View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by UTHM Institutional Repository

NONLINEAR ROBUST CONTROL OF FUNCTIONAL ELECTRICAL STIMULATION SYSTEM FOR PARAPLEGIA

MOHAMMED AHMED

A thesis submitted in
fulfillment of the requirement for the award of the
Doctor of Philosophy of Electrical Engineering

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

Faculty of Electrical and Electronic Engineering
Universiti Tun Hussein Onn Malaysia

JANUARY 2019

Dedicated to my grandparents

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

ACKNOWLEDGEMENT

All thanks and gratitude are undoubtedly due to Allah (SWT) our creator, and the most exalted for all His favours.

Firstly, I would like to express my sincere gratitude to my former supervisor Dr Mohammad Saiful Huq and supervisor Associate Professor Dr Ir. Babul Salam KSM Kader Ibrahim for their continuous support and assistance my PhD studies. I would also like to thank them for their guidance, patience, motivation, and immense knowledge. I would like to thank Associate Professor Dr Samsul Bahari Bin Mohd Noor, Associate Professor Dr Ir. Mohd Hassan Khair, Associate Professor Dr Azura Binti Che Soh, and Associate Professor Dr Muhammad Mahadi Bin Abdul Jamil. I also owe special thanks to my parents Alhaji Ahmad Mai Goloma (CNA, FANAN), Malama Fatima Muhammad and Malama Aishah Usman. Their guidance and unending inspiration were equally instrumental towards the success of my research.

I would like to thank Centre for Graduate Studies (CGS) UTHM, Research Management Office (RMC) UTHM, Universiti Tun Hussein Onn Malaysia (UTHM), Abubakar Tafawa Balewa University (ATBU), Tertiary Education Fund (TETFUND), and my parents for their support without which this research would have been challenging. I also thank my study and reading roommates for the stimulating discussions, for the sleepless nights we were working together before deadlines, and for all the fun we have had throughout the journey.

Finally, I would like to thank my brothers, sisters, relatives, friends, well-wishers for supporting me throughout the PhD journey and my life in general; I appreciate your strong faith in me. Special thanks to my wife Asmau Jummai Usman for her patience, constant encouragement, love, sacrifice and special prayers, and to my children Fatima, Muhammad, Ahmad, and Aminah for their love and patience.

May Allah rewards everyone abundantly in the best of ways.

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

ABSTRACT

The study was directed towards enhancing Functional Electrical Stimulation (FES) for sit-to-stand movement restoration in paraplegia subjects. The scarcity of FES assistive devices was due to the inability of the developed equipment to attain clinical acceptance. Applications of control systems have shown fruitful results. And based on the literature, further improvements in model, trajectory and control systems are needed. Model with a higher level of accuracy and continuous as well as bump-free trajectories are essential ingredients for better control systems. The control systems can be enhanced by giving considering to changes in mass of the subject, disturbance rejection and stability. Hence, the comprehensive control scheme is necessary for this application as well as a better model and trajectory. In modelling an additional joint has been considered to improve the accuracy. In trajectory planning, the six-order polynomial has been used to refine the desired trajectory. The comprehensive control systems have been designed with consideration of robustness, disturbance rejection, and stability. Three nonlinear control approaches have been investigated; the Sliding Mode Control (SMC), Feedback Linearisation Control (FLC), and Back-Stepping Control (BSC). Results reveal improvements in the accuracy of the kinematic model by 24%, and the dynamic model by 47%. The trajectory planning parameters are continuous, and not susceptible to jerks or spikes. Execution time enhanced by 11%, the upper and lower terminal velocities improved by 16.9% and 20.9% respectively. The system response without disturbance shows good results with the SMC, FLC, and BSC. Revelations by robustness examination also maintain remarkable enhancements in the parameters with both 53% and 126% mass. The results for disturbance rejection examinations with fatigue, spasm, tremor, and combined disturbance effects showed sustenance of refinement in the response parameters. Therefore, indicating improvements despite the changes to the system. The BSC showed the best performance, followed by the FLC, and the SMC. Hence, the BSC is recommended for such systems.

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

ABSTRAK

Kajian ini bertujuan meningkatkan keupayaan Stimulasi Elektrik Fungsional (FES) untuk memulihkan pergerakan duduk dan berdiri untuk subjek paraplegia. Kekurangan alat bantuan FES adalah kerana ketidakupayaan pembangunan peralatan untuk memenuhi keperluan klinikal semasa. Aplikasi sistem kawalan telah menunjukkan hasil yang memuaskan. Berdasarkan kajian terdahulu model, trajektori dan sistem kawalan perlu penambahbaikan. Model dengan tahap ketepatan tinggi dan trajektori yang berterusan seperti bebas-lantunan merupakan aspek penting untuk sistem kawalan yang lebih baik. Sistem kawalan boleh ditingkatkan dengan memberi penekanan dalam aspek perubahan jisim pada subjek, pengatasian gangguan dan kestabilan. Oleh itu, skim kawalan yang komprehensif serta model dan trajektori yang lebih baik diperlukan untuk aplikasi ini. Dalam pemodelan, tambahan sendi dianggap mampu meningkatkan ketepatannya. Dalam perancangan trajektori, polinomial tingkat-keenam digunakan untuk memperbaiki trajektori yang dikehendaki. Sistem kawalan komprehensif telah direka dengan menekankan aspek keteguhan, pengatasian gangguan, dan kestabilan. Tiga pendekatan kawalan tidak tegak disiasat; Kawalan Mod Gelongsor (SMC), Kawalan Penegakan Suap-balik (FLC), dan Kawalan Jangkau Belakang (BSC). Keputusan menunjukkan ketepatan model kinematik dan model dinamik masing-masing meningkat sebanyak 24% dan 47%. Parameter perancangan trajektori adalah berterusan, dan tidak terdedah kepada sentakan atau lonjakan. Masa pelaksanaan ditambah baik sebanyak 11%, halaju terminal atas dan bawah masing-masing meningkat sebanyak 16.9% dan 20.9%. Tindak balas sistem tanpa gangguan menunjukkan hasil yang luar biasa dengan SMC, FLC, dan BSC. Ujian kekukuhan juga menunjukkan peningkatan luar biasa dalam parameter tersebut, kedua-duanya sebanyak 53% dan 126%. Keputusan ujian penolakan gangguan bersama keletihan, kekejangan, gegaran dan gabungan kesan gangguan menunjukkan penambahbaikan pada tindakbalas parameter-parameter. Oleh yang demikian, ia menunjukkan penambahbaikan walaupun terdapat perubahan kepada sistem. BSC menunjukkan

prestasi paling baik, diikuti dengan FLC dan SMC. Oleh itu, BSC disyorkan untuk sistem seperti ini.

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

TABLE OF CONTENTS

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

LIST OF TABLES

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

LIST OF FIGURES

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

LIST OF SYMBOLS AND ABBREVIATIONS

A	-	For All
a_1	-	Length of the Shank Segment
a_2	-	Length of the Thigh Segment
a_3	-	Length of the Truck Segment
a_4	-	Length of the Neck Segment
α	-	Momentum coefficient
c	-	Gain of Controller
$Deg/^0$	-	Angle in Degrees
e	-	Exponent
$f(x)$	-	Function f of x
f	-	Function f
$g(x)$	-	Function g of x
g	-	Function g
≥ 0	-	Greater than or equal to 0
l_1	-	Length of Centre of Mass for the Shank Segment
l_2	-	Length of Centre of Mass for the Thigh Segment
l_3	-	Length of Centre of Mass for the Truck Segment
l_4	-	Length of Centre of Mass for the Neck Segment
m	-	Metre
mA	-	Milli-Amphere
m_1	-	Mass of the Shank Segment
m_2	-	Mass of the Thigh Segment
m_3	-	Mass of the Truck Segment
m_4	-	Mass of the Neck Segment

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

θ_j	-	Bias for the j^{th} Angle
$u(t)/u$	-	Control Law
η	-	Sliding Mode Controller Parameter
GS	-	Global Stability
ANN	-	Artificial Neural Network
BD	-	Body Dynamics
BP	-	Back Propagation
BPGD	-	Back Propagation Gradient Descent
BSC	-	Backstepping Control/Controller
CNS	-	Central Nervous System
EL	-	Euler-Lagrange
ELM	-	Euler Lagrange Method
FES	-	Functional Electrical Stimulation
HT	-	Homogeneous Transformation
IRCSC	-	Integral of Rate of Change in Stimulation Current
IRCTSC	-	Integral of Rate of Change in Time Stimulation
ISC	-	Integral of Stimulation Current
ITE	-	Integral of Tracking Error
ITSC	-	Integral of Time Stimulation Current
ITTE	-	Integral of Time Tracking Error
LC	-	Lyapunov Criteria
LC	-	Lyapunov Criteria
LESC	-	Lyapunov Exponential Stability Criteria
LF	-	Linearized Feedback
LFC	-	Linearized Feedback Control/Controller
MCS	-	Maximum Control Signal
NE	-	Newton-Euler
NEM	-	Newton-Euler Method
NS	-	Nervous System
PID	-	Proportional Integral Derivative
PIDC	-	Proportional Integral Derivative Control/Controller
PP	-	Phase Plane

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

RBD	-	Rigid Body Dynamics
RMSE	-	Root Mean Square Error
SCI	-	Spinal Cord Injury
SM	-	Sliding Mode
SMC	-	Sliding Mode Control/Controller
STS	-	Sit-to-Stand

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

LIST OF APPENDICES

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

CHAPTER 1

INTRODUCTION

1.1 Background information

The nervous system (NS) performs the coordination of the human body. The associated signals being electrical; the origin of which is ionic currents, this property made the utilisation of electrical signals crucial for so many medicinal purposes. Examples of which include: pain suppression wound healing and muscle conditioning [1-3]. In functional electrical stimulation (FES) usually, electrical signals of individual characteristics are used (generally of low amplitudes). It helps to revert or reduce abnormalities in utterances or responses of the human body parts due to ailments, injury or complications (examples are: spinal cord injury, head injury, stroke and other neurological disorders) which are usually controlled by the central nervous system (CNS) [4]. The function reversal/revival of the affected body part is achieved by systematically applying the desirable electrical signals to the appropriate muscles/nerves [5-7]. Figure 1.1 is a brief demonstration of how the functional electrical stimulation (FES) is accomplished. In reality, it is usually connected to the muscle group responsible for the target activity.

