

## **A PRELIMINARY EVALUATION OF LINEAR CONTROL SCHEMES FOR FES-ASSISTED MOVEMENTS**

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### **Abstract**

Functional Electrical Stimulation (FES) can be used to revive movement functions of the human body to a certain degree which was lost due to occurrences of the nervous system disorders resulting from accidents or diseases. It can also be employed for gait rehabilitation as well as therapy. Control systems could be employed to improve on the FES-induced motion, and the closed-loop was targeted due to its advantages. Based on the papers reviewed, studies have shown that the linear control schemes are popular for movement restoration in the lower limb, but mostly for continuous standing contributing to mainly the stance phase. Therefore, a myriad of limitations was observed which include: the need for using improved sensors, re-tuning for every subject, tests conducted using patient with more straightforward ailments, complexity in implementation and most importantly is the issue of stability. The swing phase of gait movement and the full walking motion have more complex dynamics and coupled with the nature of the plant (human with nervous system disorder and the neuromuscular structure) could render the linear control method obsolete or unsuitable. Hence, there is a need to investigate other techniques such as the nonlinear and intelligent control methods.

**Keywords:** Nervous system disorders health, electrical stimulation, functional electrical stimulation, function restoration, movement restoration, linear control systems, lower limbs

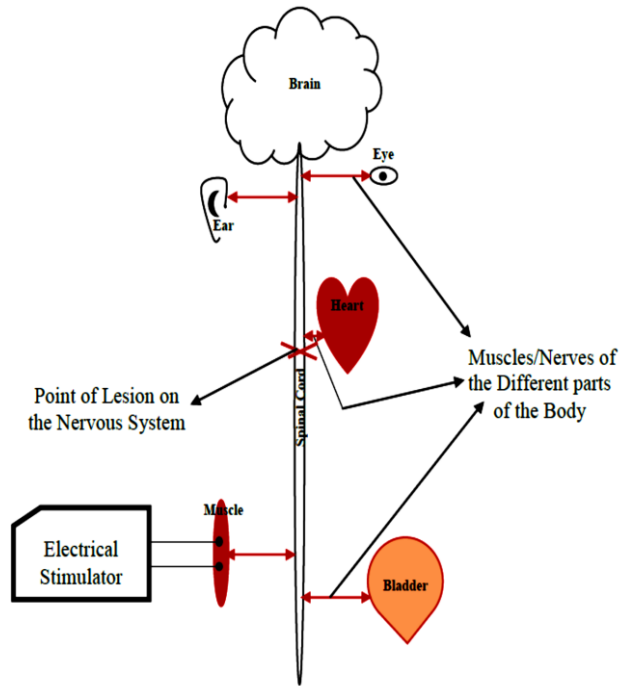
## **Introduction**

The coordination of the human body is accomplished by the central nervous system using signals which are in an electrical form originating from ionic currents. This makes the application of electrical signals useful for quite a number medical therapies such as pain suppression, wound healing, muscle conditioning and revival of functions such as for sight, hearing, heart contractions, bladder functions and movement revival by using stimulating the appropriate nerve cells/muscles involved (Chen, Hu, Peng, & Hou, 2014; Durfee, 2006; Ferrari de Castro & Cliquet, 2000; Jezernik, Inderbitzin, Keller, & Reiner, 2002).

In electrical stimulation usually electrical signals of certain characteristics are used (usually of low amplitudes) to help to revert or reduce abnormalities in utterances or responses of the human body parts due to the nervous system failure as a result of diseases, trauma or complications (such as spinal cord injury, head injury, stroke and other disorders) which are usually controlled by the central nervous system (CNS) (Arantes et al., 2007; Braz, Russold, & Davis, 2009; Chen et al., 2014; Durfee, 2006; Ethier, Oby, Bauman, & Miller, 2012; Jezernik et al., 2002; Kern et al., 2010; Lee et al., 2013; Papachristos, 2014; Tan et al., 2014). The function reversal/revival of the affected body part is achieved by systematically applying the desirable electrical signals its muscles/nerves. The term Functional Electrical Stimulation (FES) usually refers to the use of electrical stimulation for movement restoration (Arantes et al., 2007; Durfee, 2006; Papachristos, 2014; Tan et al., 2014). Figure 1 is a brief demonstration of how to use electrical stimulation is accomplished for the restoration of some functions. As earlier mentioned in reality the stimulator is usually connected to the muscle group responsible for the target activity.

