http://dx.doi.org/10.5755/j01.eee.20.1.6168 ELEKTRONIKA IR ELEKTROTECHNIKA, ISSN 1392-1215, VOL. 20, NO. 1, 2014

New FES-Assisted Knee Swinging Ergometer for Stroke Patient: A Design and Simulation Study

R. Boudville[1], Z. Hussain[1], S. Z. Yahaya[1], M. H. M. Noor[1]
[1]*Faculty of Electrical Engineering, Universiti Teknologi MARA,*
13500 Permatang Pauh, Pulau Pinang, Malaysia
rozan259@ppinang.uitm.edu.my

***Abstract*—This paper presents the development of a model of knee swinging ergometer for stroke patient. Knee swinging ergometer is introduced as a hybrid exercise for restoration of function of the knee for stroke patients through the application of functional electrical stimulation. The aim of the new FES-assisted knee swinging ergometer is to provide high intensity exercise. This will elongate the exercise duration and avoid early muscle fatigue. The ergometer is designed to utilize the voluntary non-paretic leg movement in assisting the FES-induced paretic leg of stroke patient. A humanoid with muscle model was developed and incorporated with the ergometer to perform simulation of FES-assisted knee swinging exercise. PID controller is used to achieve full knee extension during each cycle of knee swinging exercise. Simulation results show that the ergometer is able to reduce half of the required electrical stimulation. In conclusion, the new knee swinging ergometer is able to avoid early muscle fatigue in performing high intensity knee exercise through electrical stimulation.**

***Index Terms*—Functional electrical stimulation, knee swinging ergometer, muscle fatigue, muscle model.**

I. INTRODUCTION

Functional electrical stimulation (FES) is effective in producing improvements in limb function and was reported to increase the cortical intensity index in the ipsilateral primary sensory cortex [1]. Exercise or repetitive execution of the limb by FES may be crucial for motor relearning and recovery for stroke patients [2]. However, the fitness of human muscle was reported to be very nonlinear [3], [4] and depends on the amount of electrical stimulation applied to the muscles.

Many studies were conducted to solve the problem of muscle fatigue during electrical stimulation. These include FES using N-let pulse train [3], random modulation of stimulation parameters [4], and many more. However, these were not practicably viable techniques for muscle fatigue reduction, since random modulation of stimulation parameters does not affect much on the muscle fatigue rate.

FES has been combined with lower extremities orthosis [5]–[10] in solving fatigue problems. However, the study of these systems did not focus on achieving repetitive movements of the stimulated limb. Furthermore, most of their study involves complex repetitive movements which did not further enhance recovery [9]. Therefore, this study concentrates on designing an ergometer which helps to perform simple repetitive movements which have shown to accelerate recovery of limb function [10]. The ergometer was also designed to avoid early muscle fatigue during repetitive electrical stimulation.

Manuscript received April 2, 2013; accepted August 10, 2013.
This research was funded by a grant (No. 600-RMI/ERGS 5/3 (60/2012)) from the Ministry of Higher Education Malaysia. This research was performed in cooperation with the Universiti Teknologi MARA, Pulau Pinang, Malaysia.

II. METHODOLOGY

The dynamic modeling of FES-assisted knee ergometer consists of the knee ergometer model, humanoid model, and the musculoskeletal model. The knee ergometer and humanoid model are visualized by MSC.visualNastran4D (vN4D) software while the musculoskeletal model is implemented in Matlab/Simulink.

The closed-loop control system is then developed using Matlab/Simulink with incorporation of knee swinging ergometer in vN4D to perform simulation of FES-assisted knee swinging ergometer.

A. Knee Swinging Ergometer

The knee swinging ergometer model is introduced to allow stroke patient perform continuous FES-induced knee exercise as well as to avoid early muscle fatique. The idea of the knee ergometer design is based on the ability of utilizing the non-paretic leg in assisting the FES-induced paretic leg. The ergometer consists of two leg braces; right and left and a bevel gearbox as shown in Fig. 1.