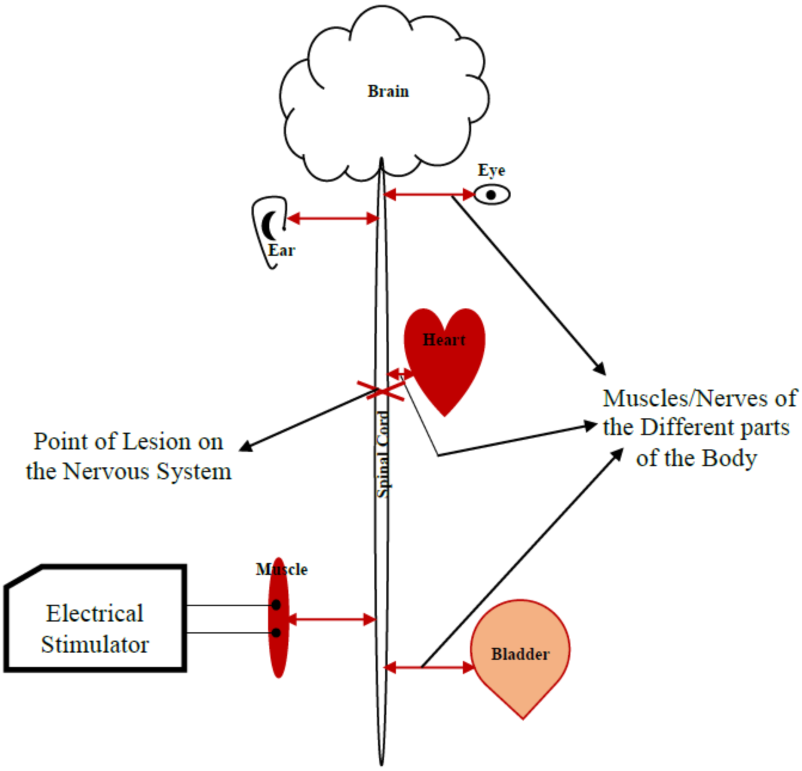

Figure 1.1: FES and the NS interaction

As demonstrated by Figure 1.1 FES has numerous applications some of which include: in the remedy of loss in urine control, in hearing restoration, in viewing disorders and in alleviating or solving problems of moving the parts of the body. The issue of urinary incontinence can be mitigated by applying the signals to the nerves responsible for bladder control which are found in the peritoneum. Hearing problems are also reduced with the aid of microphone as a transducer of the received audio signals to electrical signals after which they are converted to suitable signals that are used to stimulate the nerves inside the ear for audio. FES signals are also used to solve viewing problems with the aid of human-made retina. The cells responsible for viewing are stimulated with a proper signal after being processed from a camera. In human body joint movements, suitable FES signals are applied to the appropriate muscles via electrodes mounted on them. It could be internal or external which are technically known as implant or surface mount respectively [8].

1.2 FES induced movement

Restoration of different functions to some extent have been achieved with the aid of functional electrical stimulation (FES) in people with nervous system impairment due to spinal cord injuries (SCIs), brain injuries, strokes and related diseases. Reestablishment of skeletal movements to a certain degree such as abilities to grasp, cycle, reach and walk were some of the accomplishments of FES [9-12]. The nervous system manages and controls all protocols and actions executed by the body. It comprised up of the central and peripheral nervous systems. The first comprises of the brain and the spinal cord; the brain is the centre of management and control, and it connects to other body parts through the spinal cord, and the latter provides a platform for interconnections to the central nervous system [13]. The active cells of the nervous system used for movement coordination are the sensory and motor neurons. Records gave credit to the work of Liberson et al. in 1961 as the earliest practical application of FES as walking aid and the device produced was for foot drop disorder management. High level of success was attained in electro-neuroprosthesis applications from the 1980s due to the emergence of microprocessors which gave room for reduction in sizes and higher level devices multiplexing [14]. Walking is a movement activity that is facilitated in a regular repeated manner, and it has two primary components: the stance and swing. The stance action has to do with standing and related manoeuvres while the swing involves changes in joint(s) angles and utterances related to the angular rotation of joints [15-17].

FES is employed for therapeutic purpose in conditions where recovery is possible such as cerebral palsy and stroke; it is used mainly to train the nerves which eventually lead to their recovery [18-20]. It is also applied for movement restoration usually in cases where recovery is not possible as in the case of the majority of spinal cord injuries, achieved by initially training the nerves until eventually, they respond very well to the stimulation signals [21-29]. FES could be implemented individually, but usually, for active movement applications such as walking and rigorous exercise, it is employed with other assistive devices.

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

1.3 FES with emphasis on lower limb and SCI

FES is achieved by mimicking the operations of the nervous system due to its inability to send desired signals as results of the ailments. Suitable electrical signals are transmitted to the appropriate muscular nerves by the functional electrical stimulators via electrodes [30, 31], as described in Figure 1.2.

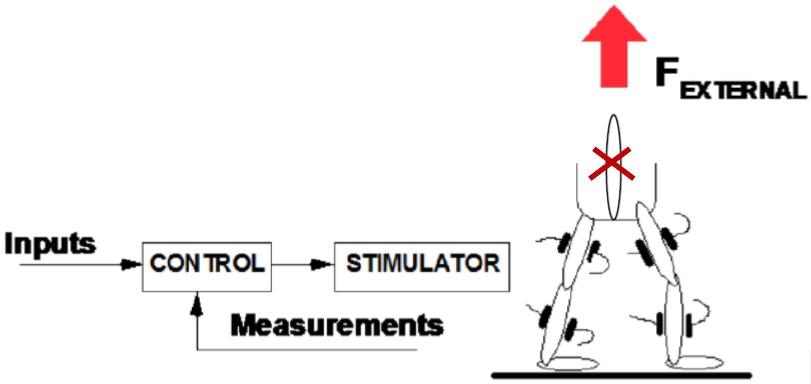

Figure 1.2: Movement restoration using FES

Figure 1.2 is an illustration of the process where the crossing is an arbitrary point indicating the area where discontinuity or the problem occurs on the central nervous system, and usual activities below the point are impaired. It is arbitrary in the sense that in some cases the problem might be in the brain itself. So, also the point of stimulation as earlier mentioned it has to be selected depending on the function restoration required.

SCI can be classified as complete or partial. In the case of complete SCIs, both sensory and motor functions are lost, while in partial SCIs one of the two is partially or wholly impaired. Figure 1.3 is an illustration of how the SCI is classified.

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

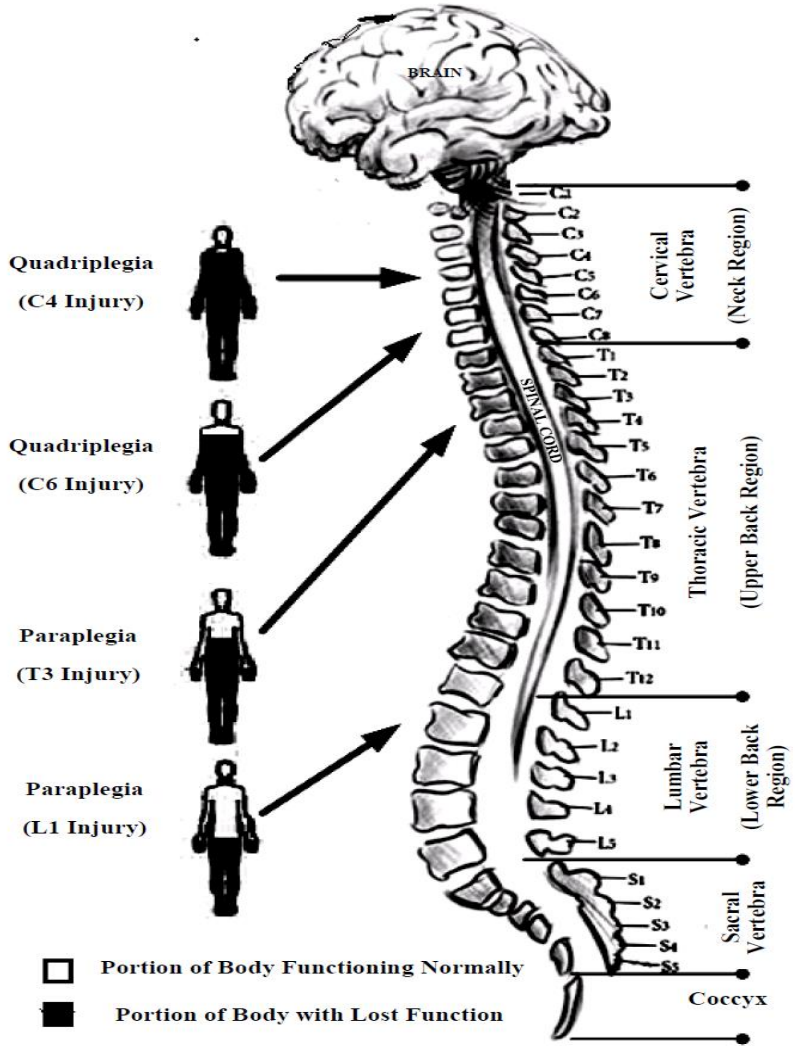

Figure 1.3: Classification of SCIs [32].

