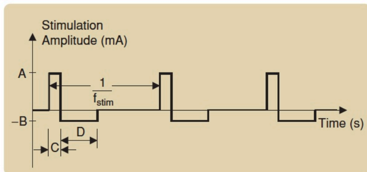



FIGURE 3 Stimulation pulse train. A typical stimulation waveform used for transcutaneous FES is a biphasic square-wave pulse train with a frequency of 20–40 Hz, an amplitude of 0–120 mA, and a pulse duration of 0–300 $\mu$s. A biphasic waveform is used because it induces charge transfer into the tissue and then immediately induces charge transfer out of the tissue. This pattern of charge transfer prevents galvanic processes that can cause tissue damage [18]. Notice that the amount of charge transferred into the tissue (given by the product AC) is the same as the charge transferred out of the tissue (given by the product BD).

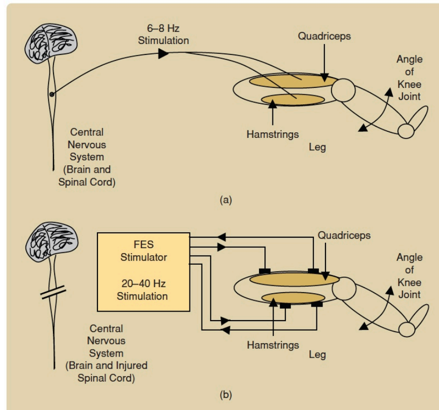



FIGURE 4 Production of tension in neurologically intact and spinal cord injured individuals. The angle of a joint, or the torque about that joint, can be regulated by varying the tension produced in the flexor and extensor muscles that actuate the joint. For the knee joint, the flexor muscles are the hamstrings group, while the extensor muscles are the quadriceps group. The hamstrings flex the knee to a bent position, while the quadriceps extend the knee and straighten the leg. (a) The intact neurological system produces tetanic contractions, which are characterized by sustained, constant tension, by stimulating each motor unit at a frequency of 6–8 Hz. Adjacent motor units are stimulated sequentially so that the overall muscle produces a tetanic contraction. If the muscle tension produced by the tetanic contraction is sufficiently high, the knee angle changes, as shown. (b) A functional electrical stimulation (FES) system can produce tetanic contractions in a spinal cord injured subject. However, the system must stimulate at 20–40 Hz to achieve this result because the individual motor units cannot be stimulated sequentially with FES.

29

## Modulated Preset Stimulation (Foot Switch)

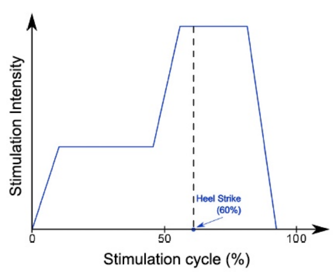



Fig. 2. Modulated stimulation profile (O'Halloran et al., 2003). Adapted and reproduced with permission from Elsevier.

30

# EMG Modulation of Intensity of Electrical Stimulation

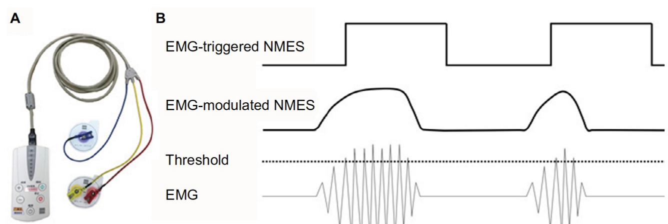



**Figure 7** (**A**) The IVES+ system (OG Wellness Technologies Co., Ltd.) that is currently used in Fujita Health University Nanakuri Memorial Hospital. (**B**) EMG-triggered and EMG-modulated modes can be used for this device. In the former mode, NMES is applied with a constant current intensity for a fixed time when an EMG that exceeds a predefined threshold is detected. In the latter mode, the intensity of the stimulation current is proportional to the amplitude of EMG.
**Abbreviations:** IVES, integrated volitional control electrical stimulator; EMG, electromyogram; NMES, neuromuscular electrical stimulation.