Closed-loop control systems have been identified as means of taking FES to higher levels (Ibitoye, Hamzaid, Hasnan, Wahab, & Davis, 2016). Earlier systems were open-loop based, but it is often used to achieve basic as well as a simple task without refinement such as in foot drop management. There are devices that combine orthosis and FES for movement restoration in the lower limbs. It is worth noting that subjects with nervous system injuries are increasing annually, and according to the World Health Organization (WHO) report, the following projections were made in relation to the world population; 6.29% in 2005, 6.39% in 2015 and 6.77% in 2030 (Aarli, Dua, Janca, & Muscetta, 2006). The shortfall and high costs of the devices could be attributed to the strict clinical requirements. Improving the FES control structures may eventually lead to more devices passing the clinical stages, and hence reduced device cost, improved healthcare delivery, improved patient independence and also reduced costs of management. The present manuscript is an appraisal of the linear control structures proposed for FES-assisted lower limb movement restoration in subjects with nervous system impairments.

The paper is made-up of three main sections: the first part introduces FES in brief. It is followed by a brief review on application of linear control methods for FES-Induced Movement; which briefly reviews existing works related control of FES for restoration movement in the lower limbs and the final section was conclusion; which closes the brief review and recommendations were made.



**Figure 1:** Electrical stimulation and nervous system interactions.

### **Linear Control Schemes Employed for FES-Assisted Movement**

The linear control methods have been applied for control of FES-assisted movements in the lower limbs. The Proportional-Integral-Derivative (PID) controllers and variants were harnessed for control of FES to achieve standing (continuous standing) in paraplegics (individuals with spinal cord injury having lost partially or complete sensation in the lower limbs region). Abbas and Chizek (1991) compared open and closed-loop control techniques for FES-assisted standing control, and it was observed that the closed-loop scheme is much superior in comparison to the open-loop scheme. The closed-loop scheme employed is the conventional PID control scheme. It was reported that based on the tests performed on two paraplegics, the proposed scheme was able to reduce the root-mean-square error by 41%, steady-state error by 52% and improve compliance on the hip during movement by 22%.

The works of Jaime et al. (2002) focussed on the ankle stiffness in order to maintain FES-assisted continuous standing in subjects with spinal cord injuries. It is achieved by using quad-hydraulic actuators (as part of the control architecture) that utilises the P controller. It was tested on a single paraplegic, and the results indicate lowered complication when trying to maintain balance while standing. The improvement in stiffness was produced by stimulating muscle components responsible for causing flexor movements in addition to that causing extension which is normally the targeted muscles. The results indicate that stiffness of the magnitude between 8 to 10 Nm/degree is required to maintain balance during the FES assisted standing.

In the works of Masani, Vette, and Popovic (2006), investigation on suppressing time delays associated with the nervous system during FES-assisted standing in paraplegics using feedforward and feedback PD controller was their main focus. From the study, it was shown that the feedback PD controller is sufficient without the need for the additional feed-forward loop. Nonetheless, it is worth noting that the investigation only considered healthy subjects' only. It was an improvement over an earlier discovery by Morasso and Schieppati (1999) that utilised the PD control technique. It was reported that a 50 ms delay in the closed-loop arrangement could make the system unstable. The study by Masani et al., 2006 extended the ability of the control system to up to 185 ms (which was above their estimate for neuromuscular systems time delays; that is 135 ms). This was achieved by considering the angular velocity component in addition to the angular position in the control system operation.

