Preliminary Study of Functional Electrical Stimulation:

Application of swinging trajectory based on Knee-Joint range-of-motion (ROM)

M.K.I.Ahmad[1]
[1]Department of Mechatronic and Robotic Engineering,
[3]Modeling and Simulation Research Laboratory,
Faculty of Electrical and Electronic Engineering,
Universiti Tun Hussein Onn Malaysia, MALAYSIA
mohdkhairulikhwan@gmail.com

B.S.K.K.Ibrahim[1,3], A.U.Shamsudin[1], D. Hanafi[1],
M. Mahadi Abdul Jamil[2,3], N.H.M.Nasir[1,3],
F. Sherwani[1,3], K.A.A.Rahman[1,3], A.Masdar[2,3]
[1]Department of Mechatronic and Robotic Engineering,
[2]Department of Electronic Engineering,
[3]Modeling and Simulation Research Laboratory,
Faculty of Electrical and Electronic Engineering,
Universiti Tun Hussein Onn Malaysia, MALAYSIA
he130106@siswa.uthm.edu.my

***Abstract*— Nowadays, research and developments of control system for spinal cord injury (SCI) using functional electrical stimulation (FES) is widely used. Restoring mobility to persons with paraplegia with regard to FES-approaches for function restoration is really challenging issues. A sarcastic view of FES is the complexity control of muscle motor function by the artificial activation of paralyzed muscles. Therefore; laboratory apparatus setup to study the knee joint control by FES electrical stimulation test with computer-controlled stimulator system consisted of Matlab/Simulink-Hasomed has been arranged. Anthropometric measurements of length of the lower limb were made. Novel wearable lower limb suit developed for FES experimental. This scenario can be seen by monitoring the sinusoidal stimulation current range muscle contraction on able-bodied (AB) subject with the simulation work was applied on knee joint swinging trajectory range-of-motion. Significant value of sinusoidal stimulation current signal is determined and regulated to vary within potential of preliminary data mining attempts to model an efficient power consume of knee joint controller. At this stage, it can improve with better technique by reduce and determine overall parameter limitation using FES.**

***Index Terms*— Functional Electrical Stimulation (FES), Spinal Cord Injury (SCI), free-swinging, rehabilitation, wearable lower limb suit, electrical stimulation test.**

I. INTRODUCTION

Currently, research and development in rehabilitation engineering by using functional electrical stimulation (FES) has been increased in recent year [5, 6, 14]. Since 1960's, as illustrated in Figure 1, FES has been explored for activation muscles [5, 11] such as means of restoring lost function of in the spinal cord injury (SCI) person with paralysis [1, 3, 5, 7, 8, 10, 16, 35] in type of electrical stimulation trains by different combinations of frequency and pulse-width [12, 13, 17].

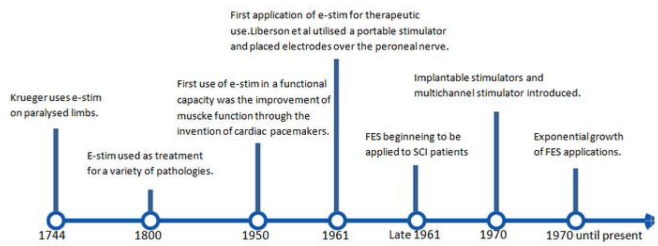

Fig. 1. Timeline history of FES applications

Nowadays, electrical stimulation can be applied via surface, intramuscular or implanted electrodes which can produce artificial contraction of paralyzed muscles provided that fibre depolarization is already achieved [1]. In fact, FES is a treatment that uses the application of small electrical current signal in order to improve mobility [2, 5, 6, 8] due to SCI, to facilitate patient-responsive ambulation, brachial plexus injury, stroke, rapid muscle wastes of the thigh, multiple sclerosis, and traumatic brain injury [5, 9, 18, 19, 27, 28]. The application of FES as a therapeutic and rehabilitation modality includes muscle strengthening and cardiovascular reconditioning, endurance, improving range-of-motion (ROM), standing and gait control, enhancement of limb function, facilitation of voluntary responses, relaxation of spastic muscles, wound healing, improve blood flow, improve sensory awareness, reduce pain associated with spasticity, reduction of osteoporosis, and orthotic substitution [20-22, 29, 38]. There are also additional benefits to

978-1-4799-6483-3/14/$31.00 ©2014 IEEE

electrically stimulating muscles, such as increase in strength, force production of the muscle contractions, voluntary movement, functional skill abilities [1, 5, 9, 25]. Moreover, FES-evoked leg muscle contractions are still able to produce muscle contractions under FES control and mainly contribute on generating force, power, and motion [1, 9, 18, 19, 24].