Another category is based on a portion of the lesion, and a brief explanation is as indicated in Figure 1.3. The vertebral column houses the spinal cord and gives it protection. The vertebral column consists of 31 bones, and it can be sub-classified into the cervical vertebra, thoracic vertebra, lumbar vertebra, the sacral vertebra bones and the coccyx accordingly. Quadriplegia results when the SCI occurs at the first bone of the thoracic vertebra or above, motion and sensing capability below the point of injury is lost; both the arms and legs cannot be moved intentionally. Paraplegia, on the other hand, occur when the damage occurs below the first bone in the thoracic vertebra. Also, sensation and motion below the point are hindered; both legs cannot be moved. Triplegia is a condition whereby sensory and motion in a single arm and both of the lower limbs are impaired. Hemiplegia occurs due to the impairment of movement and sensation in an arm and a leg in the same half of the body [32, 33].

1.4 The justification for the research

FES assisted sit-to-stand movement is achieved merely by providing support for the subject which will create more self-sufficiency (independence). Even though the majority of FES control systems for movement restoration in the lower limb are an open loop, but due to the requirement for performance which goes along with safety, the closed loop become the viable option [34, 35].

In the current world, records indicate high figures in occurrences of nervous system disorders. For instance, data showed that Denmark had between 10,000 to 15,000 new cases of stroke with a survival rate of one-fifth within the first month and a half within four years [36]. In North America, over a million individuals living with spinal cord ailments [37]. In the United States, there are about a quarter of a million SCI patients and about 12,000 of recent incidence occurrences. The record also eighty percent occur in the masculine gender with a mean age of forty years, with approximately forty-two percent from automobile accidents, twenty-seven percent from accidental fallings, fifteen percent from unrests and eight percent from sports activities [38]. The figures for new stroke cases is up to the tune of or more significant than 700,000 per year [39]. Ireland and the United Kingdom have an average of 45,000 spinal cord injury subjects with annual increments greater than 1,000. Highest figures of victims fall within 18 and 35 years age groups [40]. Reports by the World Health Organization (WHO) also indicate a global rise in neurological disorder cases as well as projections [41, 42].

Scanty amount of devices available for helping the patient group with a nervous disorder. For instance, according to the decision of the Centers for Medicare & Medicaid Services (CMS) (which is part of 'the Department of Health and Human Services (HHS), United States of America (USA)') on the use of FES devices for spinal cord injury subjects in order to improve functional abilities, only the Parastep-I system was approved [43]. And no new decision on the matter was issued up to date. It also states that just that device was approved by the US Food and Drug Administration (FDA) agency to aid in standing and to walk. The Parastep-I system was classified as a Class III system, and it has not gone through the Premarket Approval Application (PMA) process. Such category of FES devices (that is for standing and walking) is to undergo more severe checks on efficiency as well as safety compared to their counterparts.

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

Artificially stimulated muscles tend to fatigue faster than when naturally stimulated [44-51]. It contributes to time the dependent and nonlinear nature of the plant/system (neural-muscular-skeletal plant/system) [52, 53] and this presents a severe challenge in FES application. Of course, other additional complexities include the time delay from the nervous system, spasticity, tremors and others. An option for subsiding the effect of fatigue is the use of a closed-loop control system/control technique [54, 55] which is sufficiently adaptive and robust [56, 57]. Using feedback with predictive knowledge could also be beneficial for alleviating the problem of fatigue [58, 59]. Further suppression of other issues, e.g. spasticity, tremors are part of the current challenges. So also the question is re-tuning for each subject and of course the issue stability whose requirement is very stringent. Solving these persistent problems could lead to attaining clinical acceptance by more devices [54, 60-67].

Application of FES induced movements from all indication is promising. It is not only limited to restoration of movements alone but also for rehabilitation and therapeutic purposes. Existing systems are designed to operate open loop configurations. Efforts were made to shift to closed-loop systems for the FES in other to reap the benefits of automation but are yet to attain clinical approval. Linear control techniques were applied, but the results seem to be unsatisfactory which could be due to the nature of the plant and available sensors. Intelligent approaches were proposed, and results were hopeful in achieving clinical acceptability, but the absence of mathematical models in dealing with such techniques makes information/analysis on stability and robustness lacking, which may be produced using the nonlinear approach. Nonlinear control could suppress the issues regarding the plant as well, and the schemes have been proposed for the closed loop FES assisted movement systems, the results were encouraging. Therefore, these control strategies can be explored as the basis for controlling the neural-muscular-skeletal plant, with the strong expectations that could lead to obtaining/ascertaining the facts necessary which other techniques are deficient of or have failed to provide efficiently. For instance, the stability issue could be determined or improved from information on operational bandwidth or limits, and hence control scheme improvement. Knowledge of how to test for stability when the intelligent techniques are employed may also emerge. Therefore, it could lead to simplification of other things more especially integration with the intelligent approach which portrays proficiency and it’s not limited to that, others are optimising power consumption as well as learning capability.

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

REFERENCES

1. M. C. Ferrari de Castro and A. Cliquet, "Artificial grasping system for the paralyzed hand," *Artificial organs,* vol. 24, pp. 185-188, 2000.
2. J. G. Webster, *Medical instrumentation application and design*: John Wiley & Sons, 2009.
3. N. A. Maffiuletti, "Physiological and methodological considerations for the use of neuromuscular electrical stimulation," *European journal of applied physiology,* vol. 110, pp. 223-234, 2010.
4. Y. Chen, J. Hu, L. Peng, and Z.-g. Hou, "The FES-assisted control for a lower limb rehabilitation robot: simulation and experiment," *Robotics and Biomimetics,* vol. 1, p. 2, 2014.
5. N. Arantes, D. Vaz, M. Mancini, M. Pereira, F. Pinto, and T. Pinto, "Effects of functional electrical stimulation applied to the wrist and finger muscles of hemiparetic subjects: a systematic review of the literature," *Brazilian Journal of Physical Therapy,* vol. 11, pp. 419-427, 2007.
6. J. F. Tan, K. Masani, A. H. Vette, J. Zariffa, M. Robinson, C. Lynch*, et al.*, "Inverted pendulum standing apparatus for investigating closed-loop control of ankle joint muscle contractions during functional electrical stimulation," *International Scholarly Research Notices,* vol. 2014, 2014.
7. A. Papachristos, "Functional Electrical Stimulation in Paraplegia," in *Topics in Paraplegia*, Y. Dionyssiotis, Ed., ed: INTECH, 2014.
8. G. P. Braz, M. Russold, and G. M. Davis, "Functional electrical stimulation control of standing and stepping after spinal cord injury: A review of technical characteristics," *Neuromodulation: Technology at the Neural Interface,* vol. 12, pp. 180-190, 2009.
9. O. A. Howlett, N. A. Lannin, L. Ada, and C. McKinstry, "Functional electrical stimulation improves activity after stroke: a systematic review with meta-

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

analysis," *Archives of physical medicine and rehabilitation,* vol. 96, pp. 934-943, 2015.

10. R. van den Brand, J. Heutschi, Q. Barraud, J. DiGiovanna, K. Bartholdi, M. Huerlimann*, et al.*, "Restoring voluntary control of locomotion after paralyzing spinal cord injury," *science,* vol. 336, pp. 1182-1185, 2012.
11. S. Maddox, *Paralysis resource guide*: Christopher Reeve Foundation, 2013.
12. R. Héliot, C. A. Coste, and B. Espiau, "Functional rehabilitation: coordination of artificial and natural controllers," in *Rehabilitation Robotics*, S. S. Kommu, Ed., ed: Itech Education and Publishing, Vienna, Austria, 2007, pp. 163-186.
13. C. Ethier, E. R. Oby, M. J. Bauman, and L. E. Miller, "Restoration of grasp following paralysis through brain-controlled stimulation of muscles," *Nature,* vol. 485, pp. 368-371, 2012.
14. M. C. Kutlu, "A home-based functional electrical stimulation system for upper-limb stroke rehabilitation," University of Southampton, 2017.
15. S. Faraji, A. R. Wu, and A. J. Ijspeert, "A simple model of mechanical effects to estimate metabolic cost of human walking," *Scientific reports,* vol. 8, p. 10998, 2018.
16. B. R. Umberger, "Stance and swing phase costs in human walking," *Journal of the Royal Society Interface,* vol. 7, pp. 1329-1340, 2010.
17. A. Seth, J. L. Hicks, T. K. Uchida, A. Habib, C. L. Dembia, J. J. Dunne*, et al.*, "OpenSim: Simulating musculoskeletal dynamics and neuromuscular control to study human and animal movement," *PLoS computational biology,* vol. 14, p. e1006223, 2018.
18. R. Malcata, "Development of a Control Architecture for a Musculoskeletal Model of the Human Ankle Joint Using Multibody Dynamics and Hill-Type Muscle Actuators," Master MSc, Instituto Superior Técnico (Techincal University of Lisbon), Lisboa,, 2009.
19. S.-J. Kim, M. D. Fairchild, A. Iarkov, J. J. Abbas, and R. Jung, "Adaptive control of movement for neuromuscular stimulation-assisted therapy in a rodent model," *IEEE Transactions on Biomedical Engineering,* vol. 56, pp. 452-461, 2009.
20. P. J. Grahn, G. W. Mallory, B. M. Berry, J. T. Hachmann, D. A. Lobel, and J. L. Lujan, "Restoration of motor function following spinal cord injury via

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

optimal control of intraspinal microstimulation: toward a next generation closed-loop neural prosthesis," 2014.