The determination of the optimum degrees of freedom (DOF) and the pattern in which the muscles should be stimulated/actuated in order to maintain FES-induced standing in paraplegic subjects was investigated (Kim, Mills, Vette, & Popovic, 2007; Kim, Popovic, & Mills, 2006). The authors reported that the optimum DOF is six although it was not experimentally tested. In addition, the effectiveness of PD controller to suppress disturbances in the system was also evaluated. The 12 DOF dynamic modelling of the system was developed using the Newton-Euler formulation. The inverse dynamics of the system was obtained using the Nakamura's method (which is a method of efficiently determining inverse dynamics of a system) to ascertain the torques involved, and it resulted in a combination of 6 DOF for active torques and 6 DOF for passive torques. Since the interest was to obtain minimal DOF; this makes 6 DOF with active torques and non-zero passive torques a viable option. A sensitivity test was carried out to attain the optimal DOF through the best combination since there are 12 combinations of 6 DOF possible solutions (i.e. 924 possibilities).

Owing to the fact that at most only the required muscles of the ankle, knee and hip joints are needed, the possible combination is reduced to only 28 possibilities. Investigation on singularity occurrences in the matrices of the Jacobian of the passive torques further scale it down to 8. Finally, the research continued by determining a set of muscles that when stimulated would yield the least torque required to accomplish the induced standing; first, it was reduced to three possibilities and finally one after looking at the average torque required and standard deviations. It was established that the stimulation of both ankle muscles for flexor and extensor torques, both knee muscles for flexor and extensor torques, single hip muscles for flexor and extensor torques and the other for abduction and adduction are the essential DOFs with the least average torque. The configuration was used to evaluate the behaviour with perturbation with magnitude 100N applied at the center of mass of the combination of the head, arms and trunk segment at an angle 45° between x and z-axes for 0.5s. Results indicated the effect was annulled within 2 seconds.

The works of Vette, Masani, and Popovic (2007) further explored the time delay compensation ability as well as capability to produce command signals 100-200 ms in advance to tackle the swaying movement using the PD controller for continuous standing in paraplegic. The study focused an experimental examination of PD control scheme for stabilisation ability to manage the torques at the ankles in the presence of neuromuscular

time delays and generation of compensation (control) signals when tackling body sway. The test was conducted on “Von Hippel-Lindau” disease patient, and the level of control achieved was not very good. After careful observation and analysis, it was ascertained that the PD controller was able to provide a control signal 21 ms earlier for sway compensation. The centre of mass and centre of pressure parameter variations namely mean distance (cm), root mean square distance (cm), range fluctuation (cm), mean velocity (cm/s) and mean square velocity (cm/s) were scrutinised for evaluating the stabilisation ability.

In an extended study by Vette, Masani, Kim, and Popovic (2009), similar to their study reported above, but in addition, there was an elaboration on how to determine the PD controller parameters easily. According to the study, a 1 DOF model also known as the inverted pendulum model of the continuous standing system was utilised to find the range of controller parameters analytically that is; the proportional and derivative gains after which can be applied to the 12 DOF model. Hence, the range of the ratio of the proportional to derivative gains obtained was within the range of 1.45-3.83 and the gains of the system with a maximum estimated time delay of 185 ms were 750 Nm/rad and 350 Nm/rad, respectively.

Vette, Masani, Nakazawa, and Popovic (2010), further focused on investigations on the contributions of active and passive components of the neuromuscular plant. Moreover, the study evaluates the effectiveness of PD control technique in generating required ankle torque similar to those obtainable in healthy subjects during standing. According to the study, the results indicate the ability of the controller to produce the required control signal. Data were collected from 14 healthy subjects, angular variations, as well as the torque produced by the ankles, were measured. Part of the data was used to optimise the parameters of the neuromuscular system which attained an average of 98.4% fitness. Ankle torques from the optimised model were compared with those obtained experimentally (validation), and the average closeness was 96.7%. The controller was then designed using the optimised model, and the torques generated were compared which yields average values of 98.3% and 96.6% fitness for the optimised and validation conditions, respectively.