II. BACKGROUND STUDY

A. Stimulation Waveform

Throughout the years, there is various stimulation waveforms have been used to provide neural excitation [30-32]. Then, the stimulation waveforms, summarized in Figure 2 below, can be grouped into direct current (DC) flow (A), alternating current (AC) flow (B) or pulse shaped current flow (C). In this study, DC waveforms have been used clinically to increase circulation, to treat neuralgia, for electrolysis and as a tool for iontophoresis (transfer of ions through the skin) [32, 46]. Thus, this type of stimulation waveform does not provide the means to activate muscle contractions; rather it produces muscle twitches associated with the start and end of the DC waveform.

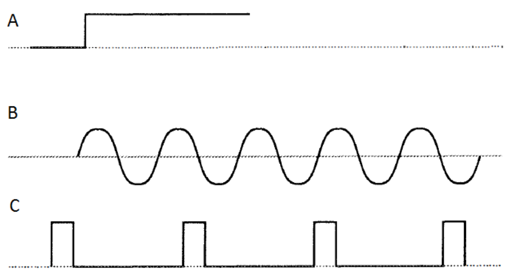

Fig. 2. Stimulation waveform types (where A. is a DC, B. is an AC and C. is a pulse shaped stimulation waveforms)

AC waveforms are defined as a constant current flow moving in one direction and then in the reverse direction. These waveforms can be of any shape including sinusoidal, square, triangular, and trapezoidal. Common characteristic of such as waveforms are the lack of electrical silence between phases. Similar to DC waveforms, AC waveforms are not usually used for therapeutic stimulation, unless they are packaged into on-off envelopes (with electrical silence between each envelope) or further modulation. Low frequency sinusoidal stimulation is known to be effective in activating de-nervated muscles [15,32,46].

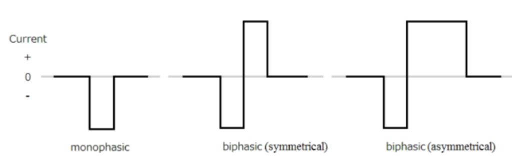

Fig. 3. Pulse-shaped stimulation waveform configurations

Stimulus waveforms are generally either monophasic or biphasic in shape. Monophasic pulses move current only in one direction. When these pulses are used for TENS or NMES applications, they have the likelihood of causing electrode deterioration and tissue damage (skin irritation or rash when surface stimulation is used) when used for prolonged periods of time (over an hour) [15, 17, 32, 46]. This effect is due to the altering of ionic distributions and causing polarization which leads to tissue breakdown and burns. Although the effect of ionic distribution is not desirable, monophasic waveforms are still used in some short-term therapeutic TENS applications. The unequal ion transfer can be reduced by using biphasic (symmetrical or asymmetrical) stimulation pulses. In the case of asymmetric biphasic waveforms (as shown in Figure 3), one direction of current is enough to cause excitable tissue to depolarize, while the opposite direction is lower in amplitude but proportionally longer in duration minimizing neural excitation. Overall most FES applications desire the use of biphasic pulse waveforms, especially when they are used for prolonged periods of time.

B. Human Body: Lower limb

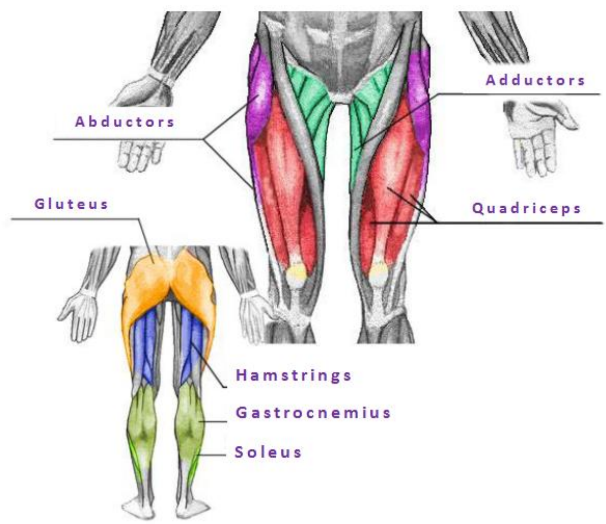

Fig. 4. The major muscle groups of legs, by Adductors, abductors, quadriceps, gluteus, harmstrings, gastrocnemius and soleus. (http://suppversity.blogspot.com).