21. D. Zhang, T. H. Guan, F. Widjaja, and W. T. Ang, "Functional electrical stimulation in rehabilitation engineering: A survey," in *Proceedings of the 1st international convention on Rehabilitation engineering & assistive technology: in conjunction with 1st Tan Tock Seng Hospital Neurorehabilitation Meeting*, 2007, pp. 221-226.
22. C. L. Lynch and M. R. Popovic, "Functional electrical stimulation," *IEEE control systems,* vol. 28, pp. 40-50, 2008.
23. K. Masani and M. R. Popovic, "Functional electrical stimulation in rehabilitation and neurorehabilitation," in *Springer handbook of medical technology*, ed: Springer, 2011, pp. 877-896.
24. A. K. Vafadar, J. N. Côté, and P. S. Archambault, "Effectiveness of functional electrical stimulation in improving clinical outcomes in the upper arm following stroke: a systematic review and meta-analysis," *BioMed research international,* vol. 2015, 2015.
25. A. J. Wilkenfeld, M. L. Audu, and R. J. Triolo, "Feasibility of functional electrical stimulation for control of seated posture after spinal cord injury: A simulation study," *Journal of rehabilitation research and development,* vol. 43, p. 139, 2006.
26. D. Guiraud, C. A. Coste, M. Benoussaad, and C. Fattal, "Implanted functional electrical stimulation: case report of a paraplegic patient with complete SCI after 9 years," *Journal of neuroengineering and rehabilitation,* vol. 11, p. 15, 2014.
27. R. Nataraj, M. L. Audu, and R. J. Triolo, "Simulating the restoration of standing balance at leaning postures with functional neuromuscular stimulation following spinal cord injury," *Medical & biological engineering & computing,* vol. 54, pp. 163-176, 2016.
28. G. Deley, J. Denuziller, and N. Babault, "Functional electrical stimulation: cardiorespiratory adaptations and applications for training in paraplegia," *Sports Medicine,* vol. 45, pp. 71-82, 2015.
29. S. Trier, T. Vrabec, J. Weisgarber, and C. F. Center, "Using functional electrical stimulation to restore movement to individuals with neuromuscular disabilities," *MATLAB Digest: Academic Edition,* vol. 2, pp. 1-4, 2008.

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

30. H. Kern, U. Carraro, N. Adami, D. Biral, C. Hofer, C. Forstner, *et al.*, "Home-based functional electrical stimulation rescues permanently denervated muscles in paraplegic patients with complete lower motor neuron lesion," *Neurorehabilitation and neural repair,* vol. 24, pp. 709-721, 2010.

31. S. Y. Lee, S.-Y. Kang, S. H. Im, B. R. Kim, S. M. Kim, H. M. Yoon, *et al.*, "The effects of assisted ergometer training with a functional electrical stimulation on exercise capacity and functional ability in subacute stroke patients," *Annals of rehabilitation medicine,* vol. 37, pp. 619-627, 2013.

32. S. Thuret, L. D. Moon, and F. H. Gage, "Therapeutic interventions after spinal cord injury," *Nature Reviews Neuroscience,* vol. 7, pp. 628-643, 2006.

33. B. S. K. K. Ibrahim, "Modelling and control of paraplegic's knee joint (FES-swinging)," PhD, University of Sheffield, 2011.

34. D. Zhang, P. Poignet, F. Widjaja, and W. T. Ang, "Neural oscillator based control for pathological tremor suppression via functional electrical stimulation," *Control Engineering Practice,* vol. 19, pp. 74-88, 2011.

35. Q. Zhang, M. Hayashibe, and C. Azevedo-Coste, "Evoked electromyography-based closed-loop torque control in functional electrical stimulation," *IEEE Transactions on Biomedical Engineering,* vol. 60, pp. 2299-2307, 2013.

36. R. S. Poulsen and R. S. Sorensen, "Real time closed loop functional electrical stimulation systeenm for use in upper extremity motor rehabilitation," Master, Biomedical Engineering, Aalborg University, 2012.

37. C. L. Lynch, "Closed-Loop Control of Electrically Stimulated Skeletal Muscle Contractions," PhD, University of Toronto, 2011.

38. P. Cooman, "Nonlinear feedforward-feedback control of an uncertain, time-delayed musculoskeletal arm model for use in functional electrical stimulation," PhD, Case Western Reserve University, 2014.

39. P. Scarborough, V. Peto, P. Bhatnagar, A. Kaur, J. Leal, and R. Luengo-Fernandez, "Stroke Statistics 2009 Edition. British Heart Foundation Statistics Database," ed, 2012.

40. Z. Hussain, "Intelligent control techniques for fes-assisted paraplegic indoor rowing exercise," PhD, The University of Sheffield, 2010.

41. W. H. Organization, *Neurological disorders: public health challenges*: World Health Organization, 2006.

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

42. A. Officer, T. Shakespeare, P. Von Groote, and J. Bickenbach, *International perspectives on spinal cord injury*: World Health Organization, 2013.

43. CMS. (2015, 24 Novenber). *Memo for Neuromuscular Electrical Stimulation (NMES) for Spinal Cord Injury*. Available: www.cms.gov/medicare-coverage-database/details/Decision Memo for Neuromuscular Electrical Stimulation (NMES) for Spinal Cord Injury (CAG-00153R)

44. G. M. Graham, T. A. Thrasher, and M. R. Popovic, "The effect of random modulation of functional electrical stimulation parameters on muscle fatigue," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 14, p. 38, 2006.

45. J. Ding, A. S. Wexler, and S. A. Binder-Macleod, "Mathematical models for fatigue minimization during functional electrical stimulation," *Journal of Electromyography and Kinesiology*, vol. 13, pp. 575-588, 2003.

46. A. Thrasher, G. M. Graham, and M. R. Popovic, "Reducing muscle fatigue due to functional electrical stimulation using random modulation of stimulation parameters," *Artificial organs*, vol. 29, pp. 453-458, 2005.

47. T. Kesar, L.-W. Chou, and S. A. Binder-Macleod, "Effects of stimulation frequency versus pulse duration modulation on muscle fatigue," *Journal of Electromyography and Kinesiology*, vol. 18, pp. 662-671, 2008.

48. B. Dreibati, C. Lavet, A. Pinti, and G. Poumarat, "Influence of electrical stimulation frequency on skeletal muscle force and fatigue," *Annals of physical and rehabilitation medicine*, vol. 53, pp. 266-277, 2010.

49. M. Hayashibe, M. Benoussaad, D. Guiraud, P. Poignet, and C. Fattal, "Nonlinear identification method corresponding to muscle property variation in fes-experiments in paraplegic patients," in *Biomedical Robotics and Biomechatronics (BioRob), 2010 3rd IEEE RAS and EMBS International Conference on*, 2010, pp. 401-406.

50. Q. Zhang, M. Hayashibe, P. Fraisse, and D. Guiraud, "FES-induced torque prediction with evoked EMG sensing for muscle fatigue tracking," *IEEE/ASME Transactions on Mechatronics*, vol. 16, pp. 816-826, 2011.

51. R. Jailani and M. Tokhi, "The effect of functional electrical stimulation (FES) on paraplegic muscle fatigue," in *Signal Processing and its Applications (CSPA), 2012 IEEE 8th International Colloquium on*, 2012, pp. 500-504.

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

52. M. Böl, H. Stark, and N. Schilling, "On a phenomenological model for fatigue effects in skeletal muscles," *Journal of theoretical biology,* vol. 281, pp. 122-132, 2011.

53. C. L. Lynch and M. R. Popovic, "A stochastic model of knee angle in response to electrical stimulation of the quadriceps and hamstrings muscles," *Artificial organs,* vol. 35, pp. 1169-1174, 2011.

54. M. Ibitoye, N. Hamzaid, and A. AbdulWahab, "Effects of muscle fatigue on FES assisted walking of sci patients: A review," in *The 15th International Conference on Biomedical Engineering*, 2014.

55. M. O. Ibitoye, N. A. Hamzaid, N. Hasnan, A. K. A. Wahab, and G. M. Davis, "Strategies for rapid muscle fatigue reduction during FES exercise in individuals with spinal cord injury: a systematic review," *PloS one,* vol. 11, p. e0149024, 2016.

56. D. Tepavac and L. Schwirtlich, "Detection and prediction of FES-induced fatigue," *Journal of Electromyography and Kinesiology,* vol. 7, pp. 39-50, 1997.

57. M. O. Ibitoye, E. H. Estigoni, N. A. Hamzaid, A. K. A. Wahab, and G. M. Davis, "The effectiveness of FES-evoked EMG potentials to assess muscle force and fatigue in individuals with spinal cord injury," *Sensors,* vol. 14, pp. 12598-12622, 2014.

58. M. O. Ibitoye, N. A. Hamzaid, J. M. Zuniga, N. Hasnan, and A. K. A. Wahab, "Mechanomyographic parameter extraction methods: an appraisal for clinical applications," *Sensors,* vol. 14, pp. 22940-22970, 2014.

59. M. O. Ibitoye, N. A. Hamzaid, J. M. Zuniga, and A. K. A. Wahab, "Mechanomyography and muscle function assessment: A review of current state and prospects," *Clinical Biomechanics,* vol. 29, pp. 691-704, 2014.

60. M. R. Kasten, A. M. Ievins, and C. T. Moritz, "Neural Prostheses," *eLS*, 2015.

61. D. B. Popović, M. B. Popović, and S. Došen, "Neural prostheses for walking restoration," *Journal of Automatic Control,* vol. 18, pp. 63-71, 2008.

62. C. Lynch and M. Popovic, "Sliding mode control of FES-induced quiet standing," in *Proceedings of the 17th Annual Conference of the International Functional Electrical Stimulation Society (IFESS), Banff, Canada*, 2012.