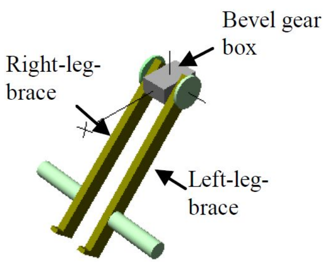


Fig. 1. The new knee swinging ergometer.

The principle of the knee ergometer is both right and left-leg-braces are arranged to move in opposite directions as shown in Fig. 2(a). The forces contributed from the reduced angle of the right-leg-brace (non-paretic-flexion) and gravity will help reduce the force and increase the angle of the left-leg-brace (paretic-extension) and vice versa. This 'changing-in-directions' movement is driven by the arrangement of three bevel gears as shown in Fig. 2(b). This mechanism is designed to utilize the flexed non-paretic knee to help extend the paretic knee and vice versa. This will also reduce the stimulation pulse and avoid early muscle fatigue hence allowing stroke patient to perform continuous and repetitive FES-assisted knee swinging exercise.

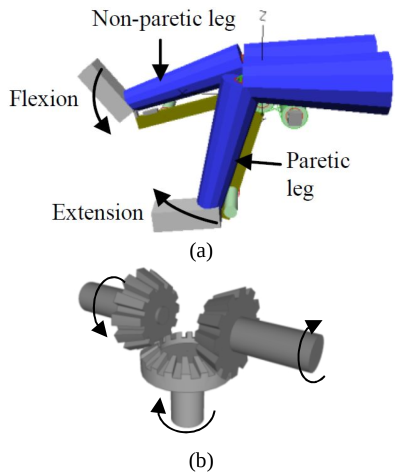


Fig. 2. Principle of the knee swinging ergometer: a) changing-in-direction, b) bevel gearbox arrangement.

The knee swinging ergometer was then attached to a wheelchair model. The wheelchair model was developed with the dimensions of a conventional manual wheelchair taken from [11]. The complete system composed of the wheelchair, knee swinging ergometer and a humanoid model developed by vN4D is shown in Fig. 3.

Fig. 3. FES-assisted knee swinging ergometer and humanoid model.

B. Humanoid Model

In order to simulate the performance of the knee swinging ergometer, a humanoid model was developed. The eleven segments contained humanoid model was developed based on the work done in [12] and the anthropometric data of the humanoid is based on Winter's work [13]. The humanoid model developed in this work is based on human body whose height is 1.70 m. The anthropometric data from [13] is used to determine the mass of each body segment and total body mass based on human body weight of 65 kg. It is also used to determine other important data such as centre of mass, segment density, segment volume and segment width. All can be found in [14].

The humanoid model was also designed to have the physical characteristic of a stroke patient. This is based on the work done in [15] where the model was developed with the characteristic cs of stroke patient taken from the study done by Remnemark et. al. [16]. The humanoid model is then seated on the wheelchair so that the shank can swing about the knee joint while the hip joints are fixed at a constant angular position. Both legs were tied up to the knee ergometer as shown in Fig. 3.

C. Musculoskeletal Model

The development of well founded physiological based muscle model is important in controlling the FES-assisted knee swinging ergometer. This section describes the development of the muscle model and segmental dynamics occurring during FES based on the work done by [17].

The muscle activation model is computed by considering the effect of nonlinear recruitment characteristic, nonlinear frequency characteristic, linear second order calcium dynamic and muscle fatigue or recovery. The muscle activation model block diagram is shown in Fig. 4.

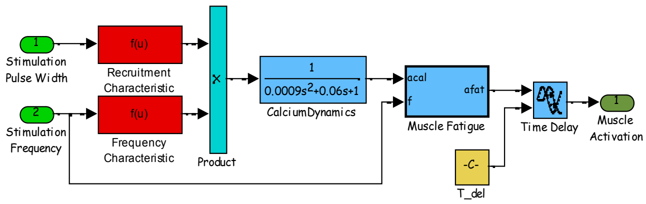


Fig. 4. Muscle activation model.