Able-bodied (AB) person normally enjoy more pleasurable forms of involving mobility, variable exercise, indoor/outdoor recreation, or sport; greater fitness brings the reward of better performance and this positive feedback is often sufficiently encouraging for regular exercise to be maintained [5, 33, 37]. During the exercise of strength-training program, there are very important to cover the entire major muscle group of bodies. These are the major muscle group of lower body, refer to Figure 4, Gluteal is the muscle group includes the gluteus maximus, which is the really large muscle that covers human buttock. Then, a Quadriceps muscle is located in front of the thigh. It is responsible for extending, or straightening our leg. The muscles in the back of the leg called Hamstrings. The hamstring is involved in flexing, or bending the knee. Moreover,, for hip abductor and adductor, is the muscles of the outer and inner thigh. The inner thigh called adductors, because there is being the leg toward the midline of the body. Hence, the abductor is the outer thigh muscles that bring the leg away from the midline of the body [39, 40-43].

In additional, function based on lower limb training using FES includes gait pattern, retraining cycle ergometry and individual muscle activation [2, 5, 25]. Therefore, exercise by cycling method of FES is an attractive rehabilitation training method for SCI patients [4, 5, 10, 25]. Therefore, preliminary implementation of FES paradigms for rehabilitation has been greatly constrained by the early occurrence of fatigue [34, 36]. Even though, in early stage, this study will investigate the passive knee joint based on free swinging trajectory [1, 5, 7, 9, 37] with some characterization of parameters using Hasomed and Arduino Mega based in real-time simulation and hardware, assuming that some criterion such as fatigue had been ignored.

III. METHODOLOGY

A. Instrumentation

TABLE 1. DESCRIPTION OF HARDWARE

Device	Description	
Rotary Encoder B-106-23983	Incremental type shaft encoder	
	Pulse:	500P/R
	Slew speed:	6000RPM
	Body diameter:	25mm
	Shaft diameter:	4mm
	Output wave form:	Square wave
Arduino Mega 2560	Microcontroller	ATmega2560
	Clock Speed	16 MHz
	Flash Memory by bootloader	256 KB of which 8 KB used
	SRAM	8 KB
	EEPROM	4 KB

TABLE 2. DESCRIPTION OF FES DAQ

Device	Description	
Tele-operatic Lower Limb with rotational sensor (DAQ)	Precision:	0.18 degree
	Sampling rate:	250hz

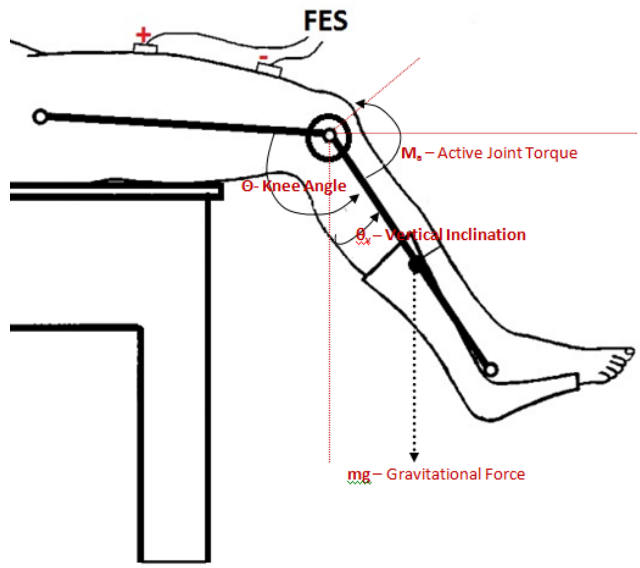

Fig. 5. Schematic representation of the lower limb with surface stimulation of the quadriceps muscle.