63. C. L. Lynch, D. Sayenko, and M. R. Popovic, "Co-contraction of antagonist muscles during knee extension against gravity: Insights for functional electrical

PTTAUTHM PERPUSTAKAAN TUNKU TUN AMINAH

stimulation control design," in *Engineering in Medicine and Biology Society (EMBC), 2012 Annual International Conference of the IEEE*, 2012, pp. 1843-1846.

64. N. V. Thakor, "Neuroprosthetics: Past, Present and Future," in *Replace, Repair, Restore, Relieve–Bridging Clinical and Engineering Solutions in Neurorehabilitation*, ed: Springer, 2014, pp. 15-21.

65. K. Minassian, U. Hofstoetter, K. Tansey, and W. Mayr, "Neuromodulation of lower limb motor control in restorative neurology," *Clinical neurology and neurosurgery*, vol. 114, pp. 489-497, 2012.

66. M. Huq and M. Tokhi, "Genetic algorithms based approach for designing spring brake orthosis–Part II: Control of FES induced movement," *Applied Bionics and Biomechanics*, vol. 9, pp. 317-331, 2012.

67. Q. Wang, N. Sharma, M. Johnson, C. M. Gregory, and W. E. Dixon, "Adaptive inverse optimal neuromuscular electrical stimulation," *IEEE transactions on cybernetics*, vol. 43, pp. 1710-1718, 2013.

68. J. Villagra and C. Balaguer, "A model-free approach for accurate joint motion control in humanoid locomotion," *International Journal of Humanoid Robotics*, vol. 8, pp. 27-46, 2011.

69. S. H. Sadati, S. E. Naghibi, I. D. Walker, K. Althoefer, and T. Nanayakkara, "Control space reduction and real-time accurate modeling of continuum manipulators using ritz and ritz–galerkin methods," *IEEE Robotics and Automation Letters*, vol. 3, pp. 328-335, 2018.

70. R. Ridley, "A more accurate current-mode control model," in *Power Supply Design Seminar*, 2011.

71. S. Timpitak, P. Prempraneerach, and E. Pengwang, "Parametric system identification of catamaran for improving controller design," in *IOP Conference Series: Materials Science and Engineering*, 2018, p. 012033.

72. K. M. Jagodnik, D. Blana, A. J. van den Bogert, and R. F. Kirsch, "An optimized proportional-derivative controller for the human upper extremity with gravity," *Journal of biomechanics*, vol. 48, pp. 3692-3700, 2015.

73. R. L. Williams II, "Simplified Robotics Joint-Space Trajectory Generation with a via Point using a Single Polynomial " *Journal of Robotics*, 2013.

74. Y.-c. Fung, *Biomechanics: mechanical properties of living tissues*: Springer Science & Business Media, 2013.

PTTAUTHM PERPUSTAKAAN TUNKU TUN AMINAH

75. S. J. Hall, *Basic biomechanics*, 6th ed.: McGraw-Hill Boston MA, 2012.
76. M. P. T. d. Silva "Human motion analysis using multibody dynamics and optimization tools," PhD, Mechanical Engineering, Instituto Superior Tecnico, Lisbon, 2003.
77. G. Tortora and B. Derrickson, "Introduction to the human body: the essentials of anatomy and physiology," 9th ed: Wiley, 2012.
78. K. Barrett, S. Barman, S. Boitano, and H. Brooks, *Ganong's Review of Medical Physiology*, 24 ed.: McGraw-Hill Medical, 2012.
79. R. M. Enoka and J. Duchateau, "Muscle fatigue: what, why and how it influences muscle function," *The Journal of physiology,* vol. 586, pp. 11-23, 2008.
80. H. Westerblad, J. D. Bruton, and A. Katz, "Skeletal muscle: energy metabolism, fiber types, fatigue and adaptability," *Experimental cell research,* vol. 316, pp. 3093-3099, 2010.
81. J. J. Abbas and H. J. Chizeck, "Feedback control of coronal plane hip angle in paraplegic subjects using functional neuromuscular stimulation," *Biomedical Engineering, IEEE Transactions on,* vol. 38, pp. 687-698, 1991.
82. R.-P. Jaime, Z. Matjacic, and K. J. Hunt, "Paraplegic standing supported by FES-controlled ankle stiffness," *IEEE Transactions on Neural Systems and Rehabilitation Engineering,* vol. 10, pp. 239-248, 2002.
83. K. Masani, A. H. Vette, and M. R. Popovic, "Controlling balance during quiet standing: proportional and derivative controller generates preceding motor command to body sway position observed in experiments," *Gait & posture,* vol. 23, pp. 164-172, 2006.
84. J.-y. Kim, M. R. Popovic, and J. K. Mills, "Dynamic modeling and torque estimation of FES-assisted arm-free standing for paraplegics," *IEEE Transactions on Neural Systems and Rehabilitation Engineering,* vol. 14, pp. 46-54, 2006.
85. J.-y. Kim, J. K. Mills, A. H. Vette, and M. R. Popovic, "Optimal combination of minimum degrees of freedom to be actuated in the lower limbs to facilitate arm-free paraplegic standing," *Journal of biomechanical engineering,* vol. 129, pp. 838-847, 2007.
86. A. H. Vette, K. Masani, and M. R. Popovic, "Implementation of a Physiologically Identified PD Feedback Controller for Regulating the Active

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

Ankle Torque During Quiet Stance," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 15, pp. 235-243, 2007.

87. A. H. Vette, K. Masani, J. Y. Kim, and M. R. Popovic, "Closed-loop control of functional electrical stimulation-assisted arm-free standing in individuals with spinal cord injury: a feasibility study," *Neuromodulation: Technology at the Neural Interface*, vol. 12, pp. 22-32, 2009.

88. M. B. Same;, H. Rouhani;, K. Masani;, and M. R. Popovic, "Closed-loop control of ankle plantarflexors and dorsiflexors using an inverted pendulum apparatus: A pilot study," *Journal of Automatic Control, University of Belgrade*, vol. 21, pp. 31-36, 2013.

89. A. H. Vette, K. Masani, K. Nakazawa, and M. R. Popovic, "Neural-Mechanical Feedback Control Scheme Generates Physiological Ankle Torque Fluctuation During Quiet Stance," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 18, pp. 86-95, 2010.

90. Z. Matjačić, K. Hunt, H. Gollee, and T. Sinkjaer, "Control of posture with FES systems," *Medical engineering & physics*, vol. 25, pp. 51-62, 2003.

91. Z. Matjacic and T. Bajd, "Arm-free paraplegic standing. II. Experimental results," *IEEE Transactions on Rehabilitation Engineering*, vol. 6, pp. 139-150, 1998.

92. Z. Matjacic and T. Bajd, "Arm-free paraplegic standing. I. Control model synthesis and simulation," *IEEE Transactions on Rehabilitation Engineering*, vol. 6, pp. 125-138, 1998.

93. K. J. Hunt, M. Munih, and N. d. N. Donaldson, "Feedback control of unsupported standing in paraplegia. I. Optimal control approach," *IEEE Transactions on Rehabilitation Engineering*, vol. 5, pp. 331-340, 1997.

94. M. Munih, N. d. N. Donaldson, K. J. Hunt, and F. Barr, "Feedback control of unsupported standing in paraplegia. II. Experimental results," *Rehabilitation Engineering, IEEE Transactions on*, vol. 5, pp. 341-352, 1997.

95. K. J. Hunt, M. Munih, N. Donaldson, and F. Barr, "Optimal control of ankle joint moment: Toward unsupported standing in paraplegia," *Automatic Control, IEEE Transactions on*, vol. 43, pp. 819-832, 1998.

96. K. Hunt, H. Gollee, R. Jaime, and N. Donaldson, "Feedback control of unsupported standing," *Technology and Health Care*, vol. 7, pp. 443-447, 1999.

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

97. J. Hung, H. Gollee, R.-P. Jaime, and N. d. Donaldson, "Design of feedback controllers for paraplegic standing," in *Control Theory and Applications, IEE Proceedings-*, 2001, pp. 97-108.

98. K. Hunt, R.-P. Jaime, and H. Gollee, "Robust control of electrically-stimulated muscle using polynomial H∞ design," *Control Engineering Practice,* vol. 9, pp. 313-328, 2001.

99. W. Holderbaum, K. Hunt, and H. Gollee, "H∞ robust control design for unsupported paraplegic standing: experimental evaluation," *Control Engineering Practice,* vol. 10, pp. 1211-1222, 2002.

100. W. Holderbaum, K. J. Hunt, and H. Gollee, "Robust Discrete-Time H∞ Control for Unsupported Paraplegic Standing: Experimental Results," *European journal of control,* vol. 10, pp. 275-284, 2004.

101. P. H. Veltink, H. Van der Kooij, and F. Van der Helm, "Discussion on:"Robust Discrete-Time H∞ Control for Unsupported Paraplegic Standing: Experimental Results"," *European Journal of Control,* vol. 10, pp. 285-287, 2004.

102. A. Arifin, T. Watanabe, and N. Hoshimiya, "Design of fuzzy controller of the cycle-to-cycle control for swing phase of hemiplegic gait induced by FES," *IEICE transactions on information and systems,* vol. 89, pp. 1525-1533, 2006.

103. A. Ariffn, Watanabe, T. and Hoshimiya, N. , " A test of fuzzy controller for cycle-to-cycle control of FES-induced hemiplegic gait: Computer simulation in single-joint control," in *36th Conference of Japaneese Society for Medical and Biological Engineering*, 2002.

104. A. Ariffin, Watanabe, T. and Hoshimiya, N., "A Test of Fuzzy Controller for Cycle-to-Cycle Control of FES-induced Hemiplegic Gait: Computer Simulation in Single-joint Control " *Biomedical Engineering: Japan M. Yee Journal,* vol. 41, p. 68, 2003.