31

# Closed Loop Control

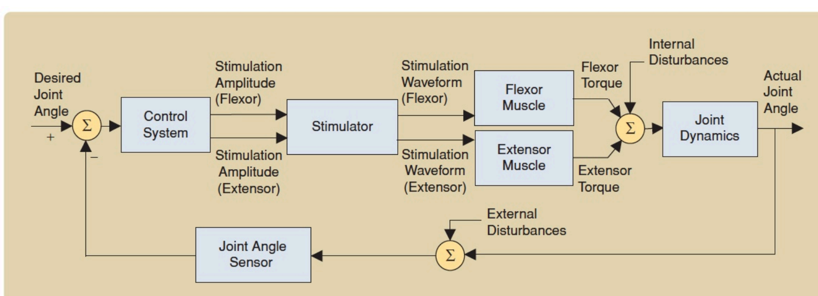



FIGURE 6 Functional electrical stimulation (FES) control system. This generic closed-loop FES system regulates joint angle by controlling the stimulation delivered to the flexor and extensor muscle groups. The input to the controller is the error between the desired and actual joint angles, while the controller's output is the required stimulation amplitude for each muscle group. The stimulator delivers a biphasic waveform with the required amplitude to each muscle group. A delay of 10–50 ms occurs between the onset of stimulation and the production of tension in the muscle [25], [26]. This delay is due to the biochemical processes that transduce electrical stimulation to muscle tension. When the stimulation causes sufficient tension in the muscle to overcome any opposing torques acting on the joint, the resulting change in joint angle is detected by the sensor in the feedback path. Although internal disturbances due to muscle spasms and spinal reflexes are shown as additional torques acting on the joint, these inputs are often treated alternatively as exogenous control signals. Also, external disturbances, such as the limb being bumped, might perturb the joint angle, as shown in the figure.

32

## Surface Electrodes

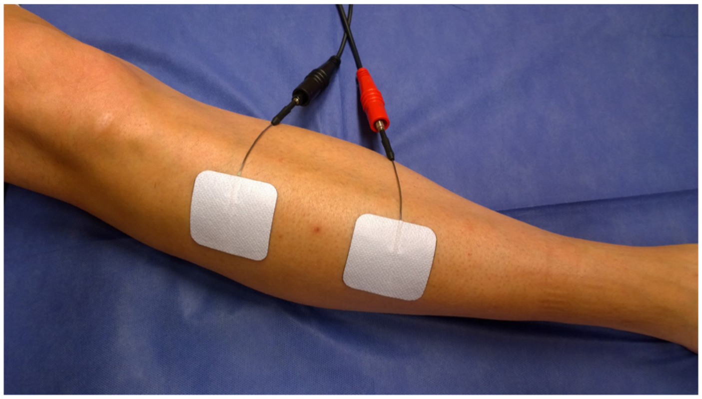


**Fig. 3** Stimulation of the tibialis anterior muscle (TA). Positioning of electrodes in bipolar arrangement with two 50Å~50 mm adhesive electrodes were used for the stimulation of the TA. Electrodes (anode and cathode) were placed over the muscle in its longitudinal plane, with one electrode at the proximal end of the muscle belly and the other electrode at the distal end of the muscle belly

33

## Anatomy of Skin

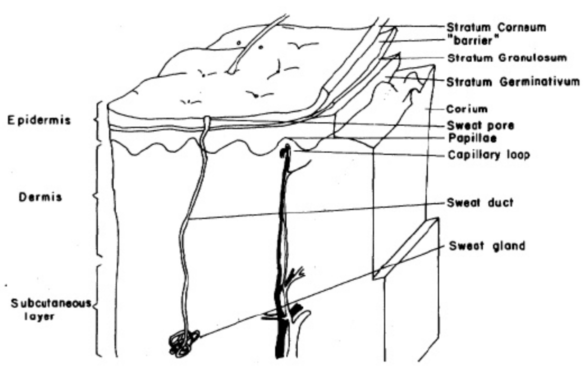



Fig. 5. Schematic diagram of the skin.

