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KINEMATIC MODELLING OF ELECTRICALLY INDUCED SIT-TO-STAND MOTION FOR SPINAL CORD INJURY SUBJECTS AFFECTING THE LOWER LIMBS

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Abstract

The work presented enhancement over the kinematic model of aided sit-to-stand (STS) movement using Functional Electrical Stimulation. More accurate models are necessary for making achieving better control systems, and it is expected that such would aid in producing improvement that could lead to achieving clinical acceptance currently still lacking. The work was compared with the STS model proposed by Nuzik et al. which is an effort to equip the physiotherapists [redacted] *with a standard reference. Results revealed that an improvement in the FES induced STS modelling with an average accuracy of 24% was achieved. Therefore, the expectation is not only limited to the enhancement of control system design, but it will also introduce a higher level of flexibility of the model.*

KEYWORDS:
Induced movement, sit-to-stand, functional electrical stimulation, control systems, kinematic model, paraplegia

Introduction

These days Functional Electrical Stimulation (FES) is a well-known method employed for restoration human movements artificially in patients with ailments associated with the nervous system. It utilises low energy electrical pulses for the purpose and also for rehabilitation and exercise (Gallas, Marie, Leroi, & Verin, 2010; Schearer et al., 2014).

Applications of control systems have been showing astonishing enhancements of the process, yet still, further improvements are required (Lynch & Popovic, 2008; Schearer et al., 2014). According to available documentation, improved plant models would yield a higher level of control system performance leading to better system fulfilment (Ibrahim & Salam, 2011; Nasir, 2017).

The investigation was limited to the determination of an enhanced version of the FES kinematic model for the aided sit-to-stand (STS) movement restoration. It is also limited to simulation and for subjects with paraplegia.

The study consists of four sections: the introduction, methodology, results and discussion and conclusion. It begins with the introduction; the introduction section tries to reveal the background information of the work. Next was the methodology section; it explained the various techniques employed. The results and discussion provide the breakdown of the results obtained. Finally, the conclusion section gives highlights of the entire research work in the compact form.

Methodology

The idea of the FES supported STS movement was conceived based on the contributions of Nuzik *et al*. (Nuzik, Lamb, VanSant, & Hirt, 1986), Tsukahara *et al*. (Tsukahara, Kawanishi, Hasegawa, & Sankai, 2010), Stevermer and Gillette (Stevermer & Gillette, 2016), Fattah *et al*. (Fattah, Hajiaghamemar, & Mokhtarian, 2008), Kamnik *et al.* (Kamnik, Shi, Murray-Smith, & Bajd, 2005), Yu *et al*. (Yu, Chen, & Ju, 2001), Jovic (Jovic, 2012), and Davoodi and Andrews (Davoodi & Andrews, 1998). Figure 2.1 gives an illustration of the concept and it is an indication of the mid of the movement transition. The sited position is the initial state and standing position is the final state of the transition. In between the two extremes are the changeover states of the paraplegic during the motion.