105. A. Ariffin, Watanabe, T. and Hoshimiya, N., "Fuzzy controller for cycle-to-cycle control of swing phase of fes-induced hemiplegic gait: a computer simulation in two-joint control," in *Proceedings of the 25th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, 2003.

106. T. Watanabe, A. Arifin, T. Masuko, and M. Yoshizawa, "An Experimental Test of Fuzzy Controller Based on Cycle-to-Cycle Control for FES-induced Gait:

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

Knee Joint Control with Neurologically Intact Subjects," in *11th Mediterranean Conference on Medical and Biomedical Engineering and Computing 2007*, 2007, pp. 647-650.

107. T. Watanabe, T. Masuko, and A. Arifin, "Preliminary tests of a practical fuzzy FES controller based on cycle-to-cycle control in the knee flexion and extension control," *IEICE TRANSACTIONS on Information and Systems,* vol. 92, pp. 1507-1510, 2009.

108. T. Watanabe, T. Masuko, A. Arifin, and M. Yoshizawa, "A feasibility study of fuzzy FES controller based on cycle-to-cycle control: An experimental test of knee extension control," *IEICE transactions on information and systems,* vol. 91, pp. 865-868, 2008.

109. R. Davoodi and B. J. Andrews, "Fuzzy logic control of FES rowing exercise in paraplegia," *Biomedical Engineering, IEEE Transactions on,* vol. 51, pp. 541-543, 2004.

110. B. S. K. K. Ibrahim, M. S. Huq, M. O. Tokhi, and S. C. Gharooni, "Modelling of Muscloskeletal System with Genetic Optimization of Fuzzy Logic Approach," in *Biomedical Engineering Research Projects and Case Studies*, ed: Penerbit UTHM, 2015, pp. 17-42.

111. B. S. K. K. Ibrahim and "Modelling and control of paraplegic's knee joint (FES-SWINGING)," PhD Dissertation, University of Sheffield, 2011.

112. B. S. K. K. Ibrahim, M. O. Tokhi, M. S. Huq, and S. Gharooni, "Fuzzy logic based cycle to cycle control of FES-induced swinging motion," presented at the 2011 International Conference on Electrical, Control and Computer Engineering (INECCE), 2011.

113. B. S. K. K. Ibrahim, M. O. Tokhi, M. S. Huq, and S. Gharooni, "Discrete-Time Cycle-to-Cycle Fuzzy Logic Control of FES-Induced Swinging Motion," in *FuzzyControllers-Recent Advances in Theory and Applications*, S. Iqbal, N. Boumella, and J. C. F. Garcia, Eds., ed: INTECH Open Access Publisher, 2012.

114. B. Ibrahim, M. Tokhi, M. Huq, R. Jailani, and S. Gharooni, "Fuzzy modelling of knee joint with genetic optimization," *Applied Bionics and Biomechanics,* vol. 8, pp. 85-99, 2011.

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

115. R. Hussain, R. Massoud, and M. Al-Mawaldi, "ANFIS-PID Control FES-Supported Sit-to-Stand in Paraplegics:(Simulation Study)," *Journal of Biomedical Science and Engineering,* vol. 7, p. 208, 2014.

116. R. Massoud, "The Influence of Control Design on Energetic Cost during FES Induced Sit-to-Stand," *Journal of Biomedical Science and Engineering,* vol. 7, p. 1096, 2014.

117. Y. Chen, J. Hu, L. Peng, and Z.-g. Hou, "The FES-assisted control for a lower limb rehabilitation robot: simulation and experiment," *Robotics and Biomimetics,* vol. 1, pp. 1-20, 2014.

118. G.-C. Chang, G.-D. Liao, J.-J. Luh, J.-S. Lai, C.-K. Cheng, and T.-S. Kuo, "Application of neural network-based controller for the knee-joint position control with quadriceps stimulation," in *Engineering in Medicine and Biology Society, 1996. Bridging Disciplines for Biomedicine. Proceedings of the 18th Annual International Conference of the IEEE*, 1996, pp. 455-456.

119. G.-C. Chang, J.-J. Lub, G.-D. Liao, J.-S. Lai, C.-K. Cheng, B.-L. Kuo*, et al.*, "A neuro-control system for the knee joint position control with quadriceps stimulation," *Rehabilitation Engineering, IEEE Transactions on,* vol. 5, pp. 2-11, 1997.

120. D. Graupe and H. Kordylewski, "Artificial neural network control of FES in paraplegics for patient responsive ambulation," *Biomedical Engineering, IEEE Transactions on*, vol. 42, pp. 699-707, 1995.

121. Z. Hussain, M. A. Zaidan, M. O. Tokhi, and R. Jailani, "The adaptive control of FES-assisted indoor rowing exercise," in *Proceedings of 2009 CACS International Automatic Control Conference*, 2009.

122. J. J. Abbas and H. J. Chizeck, " Adaptive feedforward control of cyclic movements using artificial neural networks," presented at the International Joint Conference on Neural Networks IJCNN, 1992.

123. J. J. Abbas and H. J. Chizeck, "Neural network control of functional neuromuscular stimulation systems: computer simulation studies," *Biomedical Engineering, IEEE Transactions on,* vol. 42, pp. 1117-1127, 1995.

124. J. Riess and J. J. Abbas, "Control of cyclic movements as muscles fatigue using functional neuromuscular stimulation," in *Proceedings of the First Joint Engineering in Medicine and Biology, 21st Annual Conference and the 1999*

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

Annual Fall Meetring of the Biomedical Engineering Society BMES/EMBS, 1999.

125. J. Riess and J. J. Abbas, "Adaptive neural network control of cyclic movements using functional neuromuscular stimulation," *Rehabilitation Engineering, IEEE Transactions on*, vol. 8, pp. 42-52, 2000.
126. E. C. Stites and J. J. Abbas, "Sensitivity and versatility of an adaptive system for controlling cyclic movements using functional neuromuscular stimulation," *Biomedical Engineering, IEEE Transactions on*, vol. 47, pp. 1287-1292, 2000.
127. J. Riess and J. A. Abbas, "Adaptive control of cyclic movements as muscles fatigue using functional neuromuscular stimulation," *Neural Systems and Rehabilitation Engineering, IEEE Transactions on*, vol. 9, pp. 326-330, 2001.
128. J. J. Abbas and R. Triolo, " Experimental evaluation of an adaptive feedforward controller for use in functional neuromuscular stimulation systems," in *Proceedings of the 15th Annual International Conference of the IEEE Engineering in Medicine and Biology Society* 1993.
129. J. J. Abbas and R. J. Triolo, "Experimental evaluation of an adaptive feedforward controller for use in functional neuromuscular stimulation systems," *Rehabilitation Engineering, IEEE Transactions on*, vol. 5, pp. 12-22, 1997.
130. S.-J. Kim, M. D. Fairchild, A. Iarkov, J. J. Abbas, and R. Jung, "Adaptive control of movement for neuromuscular stimulation-assisted therapy in a rodent model," *Biomedical Engineering, IEEE Transactions on*, vol. 56, pp. 452-461, 2009.
131. H. K. Roozbahani and A. Erfanian, "Control of paraplegic standing using adaptive neuro-fuzzy sliding mode control: A simulation study."
132. H. Karimi and A. Erfanian, "Adaptive Terminal Sliding Mode Control of Walker-Supported Standing in Paraplegia."
133. H.-R. Kobravi and A. Erfanian, "A decentralized adaptive fuzzy robust strategy for control of upright standing posture in paraplegia using functional electrical stimulation," *Medical engineering & physics*, vol. 34, pp. 28-37, 2012.
134. A. Ajoudani and A. Erfanian, "A neuro-sliding-mode control with adaptive modeling of uncertainty for control of movement in paralyzed limbs using

functional electrical stimulation," *Biomedical Engineering, IEEE Transactions on,* vol. 56, pp. 1771-1780, 2009.

135. V. Nekoukar and A. Erfanian, "Adaptive fuzzy terminal sliding mode control for a class of MIMO uncertain nonlinear systems," *Fuzzy Sets and Systems,* vol. 179, pp. 34-49, 2011.

136. V. Nekoukar and A. Erfanian, "A decentralized modular control framework for robust control of FES-activated walker-assisted paraplegic walking using terminal sliding mode and fuzzy logic control," *Biomedical Engineering, IEEE Transactions on,* vol. 59, pp. 2818-2827, 2012.

137. A. Farhoud and A. Erfanian, "Fully automatic control of paraplegic FES pedaling using higher-order sliding mode and fuzzy logic control," *Neural Systems and Rehabilitation Engineering, IEEE Transactions on,* vol. 22, pp. 533-542, 2014.

138. H.-R. Kobravi and A. Erfanian, "Decentralized adaptive robust control based on sliding mode and nonlinear compensator for the control of ankle movement using functional electrical stimulation of agonist–antagonist muscles," *Journal of neural engineering,* vol. 6, p. 046007, 2009.

139. S. Jezernik, R. G. Wassink, and T. Keller, "Sliding mode closed-loop control of FES controlling the shank movement," *Biomedical Engineering, IEEE Transactions on,* vol. 51, pp. 263-272, 2004.

140. S. Jezernik, P. Inderbitzin, T. Keller, and R. Riener, "Sliding mode control of functional electrical stimulation for knee joint angle tracking," presented at the Proc. of the 7th Vienna International Workshop on Functional Electrical Stimulation, 2001.

141. S. Jezernik, P. Inderbitzin, T. Keller, and R. Riener, "A novel sliding mode controller for functional electrical stimulation," in *Proceedings of the 15th IFAC World Congress on Automatic Control, Barcelona Session slot T-Mo-M20: Modelling and Control in Biomedical Systems*, 2002.