34

# Electrode on Skin Surface

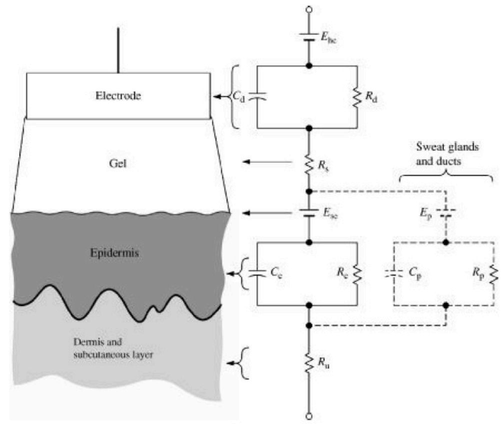
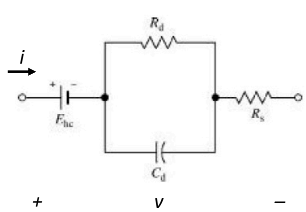



**Figure 5.8** A body-surface electrode is placed against skin, showing the total electrical equivalent circuit obtained in this situation. Each circuit element on the right is at approximately the same level at which the physical process that it represents would be in the left-hand diagram.

35

# Constant Current vs Constant Voltage Pulses

Electrode impedance




What are the pros and cons of each modality?

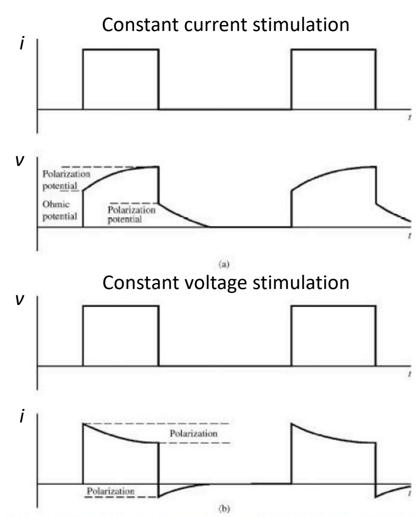



**Figure 5.23** Current and voltage waveforms seen with electrodes used for electric stimulation (a) Constant-current stimulation. (b) Constant-voltage stimulation.

36

**190219 Slide Notes**

**Slide 3**
Schuhfried O, Crevenna R, Fialka-Moser V, Paternostro-Sluga T. Non-invasive neuromuscular electrical stimulation in patients with central nervous system lesions: an educational review. *J Rehabil Med.* 2012;**44**:99-105
Melo PL, Silva MT, Martins JM, Newman DJ. Technical developments of functional electrical stimulation to correct drop foot: sensing, actuation and control strategies. *Clin Biomech (Bristol, Avon).* 2015;**30**:101-113

**Slide 4**
Takeda K, Tanino G, Miyasaka H. Review of devices used in neuromuscular electrical stimulation for stroke rehabilitation. *Med Devices (Auckl).* 2017;**10**:207-213

**Slide 5**
U.S. Patent 3,344,792. Method of muscular stimulation in human beings to aid in walking. Franklin F. Offner, 1967.

**Slides 6 & 7**
Simoneau GG. Kinesiology of walking. Chap, 15, pp. 627-671. In: Neumann DA. Kinesiology of the Musculoskeletal System: Foundations for Physical Rehabilitation, 2nd Ed. Mosby, Elsevier, St. Louis, MO, 2010.

**Slide 8**
http://www.stepwards.com/?page_id=1482
From: Foot Drop, Peroneal Nerve Injury – Everything You Need to Know – Dr. Nabil Ebraheim
https://www.youtube.com/watch?v=J7-L9MFRXD8
https://icsportstherapies.com.au/posts/monday-muscle-9/

**Slide 9**
http://www.walkaide.com/patients/Pages/HowWalkAideWorks.aspx

**Slide 10**
Takeda K, Tanino G, Miyasaka H. Review of devices used in neuromuscular electrical stimulation for stroke rehabilitation. *Med Devices (Auckl).* 2017;**10**:207-213
http://www.walkaide.com/news/Pages/OnlinePhotoLibrary.aspx

**Slide 11**
Takeda K, Tanino G, Miyasaka H. Review of devices used in neuromuscular electrical stimulation for stroke rehabilitation. *Med Devices (Auckl).* 2017;**10**:207-213