Same, Rouhani, Masani and Popovic (2013) focused on investigating the capability of the PID controller for stabilisation for FES assisted standing in subjects with neurological problems that affect the lower limbs. A new equipment was developed known as the “inverted pendulum standing apparatus (IPSA)”. Gravity compensation combined with PID controller was used and was compared with voluntary control (without FES and controller). Results indicate better performance of their proposed technique in terms of stability; evaluated using mean error and root mean square error of the ankle angle (level of oscillation), disturbance rejection ability; measured using settling time and return to original position when perturbed; quantified by measuring the mean settling time and deviation on three healthy subjects.

In the works of Yu, Chen, and Ju (2001), the PID control scheme was explored for FES assisted sit-to-stand movement. The primary objective of their research was to ascertain the effectiveness of closed-loop control technique over the open-loop counterpart. The PID and the ON-OFF were the closed-loop techniques investigated, and the work was both

simulation and experiment. In the simulation, the modified simulator/test bench proposed by Mulder (Mulder, Veltink, & Boom, 1992) was used, and the testing was conducted using two volunteer spinal cord injury patients. Results obtained showed that PID outperforms both ON-OFF and open-loop, with the ON-OFF being superior to the open-loop. It shows that the knee angle velocity with the open-loop configuration was 164.63 deg/s which was reduced to 13.41 deg/s when the ON-OFF closed-loop control system was applied, and PID control technique further suppressed it to 11.37 deg/s. Another property observed was the smoothness of the transition trajectory and the best was using the PID, then the ON-OFF and the open-loop control scheme. Involvement of high velocity and roughness in the transition trajectory (presence of higher oscillations) are detrimental to the joint as it could lead to ligament damage and instability. Stability problem persisted, so the testing was done carefully, and the integral parameter of the PID was kept minimal. The main disadvantage of these control approaches mentioned above was the stringent requirement for sensor arrangements with high precision for the guaranteed stability of the system (Lynch & Popovic, 2005).

The Linear Quadratic Regulator (LQR) control approach for the continuous standing has also been examined (Matjacic & Bajd, 1998a, 1998b). Attention was given to the effects of the regular upper part of the body and the torque developed by the ankle joints stiffness; others are vision feedback and nervous system delays. The study carried out was both simulation and experimental based. In the simulation works, the model of the system obtained was similar to that of under-actuated systems, i.e., it may have many equilibrium states. An impulse disturbance torque of magnitude 50 Nm and duration of 100 ms was applied, and results show that the maximum values of the ankle angles are almost the same for the two scenarios, but for the knee angles was lower for the second condition. The maximum values of the angular velocities are higher for the first condition, and the maximum torques required to annul the effect was about 20 Nm for the former case whereas it was 10 Nm for the latter. A feasibility study was conducted on the extent to which disturbances can be curtailed by the system and since the system can attain multi equilibriums: different possible postures were considered: upright; initial ankle angle equals 0°, forward; initial ankle angle equals 20°, and initial ankle angle equals -20°. The relationship between ankle stiffness and different constraints; the ankle and knee angles should be between -100 to 100°, trunk strength and length of the foot were evaluated. It was observed that ankle stiffness between 8-18 Nm/deg would be required to mitigate the effect of the different disturbances. The experimental test was performed on a paraplegic, and a healthy subject. The result shows that stiffness of 8 Nm/degree is sufficient to maintain balance. Nonetheless, it is worth to note that the torque attained is associated with foot length, which is unique for different individuals.