142. C. Lynch and M. Popovic, "Closed-loop control for FES: Past work and future directions," in *10th Annual Conference of the International FES Society*, 2005, pp. 2-4.

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

143. T. Schauer, W. Holderbaum, and K. Hunt, "Sliding-mode control of knee-joint angle: experimental results," in *7th Annu. Conf. Int. Functional Electr. Stimul. Soc., Ljubljana, Slovenia*, 2002.

144. S. Mohammed, P. Poignet, P. Fraisse, and D. Guiraud, "Rehabilitation of the paralyzed lower limbs using Functional Electrical Stimulation: Robust closed loop control," in *Rehabilitation Robotics*, S. S. Kommu, Ed., ed: INTECH Open Access Publisher, 2007, pp. 337-358.

145. M. Ferrarin and A. Pedotti, "The relationship between electrical stimulus and joint torque: A dynamic model," *IEEE transactions on rehabilitation engineering,* vol. 8, pp. 342-352, 2000.

146. C. L. Lynch, G. M. Graham, and M. R. Popovic, "A generic model of real-world non-ideal behaviour of FES-induced muscle contractions: simulation tool," *Journal of neural engineering,* vol. 8, p. 046034, 2011.

147. C. L. Lynch, G. M. Graham, and M. R. Popovic, "Including nonideal behavior in simulations of functional electrical stimulation applications," *Artificial organs,* vol. 35, pp. 267-269, 2011.

148. C. L. Lynch and M. R. Popovic, "A comparison of closed-loop control algorithms for regulating electrically stimulated knee movements in individuals with spinal cord injury," *Neural Systems and Rehabilitation Engineering, IEEE Transactions on,* vol. 20, pp. 539-548, 2012.

149. F. Previdi, E. Carpanzano, and C. Cirillo, "Application of a gain scheduling control strategy to artificial stimulation of the quadricepts muscle," presented at the European Control Conference, 1999.

150. F. Previdi and E. Carpanzano, "Design of a gain scheduling controller for knee-joint angle control by using functional electrical stimulation," *Control Systems Technology, IEEE Transactions on*, vol. 11, pp. 310-324, 2003.

151. N.-O. Negard, T. Schauer, and J. Raisch, "Robust nonlinear control of knee-joint angle: A simulation study," in *3. Wismarer Automatisierungssymposium*, 2002.

152. T. Schauer, N.-O. Negård, F. Previdi, K. Hunt, M. Fraser, E. Ferchland, *et al.*, "Online identification and nonlinear control of the electrically stimulated quadriceps muscle," *Control Engineering Practice*, vol. 13, pp. 1207-1219, 2005.

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

153. M. Ferrarin, F. Palazzo, R. Riener, and J. Quintern, "Model-based control of FES-induced single joint movements," *Neural Systems and Rehabilitation Engineering, IEEE Transactions on,* vol. 9, pp. 245-257, 2001.

154. P. E. Crago, N. Lan, P. H. Veltink, J. J. Abbas, and C. Kantor, "New control strategies for neuroprosthetic systems," *Journal of rehabilitation research and development,* vol. 33, p. 158, 1996.

155. M. S. Hatwell, B. J. Oderkerk, C. A. Sacher, and G. F. Inbar, "The development of a model reference adaptive controller to control the knee joint of paraplegics," *Automatic Control, IEEE Transactions on,* vol. 36, pp. 683-691, 1991.

156. M. J. Dolan, B. J. Andrews, and P. Veltink, "Switching curve controller for FES-assisted standing up and sitting down," *IEEE Transactions on Rehabilitation Engineering,* vol. 6, pp. 167-171, 1998.

157. M. Poboroniuc, S. , "New experimental results on feedback control of FES-based standing in paraplegia," *AL.I.CUZA University Scientific Annals of Biophysics, Medical Physics and Environment Physics, tom.I, ,* vol. vol. III, pp. 83-89, 2007.

158. N.-Y. Yu, J.-J. J. Chen, and M. S. Ju, "Closed-loop control of quadriceps/hamstring activation for FES-induced standing-up movement of paraplegics," *Journal of Musculoskeletal Research,* vol. 5, pp. 173-184, 2001.

159. R. Davoodi and B. J. Andrews, "Computer simulation of FES standing up in paraplegia: A self-adaptive fuzzy controller with reinforcement learning," *IEEE Transactions on Rehabilitation Engineering,* vol. 6, pp. 151-161, 1998.

160. R. Davoodi and B. J. Andrews, "Optimal control of FES-assisted standing up in paraplegia using genetic algorithms," *Medical engineering & physics,* vol. 21, pp. 609-617, 1999.

161. R. Kamnik, J. Q. Shi, R. Murray-Smith, and T. Bajd, "Nonlinear modeling of FES-supported standing-up in paraplegia for selection of feedback sensors," *IEEE Transactions on Neural Systems and Rehabilitation Engineering,* vol. 13, pp. 40-52, 2005.

162. F. Previdi, M. Ferrarin, S. M. Savaresi, and S. Bittanti, "Closed-loop control of FES supported standing up and sitting down using Virtual Reference Feedback Tuning," *Control Engineering Practice,* vol. 13, pp. 1173-1182, 2005.

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

163. R. M. Esfanjani and F. Towhidkhah, "Application of nonlinear model predictive controller for FES-assisted standing up in paraplegia," in *Engineering in Medicine and Biology Society, 2005. IEEE-EMBS 2005. 27th Annual International Conference of the*, 2006, pp. 6210-6213.
164. L. Biagiotti and C. Melchiorri, *Trajectory planning for automatic machines and robots*: Springer Science & Business Media, 2008.
165. A. Gasparetto, P. Boscariol, A. Lanzutti, and R. Vidoni, "Trajectory planning in robotics," *Mathematics in Computer Science*, vol. 6, pp. 269-279, 2012.
166. M. Zhihong, *Robotics*. Singapore: PEARSON, Prentice Hall, 2005.
167. B. Siciliano, L. Sciavicco, L. Villani, and G. Oriolo, *Robotics: modelling, planning and control*: Springer Science & Business Media, 2010.
168. R. P. Paul and H. Zhang, "Robot motion trajectory specification and generation," in *2nd International Symposium on Robotics Research, Kyoto, Japan*, 1984.
169. A. Koivo, *Fundamentals for control of robotic manipulators*: John Wiley & Sons, Inc., 1989.
170. R. E. Parkin, *Applied robotic analysis*: Prentice-Hall, Inc., 1991.
171. L. Sciavicco and B. Siciliano, *Modelling and control of robot manipulators*: Springer Science & Business Media, 2012.
172. J. J. Craig, *Introduction to robotics: mechanics and control* vol. 3: Pearson/Prentice Hall Upper Saddle River, NJ, USA:, 2005.
173. M. W. Spong, S. Hutchinson, and M. Vidyasagar, *Robot modeling and control* vol. 3: Wiley New York, 2006.
174. R. N. Jazar, *Theory of applied robotics: kinematics, dynamics, and control*: Springer Science & Business Media, 2010.
175. K. S. F. R. G. C. S. G. Lee, *Robotics: Control Sensing. Vis*: McGraw-Hill, 1987.
176. J. Angeles, *Fundamentals of Robotic Mechanical Systems: Theory, Methods, and Algorithms*, 4 ed.: Springer International Publishing, 2014.
177. N. B. M. Nasir, "Intelligent Modelling and Control with Fatigue Reduction for FES Induced Knee Joint of Hemiplegic for Rehabilitation," Doctor of Philosophy, Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia, 2017.

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

178. N. A. Kirsch, "Control methods for compensation and inhibition of muscle fatigue in neuroprosthetic devices," University of Pittsburgh, 2016.

179. C. L. Lynch and M. R. Popovic, "A comparison of closed-loop control algorithms for regulating electrically stimulated knee movements in individuals with spinal cord injury," *IEEE Transactions on Neural Systems and Rehabilitation Engineering,* vol. 20, pp. 539-548, 2012.

180. D. Simon, "Analyzing control system robustness," *IEEE Potentials,* vol. 21, pp. 16-19, 2002.

181. S. Sastry and M. Bodson, *Adaptive control: stability, convergence and robustness*: Courier Corporation, 2011.

182. O. Sename, "Robust control of MIMO systems," *GIPSA-Lab,* 2013.

183. S. Skogestad and I. Postlethwaite, *Multivariable feedback control: analysis and design* vol. 2: Wiley New York, 2007.

184. D. A. Mindell, *Between human and machine: feedback, control, and computing before cybernetics*: JHU Press, 2002.

185. A. Bartoszewicz, *Robust control, theory and applications*. Croatia: InTech, 2011.

186. B. Friedland, *Control system design: an introduction to state-space methods*. Mineola, New York: Dover Publications, Inc., 1986.

187. K.-Z. Liu and Y. Yao, *Robust control: theory and applications*: John Wiley & Sons, 2016.

188. D.-W. Gu, P. H. Petkov, and M. M. Konstantinov, *Robust control design with MATLAB®*: Springer Science & Business Media, 2013.

189. L. Fortuna and M. Frasca, *Optimal and Robust Control: Advanced Topics with MATLAB®*: CRC press, 2012.

190. J. Liu and X. Wang, *Advanced sliding mode control for mechanical systems*: Springer, 2012.

191. J.-J. E. Slotine and W. Li, *Applied nonlinear control* vol. 199: prentice-Hall Englewood Cliffs, NJ, 1991.

192. H. K. Khalil, "Nonlinear systems, 3rd," *New Jewsey, Prentice Hall,* vol. 9, 2002.

193. P. V. Kokotovic, "The joy of feedback: nonlinear and adaptive," *IEEE Control systems,* vol. 12, pp. 7-17, 1992.

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

194. R. Lozano and B. Brogliato, "Adaptive control of robot manipulators with flexible joints," *IEEE Transactions on Automatic Control,* vol. 37, pp. 174-181, 1992.