The nonlinear recruitment characteristic describes the normalized motor unit calculated as a function of the pulse width while the nonlinear frequency characteristic describes the normalized activation in a single motor unit. The linear second order calcium dynamics with time constant describes the phenomenon of calcium ion released from sacroplasmic reticulum. The muscle fatigue or recovery is modeled by considering that fatigue is increasing with rising stimulation frequencies.

In the muscle contraction dynamic as shown in Fig. 5, the muscle activation is scaled by the maximum isometric muscle force and the relation of force-length, f_{fl} and force velocity, f_{fv} in order to get the absolute muscle force. The active joint moment for each muscle is then obtained from the product of muscle force and moment arm.

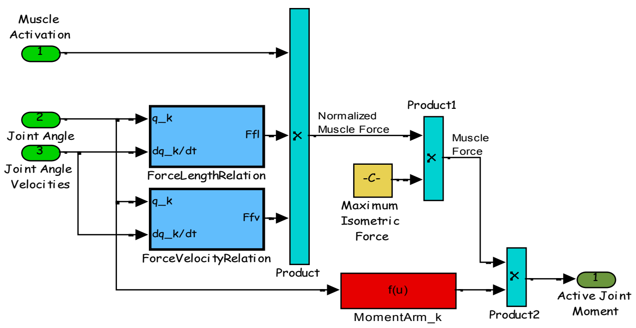


Fig. 5. Muscle contraction model.

The body segmental dynamic of the muscle model require consideration of the passive muscle properties, equation of motion and interaction with the environment. The passive muscle properties consist the passive elastic and passive viscous joint moments. The complete mathematical equation of the muscle model can be found in [17], [18]. Each of the muscle model group depends on the specific parameters of the muscle and independent parameters of the muscle derived by [17].

The equation of motion and the interaction with the environment are modeled separately from this muscle model and incorporated in the knee swinging ergometer with the developed humanoid model discussed in the previous section.

D. PID Controller

The FES-assisted knee swinging ergometer was controlled to track predefined reference knee trajectories by applying control torque to the knee joints. Two steps of simulations were considered in tuning the PID controllers' parameters. The first step do not involves the dynamic muscle model. This is to obtain the parameters for the non-paretic controller. The closed loop PID control block diagram of FES-assisted knee swinging ergometer without the muscle model is shown in Fig. 6.

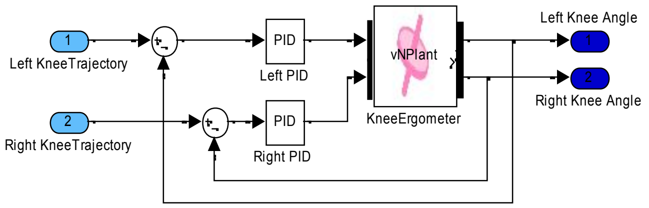


Fig. 6. Block diagram of PID control for knee swinging ergometer – without muscle model.

A sinusoidal reference signal with frequency of 0.636 Hz as used in [19] is set as the predefined reference trajectory for both knee joints. Two PID controllers are used for both paretic and non-paretic knee joints. The inputs to the controllers are the error signals (difference between reference trajectories and actual trajectories) for knee joints. The outputs of these controllers are the both left and right knee joints torque. The torques are then fed to the respective motor constraint of the knee joints of the humanoid model.

The two PID controllers parameter were manually (trial and error) tuned to obtain the best trajectories that tracked the predefined reference trajectories. Then the tuned PID parameters for the non-paretic controller was kept for the next step which involves the dynamic muscle model in the system as shown in Fig. 7.