Based on Figure 5, Knee angle (θ) and vertical inclination of the knee (θv) are defined together with the orientation of active joint torque (Ma).; mg is the gravitational force. A distinction was made between knee joint angle (used for stiffness and damping components) and the absolute angle between knee and vertical direction (used for the gravitational and inertial term). However, since the movements of the thigh, was supposed to be stationary (i.e., fixed on the supporting table). Some studies pointed out that joint stiffness and viscosity increase when muscle are active [1,48-50]. In this study these changes have been neglected, according also to other works in the field of FES [1]

IV. RESULT AND DISCUSSIONS

The aim of the present repetition experimental study was to know the relation between FES inputs current (mA) with the vertical inclination of knee angle (θ_v). Data gathering by Electrical stimulation test been developed. Herein, only the application of this procedure to the quadriceps muscle is presented, for able-bodied (AB) person,28 years old,177cm height and 100kg weight, which is gap between both surface electrodes (anode-cathode) in 10cm. Data collected between current input 31mA to the increasing 10^0 of inclination knee angle from rest position ($\theta_v = 90^0$) to 100^0. Novel wearable lower limb suit applied which is easy way to retrieve information and flexible. This application which is developed suitable for this experiment by applying surface electrodes of covered aurah. Current value amplitude of FES triggered signal input unit in miliampere and in natural trajectory swinging due to ON/OFF FES current input signal in sine wave application in MATLAB/Simulink environmental. In additionally, comparison data between current 31mA versus 39mA in Figure 6 and Figure 7 is about different type of settling time. Due to Figure 8, compare to settling time x<400 per sample data based on fatigue problem on subject. Reducing the vertical inclination of knee angle in some jerking response in that 500<x<600 per sample data. The muscle capability between able-bodied (AB) and paralyze person is totally different because of some limitation on muscle characteristic such as spasticity, fatigue, volatility, contractility, elasticity and extensibility. Figure 6 and Figure 7 shows the effective FES input current [15,32,46] which are characterized by low frequency (5 seconds period) half-rectified sinusoidal wave.

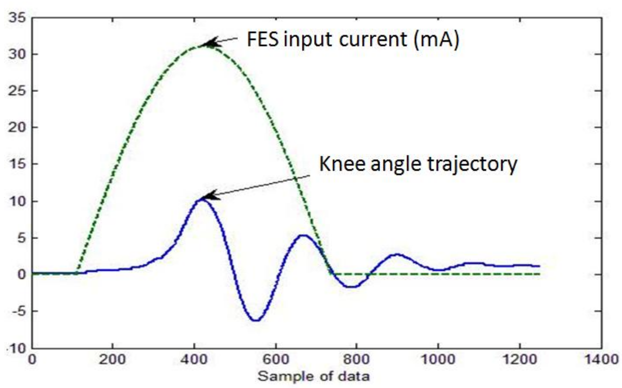

Fig. 6. Schematic representation sample data of FES input current 31mA and vertical inclination of knee angle.

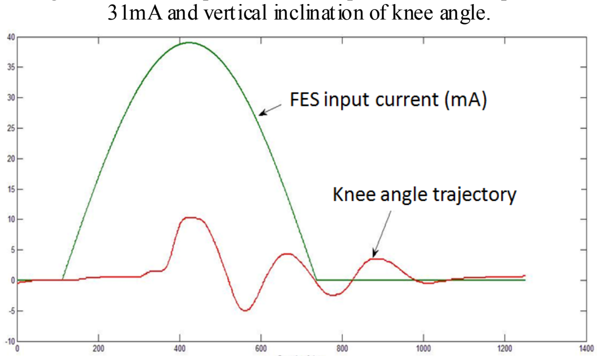

Fig. 7. Schematic representation sample data of FES input current 39mA and vertical inclination of knee angle.

In Figure 8, response combination between vertical inclination of knee angle (θ_v), FES input current and settling time give erroneous pattern overestimation of parameters. These differences were probably by jerking of knee-trajectory ROM due to system nonlinearity that cannot be captured with a pure linear system. Unsurprisingly, overall response does not too linear because some knee extension during signal triggered not varies by time, but some assumption can be set as it similar to linear response between (θ_v) and current (mA).