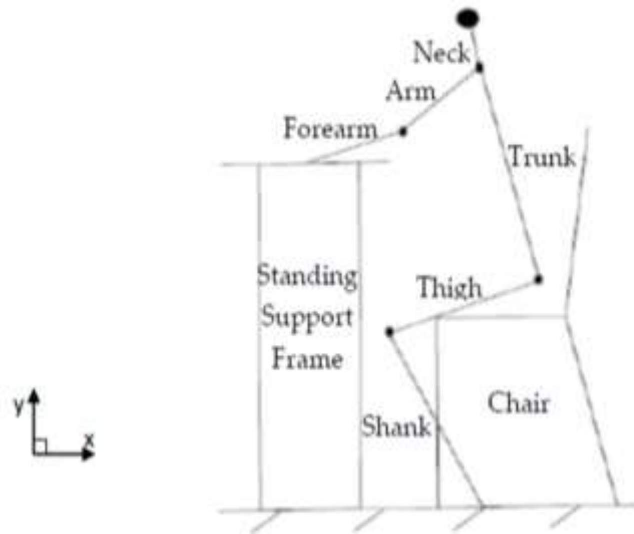

Figure 2.1 The FES supported STS transition illustration

The assumption was that the movement occurs in the x-y plane as given in Figure 2.1 above. The electrical current is passed through the muscles in the thigh segment using the electrodes. The muscles are the ones responsible for producing torques at the knee joint which is the source of generating motion. The kinematic modelling was achieved by employing the Denavit-Hartenberg (DH) technique. Figure 2.2 was a description of the movement using the convention configuration.

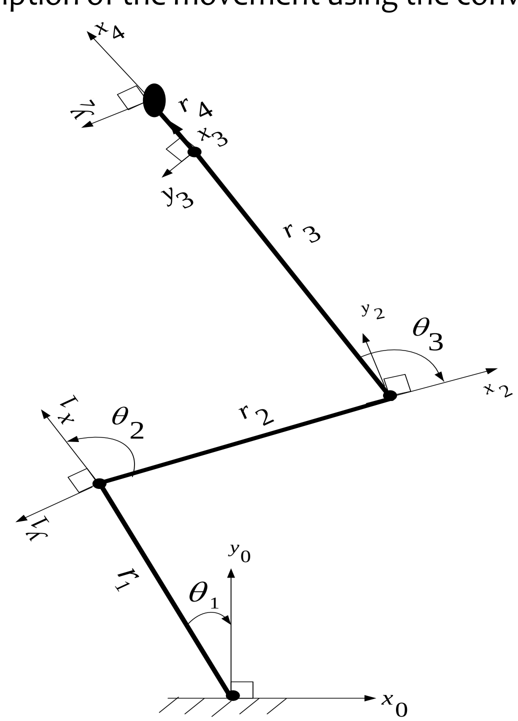

Figure 2.2 The FES supported STS transition model

Figure 2.2 was obtained after necessary evaluation and valid simplifications (Ahmed, Huq, & Ibrahim, 2017). It can be seen from the figure that the segment r_1 represents the shank and θ_1 the angle through which it moves via the ankle joint. Segment $r_2$is the thigh which is associated with movement through angle θ_2 and it corresponds to the knee joint motion. Segment r_3 although referred to as the trunk but it accommodates the trunk, arm and the forearm. It rotates through angle θ_3, the trunk angle. Finally, r_4 is called the neck segment but is the combination of the neck and head. It is associated with the neck angle θ_4.

The D-H transformation of the FES induced STS motion model is as given by Equation (1) below referring to Figure 2.2 (Siciliano, Sciavicco, Villani, & Oriolo, 2010; Spong, Hutchinson, & Vidyasagar, 2006).

$$T(\theta)_n^o = A_k^o A_n^k \qquad (1)$$

Where A_k^o represent the transformations of the various segments sequentially. Equation (2) shows the details of how to obtain the different items. Since, adjacent segments are connected and do rotate about z-axis according to the convention. The parameters: d_k are the offsets along the common z-axis, θ_k are the angles whose rotations are about the common z-axis, r_k are the various segment lengths, α_k are the angles around the x-axis, s refers to the $sine$ and c the $cosine$ of the corresponding angles. The parameter n in equation (1) gives the number of segments.

$$A_k = \begin{bmatrix} c_{\theta_k} & -s_{\theta_k}c_{\alpha_k} & s_{\theta_k}s_{\alpha_k} & r_j c_{\theta_k} \\ s_{\theta_k} & c_{\theta_k}c_{\alpha_k} & -c_{\theta_k}s_{\alpha_k} & r_j s_{\theta_k} \\ 0 & s_{\alpha_k} & c_{\alpha_k} & d_k \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (2)$$