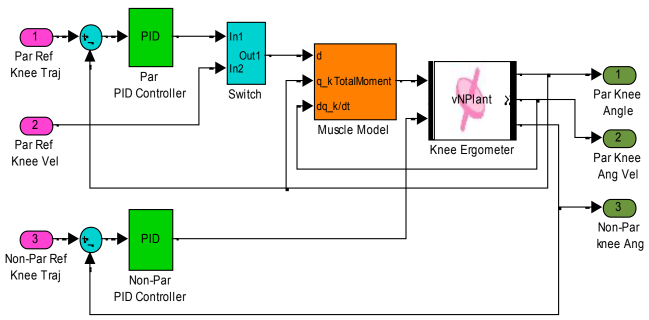


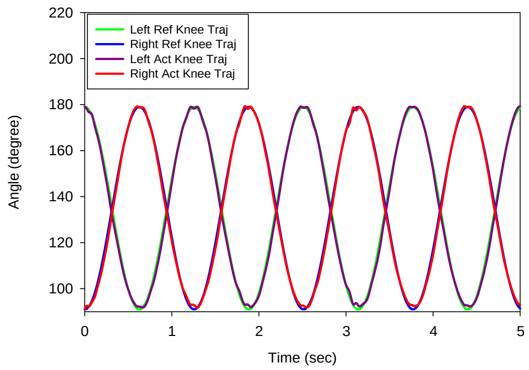
Fig. 7. Block diagram of PID control for FES-assisted knee swinging ergometer with muscle model.

The PID controllers are used to regulate the stimulation pulse widths required to drive the knee swinging exercise. The electrical stimulation is only required by the quardriceps for paretic knee extension. After full extension, the paretic knee will be left released by both gravity and the force from the extension of the non-paretic knee. A switch is used between the controller and the muscle model in order to implement the control technique. The paretic positive reference knee velocity is used as the control input of the switch to activate only paretic knee extension.

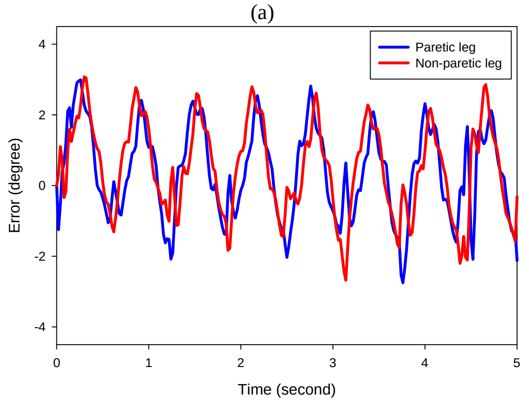
III. RESULTS AND DISCUSSIONS

The control strategy was implemented to illustrate the effectiveness of FES-assisted knee swinging ergometer in reducing electrical stimulation which leads to the reducing of muscle fatigue.

In the first step, the PID controllers of the system without muscle model were manually tuned to obtain parameters for the best trajectories that tracked the predefined reference trajectories. The controller proportional gain, K_p used was 9.8, the integral gain, K_i was 1.25 while the derivative gain, K_d was 0.3. Figure 8 shows the knee trajectories and error obtained from the first simulation. It is shown that the actual trajectories follow closely the reference trajectories and the maximum error between the actual and reference knee trajectories was recorded as 2.7°.



(a)



(b)

Fig. 8. Knee trajectories (a), and error (b), for FES-assisted knee swinging ergometer without muscle model.

Result also shows that, to perform a full knee extension, the paretic knee with the aid of knee ergometer needs only 110 μs of pulse width compared to 220 μswithout knee ergometer (free swinging knee) with the same stimulation frequency of 25 Hz. This proves that the developed knee ergometer had successfully reduces half of the required electrical stimulation.

The same non-paretic controller parameter used in the system without muscle model is used in the second simulation. Tuning of the paretic PID controller was done base on trial and error technique. The controller proportional gain, K_p used was 8.25, the integral gain, K_i was 2.35 while the derivative gain, K_d was 0.24. It was found to be very hard to get the best tuning since the system involves the nonlinear muscle model.