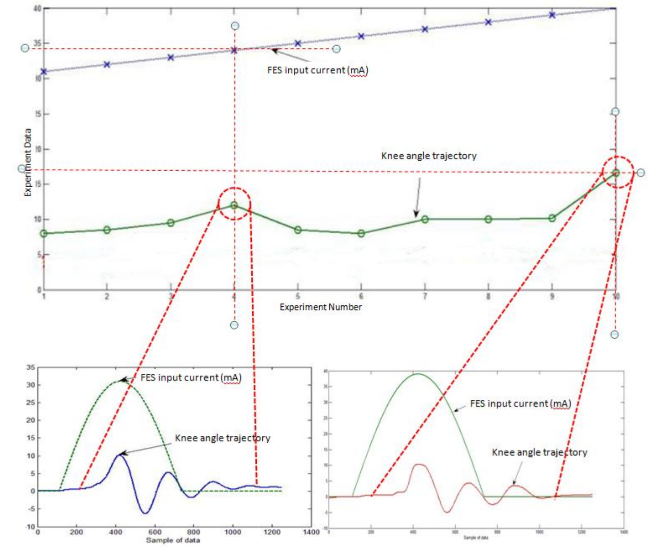

Fig. 8. Response between knee angle and input current

V. FUTURE WORKS

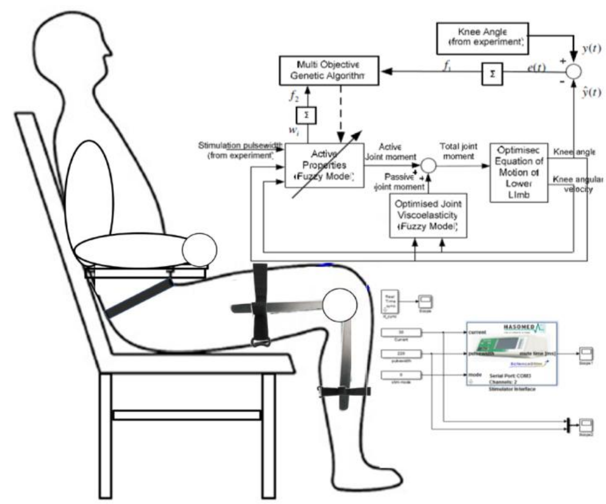

Fig. 9. Energy efficient with optimized model [2,5,7,8,12,23,41]

Recombining optimized model in Figure 9, with different exercise method and parameters will be conducted due to generate performance of cycling pattern in simulation and experimental study. Combination with Particle Swarm Optimization (PSO) and genetic-algorithm (GA) will be conduct in order to stimulate, optimize and generalize the parameters of system model. Then, some optimization based on cycling control strategies in order to reduce fatigue, optimum work load with healthy life and minimum power consumption (energy efficient control system) will be investigated.

VI. CONCLUSIONS

Restoring mobility to persons with paraplegia by means of open-loop functional electrical stimulation is an attractive yet exacting task. Due to experimental based on knee joint free swinging trajectory based vertical inclined angle with input current and relate to settling time, there some relatively low level of muscle contraction achieved in this study. Therefore, to overcome this limitation, a more general, and probably more complex and difficult to identify, non linear model suitable to any kind of stimulation pattern and optimization model should be developed.

ACKNOWLEDGMENT

Special thanks to main supervisor, Dr Babul Salam KSM Kader Ibrahim, my wife Nurfazrina Ramin, my parents, fellow friends and this research work is fully funded by Exploratory Research Grant Scheme (ERGS), Ministry of Education Malaysia, (MOE) and supported by the Office for Research Management and Innovation Centre, (ORICC) Universiti Tun Hussein Onn Malaysia, (UTHM) under contract Vot 0887.

REFERENCES

[1] Ferrarin, M.; Pedotti, A., "The relationship between electrical stimulus and joint torque: a dynamic model," *Rehabilitation Engineering, IEEE Transactions on* , vol.8, no.3, pp.342,352, Sep 2000

[2] Ibrahim, B. S K K; Tokhi, M.O.; Gharooni, S. C.; Huq, M. S., "Development of fuzzy muscle contraction and activation model using multi-objective optimisation," *Systems Conference, 2010 4th Annual IEEE* , vol., no., pp.444,449, 5-8 April 2010

[3] Cheng, K. W E; Yan Lu; Kai-yu Tong; Rad, A.B.; Chow, D.H.K.; Sutanto, D., "Development of a circuit for functional electrical stimulation," *Neural Systems and Rehabilitation Engineering, IEEE Transactions on* , vol.12, no.1, pp.43,47, March 2004