According literature earlier studies indicated that scholars gave consideration to three segments as the highest utilised for modelling the FES assisted STS action. Some of which include the works of Tsukahara *et al*. (Tsukahara et al., 2010), Fattah *et al*. (Fattah et al., 2008), Kamnik *et al*. (Kamnik et al., 2005), Yu *et al*. (Yu et al., 2001), Jovic (Jovic, 2012), and Davoodi and Andrews (Davoodi & Andrews, 1998). In this proposed mathematical model, an additional component was considered to make improvements on accuracy and flexibility. The third segment was separated into two; refferred to as the trunk and neck segments which are initially regarded as the trunk. Number of segments n equals three (3) when obtaining the earlier model and it changes the number of segments to four (4). Thus, the transformations are obtained as given by equations (3) and (4) for the earlier and proposed models respectively. Where; 1, 2, 3, and 4 refer to the ankle, knee, thigh and neck segments or angles for the different constituents parts of the model.

$$T(\theta)_3^o = \begin{bmatrix} c_{123} & -s_{123} & 0 & P_{123} \\ s_{123} & c_{123} & 0 & Q_{123} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

$$P_{123} = r_1 c_1 + r_2 c_{12} + r_3 c_{123}$$

$$Q_{123} = r_1 s_1 + r_2 s_{12} + r_3 s_{123}$$

$$T(\theta)_4^o = \begin{bmatrix} c_{1234} & -s_{1234} & 0 & P_{1234} \\ s_{1234} & c_{1234} & 0 & Q_{1234} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

$$P_{1234} = r_1 c_1 + r_2 c_{12} + r_3 c_{123} + r_4 c_{1234}$$

$$Q_{1234} = r_1 s_1 + r_2 s_{12} + r_3 s_{123} + r_4 s_{1234}$$

Results and Discussion

Figure 3.1 gives the comparisons of the separate paths along the y and x-axes of the earlier model, model proposed, and reference model and Figure 3 shows the single path.