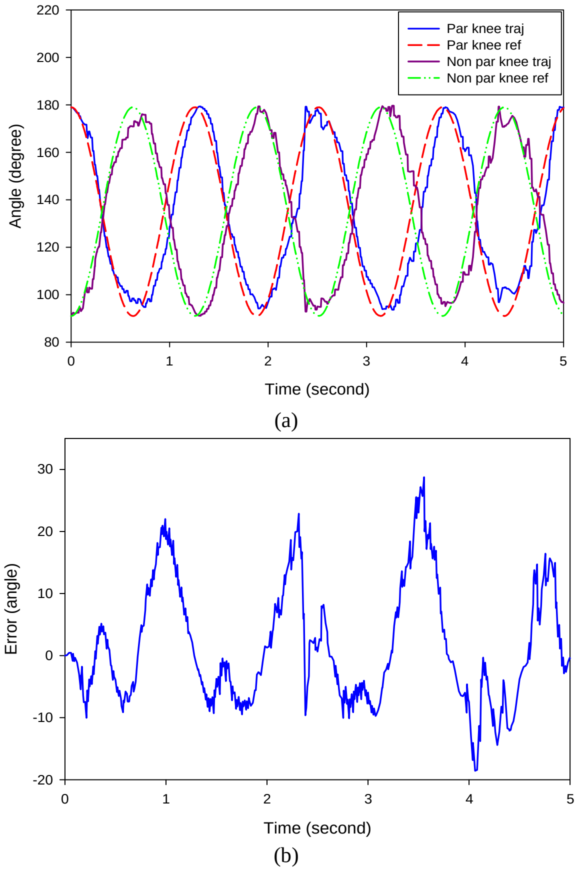


Fig. 9. Knee trajectories (a), and error (b), for FES-assisted knee swinging ergometer with muscle model.

The result from Fig. 9 shows that the error is unacceptable especially when the paretic knee starts to extend. This is due to the muscle model's dynamic behavior which is highly nonlinear which concludes that PID controller might not provide satisfactory performance and stability in FES-assisted knee swinging erdometer.

IV. CONCLUSIONS

The present study has established a model for FES-assisted knee swinging ergometer for stroke patient's knee exercise. The designed knee ergometer which allows the utilization of the voluntary non-paretic movement had reduced the required stimulation to perform repetitive full knee extension of the paretic leg. The reduced electrical stimulation is expected to reduce muscle fatigue in FES-induced knee exercise for stroke patients. The control simulation shows that the trial and error PID controller parameter tuning is insufficient to get the best and smooth performing knee swinging exercise. The controller parameter tuning must be improved with the aid of an optimizing technique which will be carried out in the future work.

REFERENCES

[1] T. J. Kimberley, S. M. Lewis, E. J. Auerbach, L. L. Dorsey, J. M. Lojovich, J. R. Carey, "Electrical stimulation driving functional improvements and cortical changes in subjects with stroke", *Exp Brain Res*, vol. 154, no. 4, pp. 450–460, Feb. 2004. [Online]. Available: http://dx.doi.org/10.1007/s00221-003-1695-y

[2] A. Ajoudani, A. Erfanian, "Neuro-sliding mode control with modular models for control of knee-joint angle using quadriceps electrical stimulation", in *Proc. Conf. IEEE Eng. Med. Biol. Soc.*, 2007, pp. 2424–2427.

[3] Z. Z. Karu, W. K. Durfee, A. M. Barzilai, "Reducing muscle fatigue in FES applications by stimulating with N-let pulse trains", *IEEE Trans. Biomed. Eng.*, vol. 42, no. 8, pp. 809–817, Aug. 1995. [Online]. Available: [Online]. Available: http://dx.doi.org/10.1109/10.398642

[4] A. Thrasher, G. M. Graham, M. R. Popovic, "Reducing muscle fatigue due to functional electrical stimulation using random modulation of stimulation parameters", *Artif. Organs*, vol. 29, no. 6, pp. 453–458, Jun. 2005. [Online]. Available: http://dx.doi.org/10.1111/j.1525-1594.2005.29076.x

[5] M. Goldfarb, W. K. Durfee, "Design of a controlled-brake orthosis for FES-aided gait", *IEEE Trans. Rehabilitation Engineering*, vol. 4, no. 1, pp. 13–24, Mar. 1996. [Online]. Available: http://dx.doi.org/10.1109/86.486053