[4] Gfohler, M.; Lugner, P., "Dynamic simulation of FES-cycling: influence of individual parameters," *Neural Systems and Rehabilitation Engineering, IEEE Transactions on* , vol.12, no.4, pp.398,405, Dec. 2004

[5] Ahmad, M.K.I.; Ibrahim, B.S.K.K.; Rahman, K.A.A.; Masdar, A.; Nasir, N.H.M.; Mahadi Abdul Jamil, M., "Knee joint impedance hybrid modeling and control of functional electrical stimulation (FES)-cyclingfor paraplegic: Free swinging trajectory," *Biomedical Engineering and Sciences (IECBES), 2012 IEEE EMBS Conference on* , vol., no., pp.984,989, 17-19 Dec. 2012

[6] Sisto, S.A.; Forrest, G.F.; Faghri, P.D., "Technology for mobility and quality of life in spinal cord injury [Analyzing a Series of Options Available]," *Engineering in Medicine and Biology Magazine, IEEE* , vol.27, no.2, pp.56,68, March-April 2008

[7] Ibrahim, B. S K K; Tokhi, M.O.; Huq, M. S.; Gharooni, S. C., "Fuzzy logic based cycle-to-cycle control of FES-induced swinging motion," *Electrical, Control and Computer Engineering (INECCE), 2011 International Conference on* , vol., no., pp.60,64, 21-22 June 2011

[8] Ibrahim, B. S K K; Tokhi, M.O.; Huq, M. S.; Gharooni, S. C., "Natural trajectory based FES-induced swinging motion control," *Mechatronics (ICOM), 2011 4th International Conference On* , vol., no., pp.1,5, 17-19 May 2011

[9] Ferrarin, M.; Palazzo, F.; Riener, R.; Quintern, J., "Model-based control of FES-induced single joint movements," *Neural Systems and Rehabilitation Engineering, IEEE Transactions on* , vol.9, no.3, pp.245,257, Sept. 2001

[10] Hussain, Z.; Tokhi, M.O., "Modelling of Muscle Extension and Flexion for FES-Assisted Indoor Rowing Exercise," *Modeling & Simulation, 2008. AICMS 08. Second Asia International Conference on* , vol., no., pp.963,967, 13-15 May 2008

[11] Jailani, R.; Tokhi, M.O.; Gharooni, S. C.; Hussain, Z., "PID Control of Knee Extension for FES-Assisted Walking with Spring Brake Orthosis," *Mathematical/Analytical Modelling and Computer Simulation (AMS), 2010 Fourth Asia International Conference on* , vol., no., pp.261,266, 26-28 May 2010

[12] Jailani, R.; Tokhi, M.O., "The effect of functional electrical stimulation (FES) on paraplegic muscle fatigue," *Signal Processing and its Applications (CSPA), 2012 IEEE 8th International Colloquium on* , vol., no., pp.500,504, 23-25 March 2012

[13] Masdar, A.; Ibrahim, B.S.K.K.; Jamil, M.M.A.; Hanafi, D.; Ahmad, M.K.I.; Rahman, K.A.A., "Current source with low voltage controlled for surface Electrical Stimulation," Signal Processing and its Applications (CSPA), 2013 IEEE 9th International Colloquium on , vol., no., pp.161,164, 8-10 March 2013

[14] Rahman, K.A.A.; Ibrahim, B.S.K.K.; Leman, A.M.; Jamil, M.M.A., "Fundamental study on brain signal for BCI-FES system development," Biomedical Engineering and Sciences (IECBES), 2012 IEEE EMBS Conference on , vol., no., pp.195,198, 17-19 Dec. 2012

[15] Masdar, A.; Ibrahim, B.S.K.K.; Mahadi Abdul Jamil, M., "Development of wireless-based low-cost current controlled stimulator for patients with spinal cord injuries," Biomedical Engineering and Sciences (IECBES), 2012 IEEE EMBS Conference on , vol., no., pp.493,498, 17-19 Dec. 2012

[16] Rahman, K.A.A.; Ibrahim, B.S.K.K.; Jamil, M.Mahadi.A.; Masdar, Aizan, "Relationship between brainwave signal and human activity of knee joint movement for paraplegic," Biomedical Engineering International Conference (BMEiCON), 2013 6th , vol., no., pp.1,5, 23-25 Oct. 2013