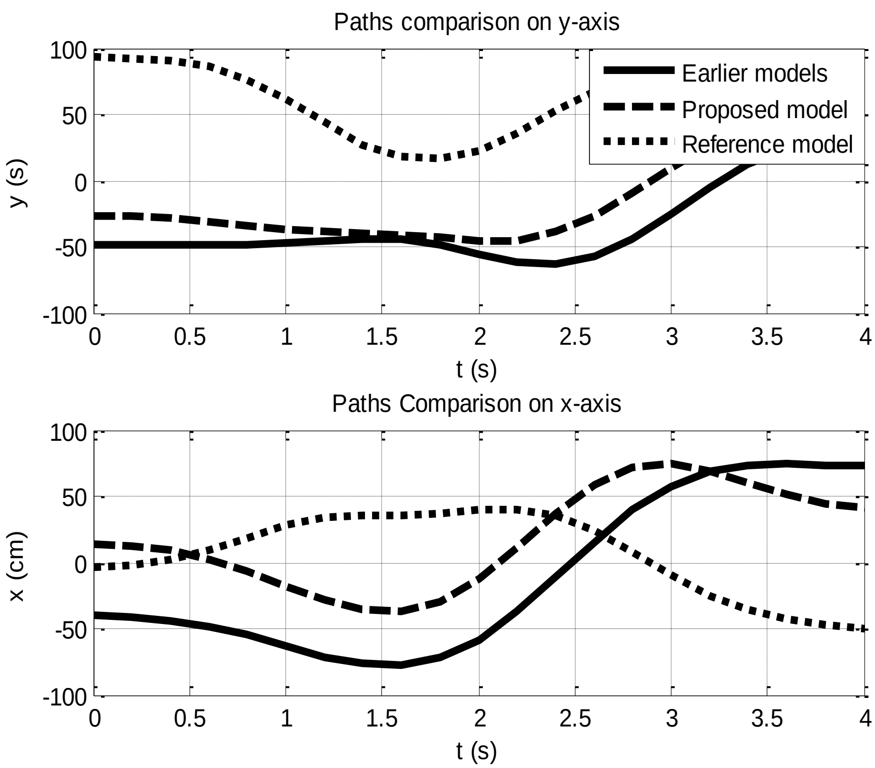

Figure 3.1 Comparison of the separate paths

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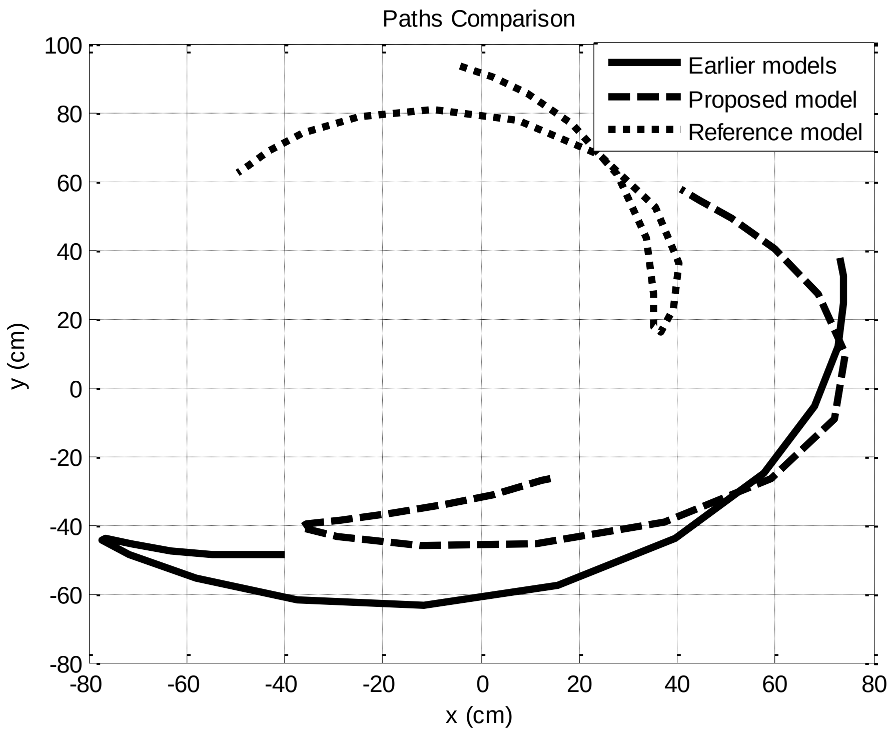

Figure 3.2 Comparison of the paths for the different models

The reference model is the benchmark model utilised for assessing the measure of improvement resulted. The sit-to-stand model proposed by Nuzik *et al*. (Nuzik et al., 1986); which was a standard sit-to-stand model developed so that it would help the physiotherapists in conducting their jobs more comfortable and better. Results in Figure 2 revealed an RMS error of 98.98 cm in the y-axis movement path. It was 85.27 cm for the x-axis path in the case of earlier models. RMS errors of 80.84 cm and 60.93 cm resulted in the proposed model. Hence, reducing the RMS errors by 18.14 cm in paths along the y-axis and 24.34 cm in the x-axis. It indicated improvements corresponding to 18% and 29% respectively. Figure 3 revealed average RMS errors of 92.13 cm and 70.89 cm for the earlier and proposed models. Therefore, resulting in an average accuracy advancement by 24%.

Conclusions

The proposed FES-aided STS movement restoration model employing four segment components; that is addition of a segment compared to existing models was successfully presented. The updating as seen is essential as it could help towards achieving clinical acceptance; in the sense that it would result in realising improvements in the design of the control system for the STS movement system. It produced a 24% improvement of accuracy compared to the best of previous models (that is; the three segment based STS model). More also it entails higher level of flexibility; taking care resent reaserch information related to the separated joints can be achieved with relative ease because there are so many researches is currently in progress in the area. Hence, the presumption is that the synthesis of SMC control systems can be realised with raised levels of performance for the STS movements asissted by FES.

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