**Slide 12**
https://www.axelgaard.com/Products/Electrodes/ValuTrode/Cloth

**Slide 13**
https://www.axelgaard.com/Education/Ankle-Dorsiflexion
PULSE WIDTH: 300uSEC HZ: 35 WAVEFORM: Asymmetric STIMULATION GRADE: 3/5
Electrode configuration for ankle dorsiflexion. The fibular head is marked, and the lateral malleolus is visible. An asymmetric biphasic waveform is used, with the negative electrode placed over the muscle belly of the anterior tib, very midline close to the tibia. The positive electrode is also placed close to the tibia, further down the shank. During stimulation a three out of five contraction can be seen, with good balance of the foot and minimal activation of the toe extensors.

**Slide 14**
https://www.axelgaard.com/Education/Ankle-Dorsiflexion-Inappropriate-Placement
PULSE WIDTH: 300uSEC HZ: 35 WAVEFORM: Asymmetric STIMULATION GRADE: N/A
Electrode placement for ankle dorsiflexion stimulation- inappropriate placement. On this same subject, the negative electrode has been moved laterally on the anterior tibial muscle about one centimeter. The result in the stimulation is activation of the peroneus longus muscles as well as the extrinsic toe extensors, resulting in inappropriate eversion and toe extension. This is not acceptable for therapeutic purposes.

**Slide 15**
Popovic DB. Advances in functional electrical stimulation (FES). *J Electromyogr Kinesiol.* 2014;**24**:795-802

Fig. 1. Model of the effects of peripheral electrical stimulation. The stimulator generates a voltage that creates a pulsatile electrical field that activates afferent and efferent neurons, resulting in direct activation of the muscles that are innervated by the stimulated nerve and several reflex responses. The top part of the figure presents two aspects that need to be considered: the lesion and the complex networking involved in the control of movement.

**Slide 16**
Taghipour-Farshi H, Frounchi J, Ahmadiasl N, Shahabi P, Salekzamani Y. Effect of contacts configuration and location on selective stimulation of cuff electrode. *Biomed Mater Eng.* 2015;**25**:237-248

**Slide 17**
Neuman MR. Biopotential electrodes. Chap. 5. In: Webster JG, Medical Instrumentation: Application and Design. John Wiley & Sons, Hoboken, NJ, 1977.

**Slide 18**
Shimada Y, Ando S, Chida S. Functional electrical stimulation. *Artif LIfe Robotics.* 2000;**4**:212-219
Fig. 2. Percutaneous intramuscular electrode.
Fig. 4. Entry points of electrodes at anterior thighs
Agarwal S, Kobetic R, Nandurkar S, Marsolais EB. Functional electrical stimulation for walking in paraplegia: 17-year follow-up of 2 cases. *J Spinal Cord Med.* 2003;**26**:86-91
Figure 1. Double-helix intramuscular electrode used for FES. The top electrode is mounted on a 26-gauge needle for implantation.
"The advantages of this system over surface stimulation are the reliable and reproducible selective activation of paralyzed muscles, stimulation of deep muscles, and reduction of painful stimulation in individuals who have had a stroke."

**Slide 19**
http://finetech-medical.co.uk/en-gb/products/stimustep®droppedfootsystem.aspx
http://finetech-medical.co.uk/Portals/0/PL003i00C%20STIMuSTEP%20Leaftlet.pdf

**Slides 20 & 21**
Peckham PH, Knutson JS. Functional electrical stimulation for neuromuscular applications. *Annu Rev Biomed Eng.* 2005;**7**:327-360

**Slide 22**
Melo PL, Silva MT, Martins JM, Newman DJ. Technical developments of functional electrical stimulation to correct drop foot: sensing, actuation and control strategies. *Clin Biomech (Bristol, Avon).* 2015;**30**:101-113

**Slide 23**
Courtesy of International Center for Spinal Cord Injury, Kennedy Krieger Institute
Christine Sadowsky, Clinical Director of the International Center for Spinal Cord Injury, KKI, and Director of the Paralysis Restoration Clinic, KKI
See also:
https://www.kennedykrieger.org/patient-care/patient-care-centers/international-center-spinal-cord-injury/clinical-program/our-approach

**Slide 24**
https://www.restorative-therapies.com/rt300_clinic_leg_fes_rehabilitation_therapy_system
RT300 is a $25,000 machine.