[17] Jailani, R.; Tokhi, M.O.; Gharooni, S.; Hussain, Z., "Development of Dynamic Muscle Model with Functional Electrical Stimulation," *Complexity in Engineering, 2010. COMPENG '10.* , vol., no., pp.132,134, 22-24 Feb. 2010

[18] Hunt, K.J.; Stone, B.; Negard, N.-O.; Schauer, T.; Fraser, M.H.; Cathcart, A.J.; Ferrario, C.; Ward, S.A.; Grant, S., "Control strategies for integration of electric motor assist and functional electrical stimulation in paraplegic cycling: utility for exercise testing and mobile cycling," *Neural Systems and Re-*

habilitation Engineering, IEEE Transactions on , vol.12, no.1, pp.89,101, March 2004

[19] Dingguo Zhang , Tan Hock Guan , Ferdinan Widjaja , Wei Tech Ang, Functional electrical stimulation in rehabilitation engineering: a survey, Proceedings of the 1st international convention on Rehabilitation engineering & assistive technology: in conjunction with 1st Tan Tock Seng Hospital Neurorehabilitation Meeting, April 23-26, 2007, Singapore

[20] Faghri, P. D., Garstang, S. V., & Kida, S. (2009). Functional Electrical Stimulation (pp. 407-429)

[21] Petrofsky JS. Electrical stimulation: neurophysiological basis and application. Basic Appl Myol. 2004; 14(4):205–213.

[22] Hussain, Z.; Tokhi, M.O.; Jailani, R.; Ahmad, S.; Ibrahim, B. S K K, "Effect of Inclined Rowing Machine on FES-Assisted Indoor Rowing Exercise Performance," Modelling & Simulation, 2009. AMS '09. Third Asia International Conference on , vol., no., pp.242,245, 25-29 May 2009

[23] Hamzaid NA, Davis GM. Health and fitness benefits of functional electrical stimulation-evoked leg exercise for spinal cord-injured individuals: a position review. Top Spinal Cord Inj Rehabil. 2009; 14(4):88-121.

[24] Popovic, D.B.; Stein, R.B.; Jovanovic, K.L.; Dai, R.; Kostov, A.; Armstrong, W.W., "Sensory nerve recording for closed-loop control to restore motor functions," Biomedical Engineering, IEEE Transactions on , vol.40, no.10, pp.1024,1031, Oct. 1993

[25] Dinesh Bhatia, Gagan Bansal, R.P. Tewari, K.K. Shukla. State of art: Functional Electrical Stimulation (FES). Int. J. of Biomedical Engineering and Technology, 2011 Vol.5, No.1, pp.77 – 99

[27] Grant, L., "Functional electrical stimulation [bioengineering]," *IEE Review* , vol.34, no.11, pp.443,445, 8 Dec 1988

[28] Dong Ming; Ding Yuan; Yanan Li; Minpeng Xu; Xingwei An; Wuyi Wang; Hongzhi Qi; Baikun Wan; Weijie Wang; Abboud, R., "Neuroprosthesis system for lower limbs action based on functional electrical stimulation," *Electrical and Control Engineering (ICECE), 2011 International Conference on* , vol., no., pp.4583,4586, 16-18 Sept. 2011

[29] E . Sampson , R . Burnham , B . Andrews, “Functional electrical stimulation effect on orthostatic hypotension after spinal cord injury”, Archives of Physical Medicine and Rehabilitation, vol. 81, no. 2, pp. 139-143, 2000.

[30] M. R. Popovic and T. A. Thrasher, "Neuroprostheses", *Encyclopedia of biomaterials andbiomedical engineering,* vol. 3, pp. 1924-1933, 2004.

[31] G. Grimby, C. Broberg, I.Krotkiewska, and M. Krotkiewski. Muscle fibre composition in patients with traumatic cord lesion. Scandinavian Journal of Rehabilitation Medicine, 8:37–42, 1976.

[32] Davide Agnello (2011), New-Generation Fully Programmable Controller For Functional Electrical Stimulation Applications. Master Thesis of Applied Science, Universiti of Toronto.