[6] P. J. Greene, M. H. Granat, "A knee and ankle flexing hybrid orthosis for paraplegic ambulation", *Medical Engineering & Physics*, vol. 25, no. 7, pp. 539–545, Sept. 2003. [Online]. Available: http://dx.doi.org/10.1016/S1350-4533(03)00072-9

[7] M. McClelland, B. J. Andrews, J. H. Patrick, W. S. E. Masri, "Augmentation of the Oswestry Parawalker orthosis by means of surface electrical stimulation: gait analysis of three patients", *Spinal Cord*, vol. 25, no. 1, pp. 32–38, 1987. [Online]. Available: http://dx.doi.org/10.1038/sc.1987.10

[8] R. E. Major, J. Stallard, G. K. Rose, "The dynamics of walking using the hip guidance orthosis (hgo) with crutches", *Prosthet. Orthot. Int.*, vol. 5, no. 1, pp. 19–22, Apr. 1981.

[9] H. Woldag, G. Waldmann, G. Heuschkel, H. Hummelsheim, "Is the repetitive training of complex hand and arm movements beneficial for motor recovery in stroke patients?", *Clin. Rehabil.*, vol. 17, no. 7, pp. 723–730, Nov. 2003. [Online]. Available: http://dx.doi.org/10.1191/0269215503cr669oa

[10] C. Butefisch, H. Hummelsheim, P. Denzler, K. H. Mauritz, "Repetitive training of isolated movements improves the outcome of motor rehabilitation of the centrally paretic hand", *J. Neurol. Sci.*, vol. 130, no. 1, pp. 59–68, May 1995. [Online]. Available: http://dx.doi.org/10.1016/0022-510X(95)00003-K

[11] "Accessibility for the disabled - a design manual for a barrier free environment", *United Nations*. [Online]. Available: http://www.un.org/esa/socdev/enable/designm/AD5-02.htm

[12] Z. Hussain, M. O. Tokhi, S. Gharooni, R. Jailani, B. S. K. Kader Ibrahim, "Inclined ergometer to enhance FES-assisted indoor rowing exercise performance", *IJSSST*, vol. 10, no. 6, pp. 16–25, Nov. 2009.

[13] D. A. Winter, *Biomechanics and Motor Control of Human Movement*. John Wiley & Sons, 2009. [Online]. Available: http://dx.doi.org/10.1002/9780470549148

[14] Z. Hussain, M. O. Tokhi, S. Gharooni, "Dynamic simulation of indoor rowing exercise for paraplegics", in *Proc. of 2nd Asia Int. Conf. Modeling Simulation (AICMS 08)*, 2008, pp. 901–904.

[15] R. Boudville, Z. Hussain, M. N. Taib, S. Z. Yahaya, "Dynamic modeling and simulation of free swinging shank for hemiplegics", in *2011 IEEE Int. Conf. Control System, Computing and Engineering (ICCSCE)*, 2011, pp. 596–598. [Online]. Available: http://dx.doi.org/10.1109/ICCSCE.2011.6190596

[16] A. Ramnemark, L. Nyberg, R. Lorentzon, T. Olsson, Y. Gustafson, "Hemiosteoporosis after severe stroke, independent of changes in body composition and weight", *Stroke*, vol. 30, no. 4, pp. 755–760, Apr. 1999. [Online]. Available: http://dx.doi.org/10.1161/01.STR.30.4.755

[17] R. Riener, T. Fuhr, "Patient-driven control of FES-supported standing up: a simulation study", *IEEE Trans. Rehabilitation Engineering*, vol. 6, no. 2, pp. 113–124, Jun. 1998. [Online]. Available: http://dx.doi.org/10.1109/86.681177

[18] Z. Hussain, M. O. Tokhi, "Modelling of muscle extension and flexion for FES-assisted indoor rowing exercise", in *Second Asia Int. Conf. on Modeling Simulation, 2008, (AICMS 08)*, 2008, pp. 963–967.

[19] R. Massoud, "Intelligent control techniques for spring assisted FES-cycling", Ph.D. dissertation, The University of Sheffield, UK, 2007.