Hunt and together with others (K. J. Hunt, Munih, & Donaldson, 1997; Munih, Donaldson, Hunt, & Barr, 1997) went ahead and implemented the Linear Quadratic Gaussian (LQG) control scheme. Braces were used to reduce the complexity of contribution by the hold upper body to magnify the torque effect at the ankle, and the torque and the ankle angle were regulated in the approach. The rise time was observed to reduce to 0-0.4 s. The tuning process was further enhanced by introducing the polynomial equation together with the LQG; the bandwidth was increased by 2.5 times and therefore stability improving stability (Kenneth J Hunt, Munih, Donaldson, & Barr, 1998). Another technique employed

was the pole placement control approach for solving the problem (Gollee, Hunt, & Wood, 2004; Hung, Gollee, Jaime, & Donaldson, 2001; K. Hunt, Gollee, Jaime, & Donaldson, 1999). The torque loop was discarded, improved operation bandwidth maintained and longer duration of standing was realised (more than two minutes). Improvement in performance was observed although it was not significant. The system is quite complicated, and it could drift to the unstable mode when the response becomes slow which may readily occur in reality due to the effect of fatigue and other forms of disturbances.

In another development Ricci, Santaniello, Fiengo, and Glielmo, (2009) explored the utilisation of LQR and Kalman filter estimation methods for enhancing the effects of rehabilitation for standing in paraplegics. Both the flexor and extensor muscles were stimulated. The work was entirely simulation-based, and the human standing model was approximated using the double inverted pendulum with three factors that take into account of the muscles and joint movement initiations. Results show that the centre of the mass movement was lowered; its variation was around 1.3 mm against previous works that were around 4 mm to 4.5 cm. Lower knee and ankle angles changes were also noticed and are between 10 to 100° less. Estimates of the velocities of the angles were observed to be close to the measured values (i.e. error between measured and estimated values are close to zero) and converge at a fast rate while stability was maintained. The robustness of the proposed control scheme was improved as it was demonstrated from the study that disturbance in the form of impulse of about 50 Nm could be eliminated in 100 ms.

H-infinity control approach was presented, which has an advantage over previous techniques by giving room to capture un-modelled disturbances (Holderbaum, Hunt, & Gollee, 2002; Holderbaum, Hunt, & Gollee, 2004; K. Hunt, Jaime, & Gollee, 2001). Tests were conducted on a paraplegic and even though successful, stability was found to be guaranteed within a particular range. According to the works of Lynch and co-researchers (Lynch & Popovic, 2005; Lynch, 2011), assumption that intentional movements resulting from the upper part of the body which was healthy was in opposite direction of flex motions produce by stimulated muscles could be solved by application of stimulation signals to both muscles responsible for generation of movements in the two opposite directions at the same time.

It can be seen from the discussion most of the proposed applications of the linear control technique for lower FES-Induced movements is for standing. The standing phase is less complicated (as its dynamics is non-complex or static in nature) in comparison to the swing phase of gait in which its dynamics varies. Despite that, so many shortcomings were identified such as the sensing requirement, re-tuning requirement for different individuals, tests were conducted on subjects with less complicated disorders (mainly paraplegics), the complexity of implementation and limitations regarding stability. The nature of the plant (that is human with failure on the nervous system) couple with nature of neuromuscular behaviour could be the primary contributing factor which is associated with some or all of the following: spasm, fatigue and delayed response. Based on the aforesaid argument, some researchers are of the view that the control task may be difficult is the 'linear approach' is taken. However, despite the observed challenges the linear control systems have been successfully implemented of for continuous standing only to a certain extent with significant challenge being that of the overall system stability.

## **Conclusion**

It is apparent from the preliminary review carried out that there exist numerous challenges that are associated with the implementation of traditional linear control systems. Although significant improvements have been demonstrated via the incorporation of the aforesaid control schemes, nonetheless, it is limited to the standing (stance) phase alone. Hence, the need to explore other techniques available (that is nonlinear and intelligent control methods) more especially for the swing phase, partial movement (sit-to-stand, stand-to-sit, and standing) or complete movement (walking). Moreover, for improving existing ones to pave the way for clinical acceptance of more devices for FES-aided movements.

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## **Conflict of Interest**

“The authors declare that they have no conflict of interest”.

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