[33] Duffell, L.D.; de N.Donaldson, N.; Newham, D.J., "Why is the Metabolic Efficiency of FES Cycling Low?," *Neural Systems and Rehabilitation Engineering, IEEE Transactions on* , vol.17, no.3, pp.263,269, June 2009

[34] Zhang, Qin; Hayashibe, M.; Guiraud, D., "Muscle fatigue tracking based on stimulus evoked EMG and adaptive torque prediction," *Robotics and Automation (ICRA), 2011 IEEE International Conference on* , vol., no., pp.1433,1438, 9-13 May 2011.

[35] Franken, H.M.; Veltink, P.H.; Tijsmans, R.; Nijmeijer, H.; Boom, H. B K, "Identification of passive knee joint and shank dynamics in paraplegics using quadriceps stimulation," *Rehabilitation Engineering, IEEE Transactions on* , vol.1, no.3, pp.154,164, Sep 1993

[36] Zhang, Qin; Hayashibe, M.; Fraisse, P.; Guiraud, D., "FES-Induced Torque Prediction With Evoked EMG Sensing for Muscle Fatigue Tracking," *Mechatronics, IEEE/ASME Transactions on* , vol.16, no.5, pp.816,826, Oct. 2011.

[37] Grohler, M.; Angeli, T.; Eberharter, T.; Lugner, P.; Mayr, W.; Hofer, C., "Test bed with force-measuring crank for static and dynamic investigations on cycling by means of functional electrical stimulation," *Neural Systems and Rehabilitation Engineering, IEEE Transactions on* , vol.9, no.2, pp.169,180, June 2001.

[38] P Taylor.et,al. , Upper limb electrical stimulation exercises. Salisbury FES Newsletter Jan 2002

[39]http://www.apparelyzed.com/spinal_cord_injury.html (retrieved on: 23 December 2013).

[40]https://www.aans.org/Patient%20Information/Conditions%20and%20Treatments/Spinal%20Cord%20Injury.aspx (retrieved on: 23 December 2013).

[41] B.S.K.K Ibrahim (2011). Modelling and Control of Paraplegic’s Knee Joint (FES-SWINGING). Doctor of Philosophy, Department of Automatic Control and Systems Engineering, University of Sheffield, UK, January 2011.

[42] Gondim, F.A.A. and Thomas, F.P. (1998). Spinal Cord, Topographical and Functional Anatomy. Journal of Electromyography and Kinesiology, 8(2):125-132.

[43] Vaccaro, A.R., Rizzolo, S.J., Balderston, R.A., Allardyce, T.J., Garfin, S.R., Dolinskas, C., and An, H.S. (1995). *Placement of pedicle screws in the thoracic spine.* Journal Bone Joint Surg Am, **77**:1200-1206.

[44] Thomas, C. K., Zaidnera, E. Y., Calanciea B., Brotona J. G. and Bigland-Ritchiec B. R. (1997). *Muscle Weakness, Paralysis, and Atrophy after Human Cervical Spinal Cord Injury.* Experimental Neurology, 148(2):414-423.

[45]Liverman, C.T., Altevogt, B.M., Joy, J. E. and Johnson, R. T. (2005). *Spinal cord injury: progress, promises and priorities*, National Academies Press, Washington, DC, USA.

[46] L. Baker, *et al.*, "NeuroMuscular Electrical Stimulation - a Practical Guide", *4th ed.Downey California, USA: Los Amigos Research & Education Institute,* p. 251, 2000.

[47] F. S. Grodins, *et al.*, "Stimulation of denervated skeletal muscle with alternating current", *American Journal of Physiology,* vol. 142, pp. 0216-0221, Sep 1944.

[48] P. L.Weiss, I.W. Hunter, and R. E.Kearney, “Human ankle joint stiffness over the full range of muscle activation levels,” *J. Biomech.*, vol. 21, pp. 539–544, 1988.

[49] L.-Q. Zhang, G. Nuber, J. Butler, M. Bowen, andW. Z. Rymer, “In vivo human knee joint dynamic properties as functions of muscle contraction and joint position,” *J. Biomech.*, vol. 31, pp. 71–76, 1998.

[50] C. Tai and C. J. Robinson, “Knee elasticity influenced by joint angle and perturbation intensity,” *IEEE Trans. Rehab. Eng.*, vol. 7, pp. 111–115,Mar. 1999.