**Slide 25**
Hunter SK, Brown DA. Muscle: the primary stabilizer and mover of the skeletal system. In: Neumann DA. Kinesiology of the Musculoskeletal System: Foundations for Physical Rehabilitation, 2nd Ed. Mosby, Elsevier, St. Louis, MO, 2010.
**FIGURE 3-1.** Basic components of muscle are shown, from the belly to the individual contractile, or active, proteins (myofilaments). Three sets of connective tissues are also depicted. **A,** The muscle belly is enclosed by the *epimysium*; individual fascicles (groups of fibers) are surrounded by the *perimysium*. **B,** Each muscle fiber is surrounded by the *endoymysium*. Each *myofibril* within the muscle fibers contains many myofilaments. **C,** These filaments consist of the contractile proteins of actin and myosin. (Modified from Standring S: *Gray's anatomy: the anatomical basis of clinical practice*, ed 39, New York, 2005, Churchill Livingstone.)

**Slide 26**
Takeda K, Tanino G, Miyasaka H. Review of devices used in neuromuscular electrical stimulation for stroke rehabilitation. *Med Devices (Auckl).* 2017;**10**:207-213

**Slide 27**
Melo PL, Silva MT, Martins JM, Newman DJ. Technical developments of functional electrical stimulation to correct drop foot: sensing, actuation and control strategies. *Clin Biomech (Bristol, Avon).* 2015;**30**:101-113
Ramping up and down avoids sudden responses and more physiological type of contraction.

**Slide 28**
Lynch CL, Popovic MR. Functional electrical stimulation. Closed-loop control of induced muscle contractions. *IEEE Control Sys Mag.* 2008:40-50
Increase in muscle force achieved by increased amplitude, duration or frequency of stimulation (spatial and termporal summation). But spatial summation is non-physiological, since motor units are activated synchronously.

**Slide 29**
Lynch CL, Popovic MR. Functional electrical stimulation. Closed-loop control of induced muscle contractions. *IEEE Control Sys Mag.* 2008:40-50
FES recruits motor units in a synchronous, non-physiological manner. This means higher frequencies are required to achieve tetanic contraction, and the muscle is more prone to fatigue. FES also recruits fast-twitch fibers before slow-twitch fibers (nonphysiological recruitment) because fast-twich fibers are innervated by larger diameter axons. This also leads to greater muscle fatigue.

**Slide 30**
Melo PL, Silva MT, Martins JM, Newman DJ. Technical developments of functional electrical stimulation to correct drop foot: sensing, actuation and control strategies. *Clin Biomech (Bristol, Avon).* 2015;**30**:101-113
Increased intensity just before heel strike improved plantarflextion during loading response. Prolonging stimulus after heel strike helps to control slap foot (plantarflexion).

**Slide 31**
Takeda K, Tanino G, Miyasaka H. Review of devices used in neuromuscular electrical stimulation for stroke rehabilitation. *Med Devices (Auckl).* 2017;**10**:207-213

**Slide 32**
Lynch CL, Popovic MR. Functional electrical stimulation. Closed-loop control of induced muscle contractions. *IEEE Control Sys Mag.* 2008:40-50

**Slide 33**
Pieber K, Herceg M, Paternostro-Sluga T, Schuhfried O. Optimizing stimulation parameters in functional electrical stimulation of denervated muscles: a cross-sectional study. *J Neuroeng Rehabil.* 2015;**12**:51

**Slide 34**
Tam HW, Webster JG. Minimizing electrode motion artifact by skin abrasion. *IEEE Trans Biomed Eng.* 1977;**24**:134-139

**Slides 35 & 36**
Neuman MR. Biopotential electrodes. Chap. 5, pp. 189-240. In: Webster JG, Medical Instrumentation: Application and Design, 4$^{th}$ ed. John Wiley & Sons, Hoboken, NJ, 2010.