195. A. Tsukahara, R. Kawanishi, Y. Hasegawa, and Y. Sankai, "Sit-to-stand and stand-to-sit transfer support for complete paraplegic patients with robot suit HAL," *Advanced robotics,* vol. 24, pp. 1615-1638, 2010.

196. A. Fattah, M. Hajiaghamemar, and A. Mokhtarian, "Design of a Semi-Active Semi-Passive Assistive Device for Sit-to-Stand Tasks," presented at the 16 th Annual (International) Conference on Mechanical Engineering-ISME2008, May 14-16, 2008, Shahid Bahonar University of Kerman, Iran, 2008.

197. T. Afzal, L. Khan, and M. Tokhi, "Simulation of a patient driven strategy for FES supported sit-to-stand movement," in *Information and Emerging Technologies (ICIET), 2010 International Conference on*, 2010, pp. 1-5.

198. M. W. Spong, S. Hutchinson, and M. Vidyasagar, *Robot modeling and control*: Wiley New York, 2006.

199. S. Nuzik, R. Lamb, A. VanSant, and S. Hirt, "Sit-to-stand movement pattern," *Physical Therapy,* vol. 66, pp. 1708-1713, 1986.

200. C. A. Stevermer and J. C. Gillette, "Kinematic and Kinetic Indicators of Sit-to-Stand," *Journal of applied biomechanics*, vol. 32, pp. 7-15, 2016.

201. K. Lynch and F. Park, *Modern Robotics: Mechanics, Planning, and Control*: Cambridge University Press, 2017.

202. R. N. Kamal, M. J. Rainbow, E. Akelman, and J. J. Crisco, "In vivo triquetrum-hamate kinematics through a simulated hammering task wrist motion," *The Journal of Bone and Joint Surgery. American volume.*, vol. 94, p. e85, 2012.

203. D. A. Winter, *Biomechanics and motor control of human movement*: John Wiley & Sons, 2009.

204. D.-W. Gu, P. H. Petkov, and M. M. Konstantinov, *Robust control design with MATLAB®*: Springer Science & Business Media, 2014.

205. J. Ackermann, *Robust control: Systems with uncertain physical parameters*: Springer Science & Business Media, 2012.

206. P. Gáspár, Z. Szabó, J. Bokor, and B. Németh, "Robust Control Design for Active Driver Assistance Systems," *Springer, DOI,* vol. 10, pp. 978-3, 2017.

207. N. Hovakimyan and C. Cao, *L1 adaptive control theory: guaranteed robustness with fast adaptation* vol. 21: SIAM-Society for Industrial and Applied Mathematics, 2010.

208. C. Freeman, "Control system design for electrical stimulation in upper limb rehabilitation," *Switzerland: Springer International Publishing,* 2016.

209. C. D. Fryar, Q. Gu, C. L. Ogden, and K. M. Flegal, "Anthropometric reference data for children and adults; United States, 2011-2014," 2016.

210. S. C. Walpole, D. Prieto-Merino, P. Edwards, J. Cleland, G. Stevens, and I. Roberts, "The weight of nations: an estimation of adult human biomass," *BMC public health,* vol. 12, p. 439, 2012.

211. A. K. Chang and J. Y. Choi, "Factors influencing BMI classifications of Korean adults," *Journal of physical therapy science,* vol. 27, pp. 1565-1570, 2015.

212. J. Nagrath, Gopal, M., *Control Systems Engineering*: New Age International, 2007.

213. R. C. Dorf and R. H. Bishop, *Modern control systems*: Pearson, 2011.

214. B. B. Alagoz, F. N. Deniz, C. Keles, and N. Tan, "Disturbance rejection performance analyses of closed loop control systems by reference to disturbance ratio," *ISA transactions,* vol. 55, pp. 63-71, 2015.

215. RehaMove, "FES Cycling with RehaMove," ed. Germany: Hasomed, 2014.

216. RehaMove, "Functional Electrical Stimulation, FES Applications," ed: Hasomed, 2015.

217. J. Liu and X. Wang, *Advanced sliding mode control for mechanical systems: design, analysis and MATLAB simulation*: Springer Science & Business Media, 2012.

218. G. M. Freitas, A. C. Leite, and F. Lizarralde, "Kinematic control of constrained robotic systems," *Sba: Controle & Automação Sociedade Brasileira de Automatica,* vol. 22, pp. 559-572, 2011.

219. J. Jovic, S. Lengagne, P. Fraisse, and C. Azevedo-Coste, "Impact of functional electrical stimulation of lower limbs during sitting pivot transfer motion for paraplegic people," *International Journal of Advanced Robotic Systems,* vol. 10, p. 25, 2013.

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

220. J. Jović, C. A. Coste, P. Fraisse, and C. Fattal, "Upper and lower body coordination in FES-assisted sit-to-stand transfers in paraplegic subjects—A case study," *Paladyn,* vol. 2, pp. 211-217, 2011.

221. S. Kim, S. Lee, H. Kang, and J. Jeong, "Study of knee and hip joints' moment estimation by biomechanical simulation during various motion changes," in *Proceedings of the world congress on engineering and computer science,* 2009.

222. J. Jovic, "Towards a functional assistance in transfer and posture of paraplegics using FES: From simulations to experiments," Université Montpellier II-Sciences et Techniques du Languedoc, 2012.

223. E. Gallasch, D. Rafolt, G. Kinz, M. Fend, H. Kern, and W. Mayr, "Evaluation of FES-Induced Knee Joint Moments in Paraplegics with Denervated Muscles," *Artificial organs,* vol. 29, pp. 207-211, 2005.

224. B. Ibrahim, M. Tokhi, M. Huq, and S. Gharooni, "Fuzzy logic based cycle-to-cycle control of FES-induced swinging motion," in *Electrical, Control and Computer Engineering (INECCE), 2011 International Conference on*, 2011, pp. 60-64.

225. B. Ibrahim, M. Tokhi, M. Huq, S. Gharooni, N. Boumella, and J. Garcia, *Discrete-Time Cycle-to-Cycle Fuzzy Logic Control of FES-Induced Swinging Motion*: INTECH Open Access Publisher, 2012.

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

APPENDIX A: Publications

The publications originated from the research work which yielded the thesis. It comprises conference of proceedings and journal papers.

Conference Papers

- Ahmed, M., M. S. Huq, B. S. K. K. Ibrahim, (2017) Evolution of Intelligent And Nonlinear Control Approaches For Fes Induced Movement Generation of The Lower Limb, Advances in Cooperative Robotics: pp. 596-607.
- Mohammed Ahmed, M. S. Huq, B. S. K. K. Ibrahim, Aisha Ahmed, Zainab Ahmed, (2016) New Concepts for FES-Induced Movements, IOP Conf. Series: Materials Science and Engineering 160 (2016) 012104 doi:10.1088/1757-899X/160/1/012104.
- Ahmed, M., Huq, M. S., & Ibrahim, B. S. K. K. (2018). Restoration of Movement using FES: An Introductory Study I. In *IOP Conference Series: Materials Science and Engineering* (Vol. 341, No. 1, p. 012009). IOP Publishing.
- Ahmed, M., Huq, M. S., & Ibrahim, B. S. K. K. (2018).” Symposium on Electrical, Mechatronics and Applied Science 2018 (SEMA’18)” Manuscript Accepted.

Journal Papers

- Ahmed, M., M. S. Huq, B. S. K. K. Ibrahim, (2017). SMC Scheme for FES Aided Restoration of STS Movement in Paraplegics. *International Journal of Integrated Engineering*, *9*(4).
- Ahmed, M., Huq, M. S., & Ibrahim, B. S. K. K. (2017). Kinematic Modelling of FES Induced Sit-to-stand Movement in Paraplegia. *International Journal of Electrical and Computer Engineering (IJECE)*, *7*(6), 3060-3069.
- Ahmed, M., Huq, M. S., Ibrahim, B. S. K., & Ahmed, A. (2018). A Preliminary Evaluation of Linear Control Schemes for FES-Assisted Movements. *Malaysian Journal of Movement, Health & Exercise*, *7*(1).

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

- Ahmed, M., M. S. Huq, B. S. K. K. Ibrahim, "Sliding Mode Control of FES Aided Restored Movement**,"** IEEE Transactions on Control Systems Technology**,** Manuscript Preparation in Process.
- Ahmed, M., M. S. Huq, B. S. K. K. Ibrahim, "Evaluation of Linearized Feedback Control Technique for Restoration of Sit-to-Stand Movement in Paraplegia," *IET Control Theory & Applications*, Manuscript Preparation in Process.
- Ahmed, M., M. S. Huq, B. S. K. K. Ibrahim, "FES Induced Restoration of STS Manoeuvre utilising the Backstepping Control Technique," Automatica, Manuscript Preparation in Process.
- Ahmed, M., M. S. Huq, B. S. K. K. Ibrahim, "Improved Trajectory Planning for FES-Induced STS Movement Restoration in Paraplegia," Robotica, Manuscript Preparation in Process.
- Ahmed, M., M. S. Huq, B. S. K. K. Ibrahim, "An Improved Dynamic Model for FES Assisted Sit-to-Stand Movement in Paraplegia," International Journal of Integrated Engineering (IJIE), Manuscript Preparation in Process.
- Ahmed, M., M. S. Huq, B. S. K. K. Ibrahim, "Comparison of Nonlinear Control Techniques for the Regulation of Functional Electrical Stimulation Induced Sit-to-Stand in Paraplegia**,"** IEEE Transactions on Control Systems Technology**,** Manuscript Preparation in Process.

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH