

## Kinematic Modelling of FES Induced Sit-to-stand Movement in Paraplegia

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### Article Info

#### Article history:

Received Aug 23, 2017

Revised Nov 10, 2017

Accepted Nov 24, 2017

#### Keyword:

FES-induced movement

Kinematic model

Nervous system disorders

Rehabilitation robotics

Sit-to-stand movement

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### ABSTRACT

FES induced movements from indication is promising due to encouraging results being obtained by scholars. The kinematic model usually constitute the initial phase towards achieving the segmental dynamics of any rigid body system. It can be used to ascertain that the model is capable of achieving the desired goal. The dynamic model builds on the kinematic model and is usually mathematically cumbersome depending on the number of degrees-of-freedom. This paper presents a kinematic model applicable for human sit-to-stand movement scenario that will be used to obtain the dynamic model the FES induced movement in a later study. The study shows that the 6 DOF conceptualized sit-to-stand movement can be achieved conveniently using 4 DOF. The 4 DOF has an additional joint compared to similar earlier works which makes more it accurate and flexible. It is more accurate in the sense that it accommodates additional joint i.e. the neck joint whose dynamics could be captured. And more flexible in the sense that if future research uncover more contributions by the segments it can be easily incorporated including that of other segments e.g. the trunk, neck and upper limbs.

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## 1. INTRODUCTION

Restoring the ability to reestablished movements impaired due occurrence of failure in the nervous system using electrical current is known as functional electrical stimulation (FES). Illnesses and mishaps are the causes of the disorders and could be partial or complete [1-6]. The electrical signals are processed suitable form before being applied to right muscles for initiating the intended movement [2], [4], [7], [8]. Apart from restoring movements, FES is also utilized for rehabilitation (of the neural system) and for therapy as well [9-11]. The trend indicated annual rise in neural disorder subjects [12], [13]. There are in existence low number of assist devices employing FES and this might be due to strict requirements (www.cms.gov/CAG-00153R). Open loop control are popular among the few systems and are characterized by having fixed and built-in commands which are initiated by the user. These constitute weaknesses and can be highly improved using closed loop control techniques that may lead to passing the clinical requirements for FES assisted movements restoration devices [14-16].

There are works that further confirm the superiority of the closed loop schemes over the open loop in the case of FES-assisted sit-to-stand [17], [18]. Stability is a very important concern in FES induced movements perhaps it could be one of the important factor hindering clinical acceptance. According to scholars the linear control scheme might not provide solution to the system under consideration in this study (paraplegics i.e. humans with lost neural/movement functions in the lower limbs) due its nonlinear nature [18], [19]. Linear control methods were applied for control of FES-assisted sit-to-stand movements as depicted in the works of Dolan et al. [17], Poboronic [20], Yu et al. [18], the authors did not indicate mathematical model used even though for linear control schemes the model has to be linearized if it is not linear. The intelligent control schemes were also proposed and some of the works in that regards include that of Davoodi and Andrews [21], [22]. Computer models were used and one of the major shortcomings of the intelligent approach is lack of mathematical model for stability studies. Hence, stability analysis cannot be achieved easily [23] even though the methods used to yield good results. Combined linear and nonlinear methods was proposed by Previdi et al. [24] and nonlinear approaches were presented by Espanjani and Towhidkahr [25], also virtual models were used. The advantage of the nonlinear control scheme is that they can be used with nonlinear models which are usually closer to real systems. Additionally, the mathematical models can be used for stability studies.

This study is an initial phase of developing an improved nonlinear model of the FES-assisted sit-to-stand movements using the principle of robotics. Involving more joints; which improves accuracy and flexibility, more gray model; combines more experimental and analytical properties and incorporating finding; which portrays that the upper limbs supports about 10% of the weight. The manuscript was structured such that the introduction gives an overview on the study. Modelling methodology; briefly explain the whole concept employed and was followed by short results explanation referred to as 'results and discussion'. Finally, the conclusion rounds up everything.

## 2. MODELLING METHODOLOGY

Kinematics basically shows the relationship between the link or segment lengths and joint angles of the model, and hence, the coordinates and orientation in space [26], [27]. It yields equations that portray motions of robotic structure without given considerations to the effects of torques and forces, emphasizes is given to the geometry.

In the modeling relevant robotics principles were applied. The model proposed was based on the works of Nuzik et al. [28], Davoodi and Andrews [21], Yu et al. [18], Kamnik et al. [29], Fattah et al. [30], Tsukahara et al. [31] and Stevermer and Gillette [32]. The sit-to-stand movement was conceptualized as having three phases; the initial, transitional and the final phases. Figure 1(a) and Figure 1(b) were illustrations of the first and last phases respectively. The transition phase is in between the two, which are terminal points in the maneuver. The movement was assume to occur on the sagittal plane, making it a planar motion.

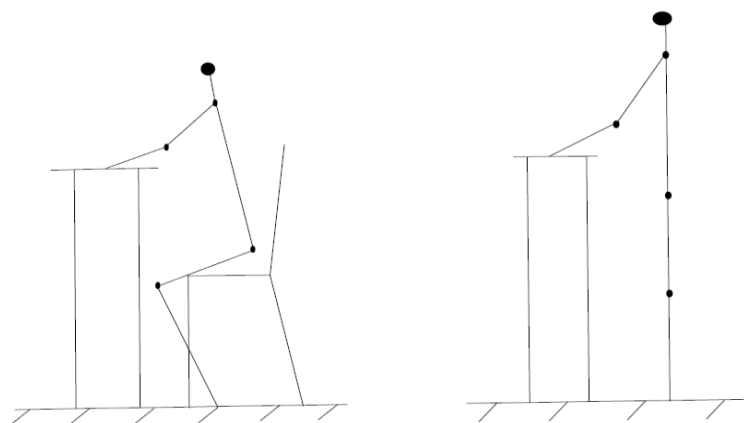


Figure 1. Conceptualized initial and final sit-to-stand positions

The various segment lengths were obtained as described in the works of Winter, [33] which are anthropometry based. Paraplegic subject P3 from the works of Ferrarin and Pedotti, [34] was selected for the study. The segmental lengths are as listed in Table 1.

Table 1. Segment Lengths of the Paraplegic P3 with Height 178 cm, Weight 85 Kg and Age 25 Years

S/No.	Segment	Length (cm)
1	Shank	50.7
2	Thigh	43.6
3	Trunk	51.3
4	Feet to Support Distance	30.0
5	Support	98.0
6	Lower Arm	25.8
7	Upper Arm	33.5
8	Head and Neck	32.4

In robotics however the manipulators were made up of links and are interconnected by joints forming the entire structure called the kinematic chain. There are basically three types of joints; revolute, prismatic and socket joints. Revolute or rotary joint as the name implies usually give rise to rotation between a pair of links, the prismatic or linear joint is for linear movement between dual adjacent links and the socket joint has the combine properties of the revolute and prismatic joints [35]. The counting of the joints usually starts from zero from the base frame and highest number of the joints gives the degree of freedom (DOF) of the robot for simple planer open loop chain configurations also known as serial configurations. In the case of closed loop chains or combinations of open and closed loop chains the Grübbler's method can be applied [35]. The body segments in Figure 1(a) and Figure 1(b) were carefully assigned configurations of links and joint angles as shown in Table 2, which are more appropriate for the next stage of study.

Table 2. Parameters of the Segments

Segment	Link	Length (cm)	Angles ( $\theta_i$ )
Shank	1 <sub>1</sub>	50.7	$\theta_{1_1}$
Thigh	1 <sub>2</sub>	43.6	$\theta_{1_2}$
Trunk	1 <sub>3</sub>	51.3	$\theta_{1_3}$
Feet to Support Distance	2 <sub>1</sub>	30.0	$\theta_{2_1}$
Support	2 <sub>2</sub>	98.0	$\theta_{2_2}$
Lower Arm	2 <sub>3</sub>	25.8	$\theta_{2_3}$
Upper Arm	2 <sub>4</sub>	33.5	$\theta_{2_4}$
Head and Neck	5	32.4	$\theta_5$

Figure 2 was the proposed model which clearly describe the motion and suitable for the kinematics analysis. The various segments; shank, thigh, trunk, feet to support distance, support, lower arm upper arm and head and neck segments were represented as 11, 12, 13, 21, 22, 23, 24 and 5 respectively in the figure. And the angles  $\theta_{1_1}$ ,  $\theta_{1_2}$ ,  $\theta_{1_3}$ ,  $\theta_{2_1}$ ,  $\theta_{2_2}$ ,  $\theta_{2_3}$ ,  $\theta_{2_4}$ , and  $\theta_5$  were Theta 11, Theta 12, Theta 13, Theta 23, Theta 24 respectively. It comprise of a closed chain at the beginning. Hence, the structure forms a closed link at joint 0, where it connects the first joints via links 1 (branch 1) and 2 (branch 2), and interconnections continue up to joint 5. Branch 1 is made up of links: 11, 12 and 13, while branch 2 comprises of links: 21, 22, 23 and 24. Both branches combine at joint 5 and after it was the link 5; the head-neck segment. The suitable joint as the cut joint for this condition was joint 5. Denavit-Hartenberg (DH) method is applied for the analysis and Table 3 shows the DH parameters of the proposed sit-to-stand model. The equation constituting the direct kinematics for the above scenario can be obtained using Equation (1) [27].

Where;  $T_m^0(q)$  is the overall transformation matrix which gives the kinematics equation,  $A_i^0$  are the sequential transformation within the closed chain and  $A_m^i$  are the transformations after the closed loop chain.

The process of computing  $T_m^0(q)$  is usually achieved in stages: First a suitable joint is selected in the closed chain region, the homogenous transformations are then determined by applying the DH principle for each of the frames branches, determine the equality constraints for the frames such that it resulted in lower number of joint variables and finally the overall transformation is computed by combining that of the closed loop chain obtained and others (which are multiplied).

$$T_m^0(q) = A_i^0 A_m^i \quad (1)$$

The terms  $A^i$  are vector multiplication of certain properties of the DH parameters which are; the rotation of the link about the z-axis ( $Rotation_{z,\theta_i}$ ) the extent of which is given by the joint angle ( $\theta_i$ ), translation along the z-axis ( $Translation_{z,d_i}$ ) referred to as the link offset  $d_i$ , translation on the x-axis

( $Translation_{x,a_i}$ ) which corresponds to the link length ( $a_i$ ) and finally the rotation of link about the x-axis ( $Rotation_{x,\alpha_i}$ ) measured as the link twist ( $\alpha_i$ ).

$$A^i = (Rotation_{z,\theta_i})x(Translation_{z,d_i})x(Translation_{x,a_i})x(Rotation_{x,\alpha_i}) \tag{2}$$

In order to make the matrices more compact, sin and cos were represented by s and c respectively.

$$A^i = \begin{bmatrix} c\theta_i & -s\theta_i c\alpha_i & s\theta_i s\alpha_i & a_i c\theta_i \\ s\theta_i & c\theta_i c\alpha_i & -c\theta_i s\alpha_i & a_i s\theta_i \\ 0 & s\alpha_i & c\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3}$$

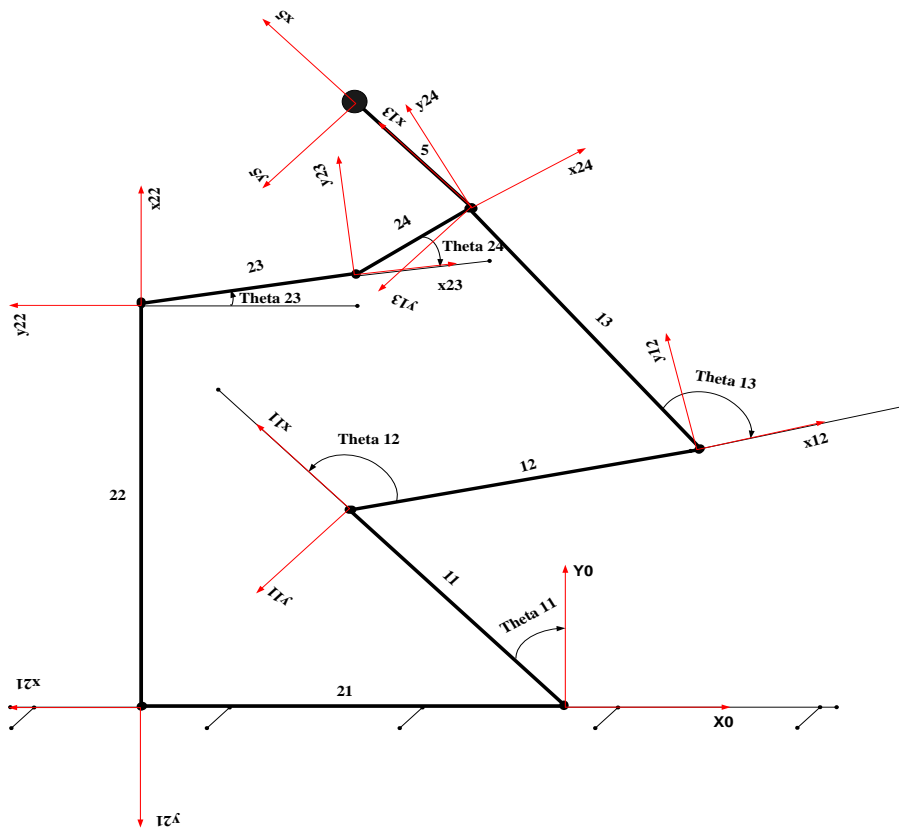


Figure 2. Joint kinematic convention for the FES assisted sit-to-stand model

Table 3. DH Parameters of the Model

Link	$a_i$	$\alpha_i$	$d_i$	$\theta_i$
1 <sub>1</sub>	a1 <sub>1</sub>	0	0	$\theta_{1_1}$
1 <sub>2</sub>	a1 <sub>2</sub>	0	0	$\theta_{1_2}$
1 <sub>3</sub>	a1 <sub>3</sub>	0	0	$\theta_{1_3}$
2 <sub>1</sub>	a2 <sub>1</sub>	0	0	180 <sup>0</sup>
2 <sub>2</sub>	a2 <sub>2</sub>	0	0	270 <sup>0</sup>
2 <sub>3</sub>	a2 <sub>3</sub>	0	0	$\theta_{2_3}$
2 <sub>4</sub>	a2 <sub>4</sub>	0	0	$\theta_{2_4}$
5	a5	0	0	0

Coordinate transformation for branch 1 frames was obtained as shown in (4) and it involves links 1<sub>1</sub>, 1<sub>2</sub> and 1<sub>3</sub>.

$$A_{1_3}^0(q_1) = A_{1_1}^0 A_{1_2}^1 A_{1_3}^2 = \begin{bmatrix} c_{1_1 1_2 1_3} & -s_{1_1 1_2 1_3} & 0 & a_1 c_{1_1} + a_2 c_{1_2} + a_3 c_{1_1 1_2 1_3} \\ s_{1_1 1_2 1_3} & s_{1_1 1_2 1_3} & 0 & a_1 s_{1_1} + a_2 s_{1_2} + a_3 s_{1_1 1_2 1_3} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

$$q_1 = \begin{bmatrix} \theta_{1_1} \\ \theta_{1_2} \\ \theta_{1_3} \end{bmatrix} \quad (5)$$

Coordinate transformation for branch 2 frames was obtained as given by (6) which involve links 2<sub>1</sub>, 2<sub>2</sub>, 2<sub>3</sub> and 2<sub>4</sub>.

$$A_{2_4}^0(q_2) = A_{2_1}^0 A_{2_2}^1 A_{2_3}^2 A_{2_4}^3 = \begin{bmatrix} s_{2_3 2_4} & c_{2_3 2_4} & 0 & -a_{2_1} + a_{2_3} s_{2_3} + a_{2_4} s_{2_3 2_4} \\ -c_{2_3 2_4} & s_{2_3 2_4} & 0 & -a_{2_2} - a_{2_3} s_{2_3} - a_{2_4} c_{2_3 2_4} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (6)$$

$$q_2 = \begin{bmatrix} 180^\circ \\ 270^\circ \\ \theta_{2_3} \\ \theta_{2_4} \end{bmatrix} \quad (7)$$

The constant homogenous transformation for the final link is given by;

$$A_5^3 = \begin{bmatrix} 1 & 0 & 0 & a_5 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (8)$$

In order to satisfy the constraints; that is at the meeting joint (point/joint 5) the coordinates of both branches at any instant should be same. Therefore, if subtracted for the branches will be zero ( i.e.  $d_{2_4 1_3} = 0$ ) and this may reduce the burden of computation or analysis by lowering the number of joint variables, that is no need to use all joints parameters [27], [36].

$$R_0^{2_4}(q_2)(p_{2_4}^0(q_2) - p_{1_3}^0(q_1)) = [0 \ 0 \ 0]^T \quad (9)$$

The branches without any adjustment satisfied the above constraint, therefore any of the branches can be used. Therefore, for simplicity as well as relevance, branch 1 was chosen and that makes Equation (10) the required kinematics equation (model).

$$T_5^0(q) = A_{1_3}^0(q) A_5^3(q) = \begin{bmatrix} c_{1_1 1_2 1_3} & -s_{1_1 1_2 1_3} & 0 & a_1 c_{1_1} + a_2 c_{1_2} + a_3 c_{1_1 1_2 1_3} + a_5 c_{1_1 1_2 1_3} \\ s_{1_1 1_2 1_3} & s_{1_1 1_2 1_3} & 0 & a_1 s_{1_1} + a_2 s_{1_2} + a_3 s_{1_1 1_2 1_3} + a_5 s_{1_1 1_2 1_3} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (10)$$

$$P_5^0 = T_5^0 P_5^5 \quad (11)$$

$P_5^0$ ; gives the coordinates with reference to the zero frame (reference frame),  $P_5^5$  are the coordinates with reference the fifth frame that is the final frame (end-effector frame) and  $T_5^0$  is given by Equation (10), that is; the transformation matrix.

In robotics, path describes the motion of a robot geometrically only, hence it remains silent about the system dynamics. Path simply specifies the locus of points within a specified operational or joint domain. On the other hand the trajectory is the time domain description of the movement and system dynamics are also captured when needed such as velocity and acceleration. Therefore, it is a time dependent path. Usually the trajectory is planned which can be done using algorithms. The algorithms describe the path, also incorporated are the constraints of both the path as well as that of dynamics. Results of which are the trajectories in relation to time for positions, velocities and accelerations reached [26], [27].

### 3. RESULTS AND DISCUSSION

It can be seen from Figure 2 that the complete movement model has 6 DOF which was obtained using the Grübbler's approach. According to the method number of DOF of any given structure can be obtained using Equations (12) and (13) [35]. Where: DOF; is the number of degrees of freedom, n; rigid body number of degrees of freedom, M; the number of links, J; the number of joints,  $c_k$ ; the number of constraints on a given joint k, and  $f_k$ ; joint k number of freedom. Applying to Figure 2: n equals 3 (planer mechanism), M equals 8, J equals 7 and f equals 1 for all the revolute joints except the fixed joint which is 0. Hence, on substituting in (12) and (13) appropriately, DOF was obtained as 6.

$$DOF = n(M - 1) - \sum_{k=1}^J c_k \quad (12)$$

$$c_k = n - f_k \quad (13)$$

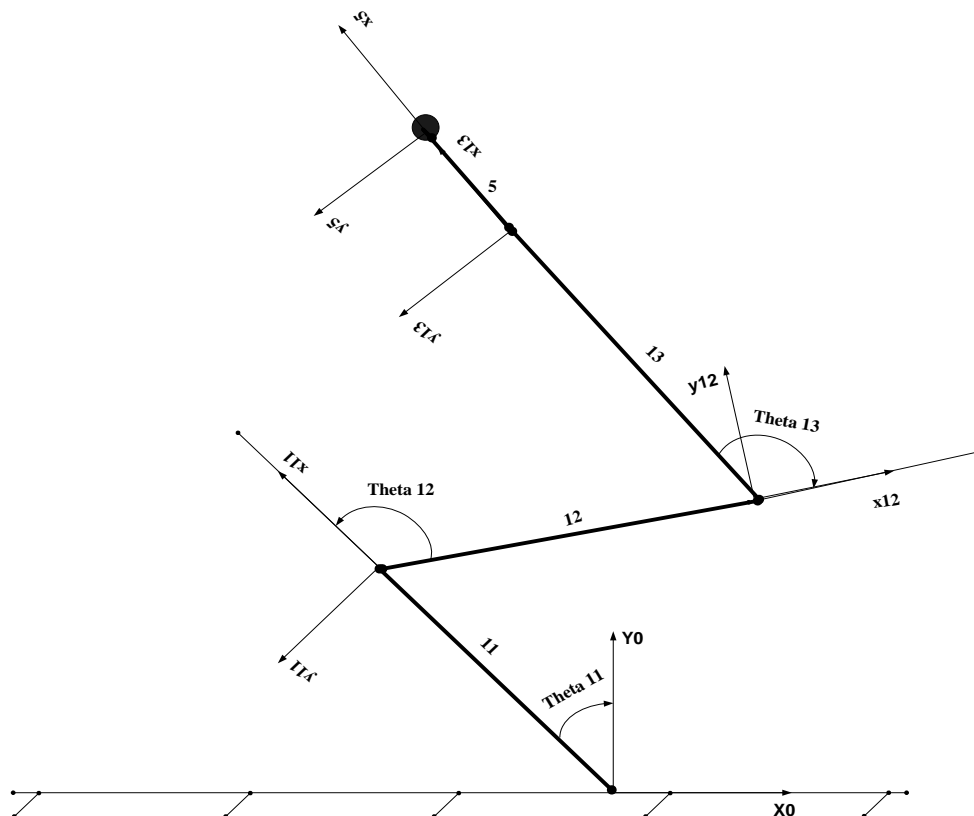


Figure 3. Joint kinematic convention for the approximated FES assisted sit-to-stand model

Therefore the mathematical representation would involve all the eight segments of the structure. Its transformation would be combination Equations (4), (6) and (8). The robotics principle had aid in reducing it

to 4 DOF via Equation (9) and led to the mathematical model involving only four segments as illustrated by Figure 3. The transformation only involves Equations (6) and (8). The number of the DOF can be determined using the formular as well. Hence, reducing the model complexity.

The paths of the joints associated with the sit to stand movement can be obtained from Equation (10). Hence, the coordinates of the knee joint, hip joint, neck joint and the head with respect to the reference frame are given by Equations (14), (15), (16) and (17) respectively. And the associated angles considered were five points from the sit to the stand positions and are as described by Equations (18)-(22).

$$x_{1_1}^0 = a_{1_1}c_{1_1}; y_{1_1}^0 = a_{1_1}s_{1_1} \quad (14)$$

$$x_{1_2}^0 = a_{1_1}c_{1_1} + a_{1_2}c_{1_2}; y_{1_2}^0 = a_{1_1}s_{1_1} + a_{1_2}s_{1_2} \quad (15)$$

$$x_{1_3}^0 = a_{1_1}c_{1_1} + a_{1_2}c_{1_2} + a_{1_3}c_{1_3}; y_{1_3}^0 = a_{1_1}s_{1_1} + a_{1_2}s_{1_2} + a_{1_3}s_{1_3} \quad (16)$$

$$x_5^0 = a_{1_1}c_{1_1} + a_{1_2}c_{1_2} + a_{1_3}c_{1_3} + a_5c_{1_1 1_2 1_3}; y_5^0 = a_{1_1}s_{1_1} + a_{1_2}s_{1_2} + a_{1_3}s_{1_3} + a_5s_{1_1 1_2 1_3} \quad (17)$$

$$q(\theta) = [\theta_{1_1} \quad \theta_{1_2} \quad \theta_{1_3} \quad \theta_5] \quad (18)$$

$$\theta_{1_1} = [105^0 \quad 101.25^0 \quad 97.5^0 \quad 93.75^0 \quad 90^0] \quad (19)$$

$$\theta_{1_2} = [278^0 \quad 298.5^0 \quad 319^0 \quad 339.5^0 \quad 360^0] \quad (20)$$

$$\theta_{1_3} = [75^0 \quad 56.25^0 \quad 37.5^0 \quad 18.75^0 \quad 0^0] \quad (21)$$

$$\theta_5 = [0^0 \quad 0^0 \quad 0^0 \quad 0^0 \quad 0^0] \quad (22)$$

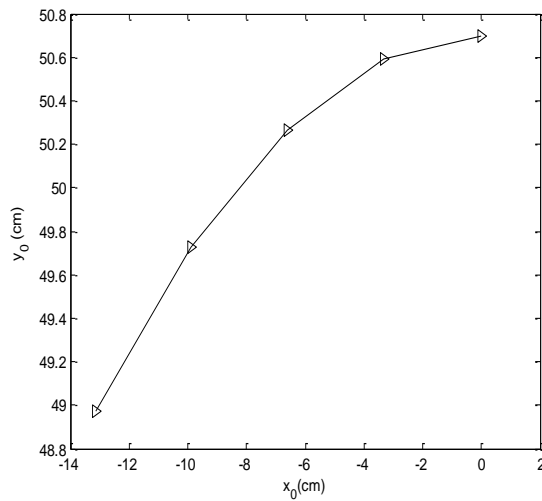


Figure 4. Knee joint locus in the fixed frame during the movement

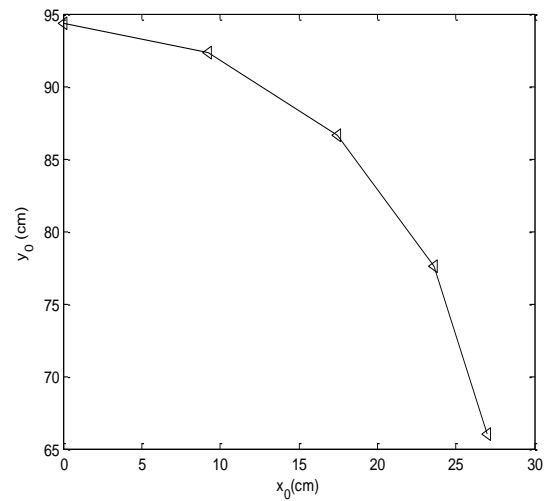


Figure 5. Hip joint locus in the fixed frame during the movement

Figure 4, Figure 5 and Figure 6 show the paths/loci of the knee, hip and neck joints respectively, with reference to the fixed frame during the sit-to-stand movements from the initial to the final positions. Figure 7 shows that of the head during the transition, it indicates how the height changes during movement. All the paths were given with reference to the reference or zero frame. It can be clearly seen that the desired paths were obtained which means the concept can be continued and the next stage would be determining the dynamic model. The model can be used for control system design as well as stability analysis.

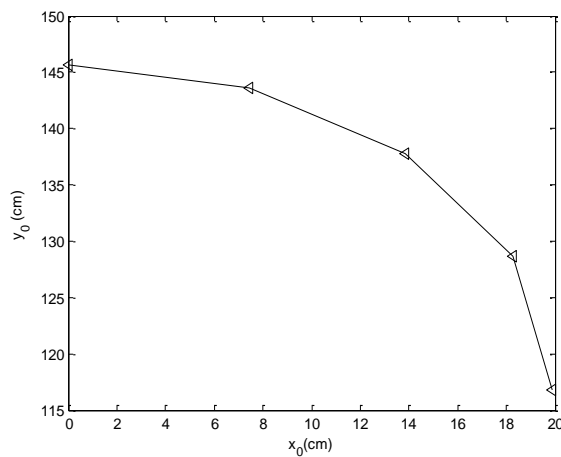


Figure 6. Neck joint locus in the fixed frame during the movement

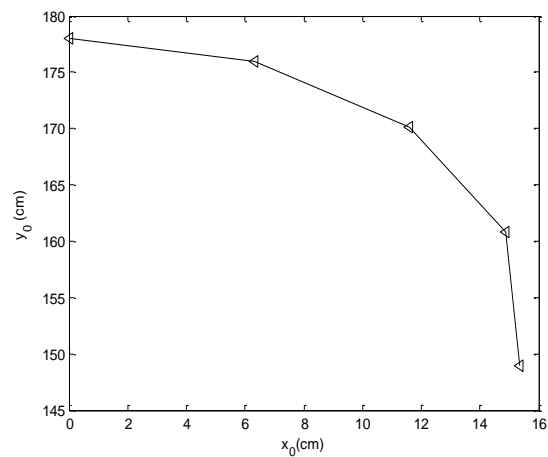


Figure 7. Head locus in the fixed frame during the movement

#### 4. CONCLUSION

Kinematic model is the first step towards developing the dynamic model. Besides constituting the initial building block for the desired dynamic model, the kinematic model also serves to facilitate the study of various kinematic feasibilities. The dynamic modelling which is usually more tasking can then be developed and it aids as well in obtaining a configuration with minimal complexity.

The study showed that the 6 DOF closed chain FES aided sit-to-stand maneuver idea could be implemented conveniently using 4 DOF. Although both branches can be used to achieve the desired movement goal but branch 2 is easier for analysis. It is because it has its first two links fixed from the reference, but branch 1 was more relevant because it has the joint to be stimulated which is the basis of the research. Reason of this assertion was as shown that no additional constrain is needed as depicted after applying Equation (9) [27], [36] and the loci in Figure 4, Figure 5, Figure 6 and Figure 7 give the intended paths for the movement. It can be seen that the final points in Figure 6 correspond to the subject height. The 4 DOF has additional single joint compared to earlier works such as that of Fattah et al. [30] and Tsukahara et al. [31] models which makes it more accurate and flexible; accurate in the sense that it accommodates addition joint i.e. the neck joint and also more flexible in the sense that if future research uncover more contributions by the segments it can be easily incorporated most especially that of the truck, neck and upper limbs.

The work is novel in the sense that it is an improvement over the existing models. And additionally others are; making it a more gray model (by adding more experimental findings) and adding an outcome indicating that about 10% of the weight is supported by the upper limbs in paraplegics [37]. It would be incorporated in the dynamic modelling prior to other studies i. e. controller design and stability analysis.

#### ACKNOWLEDGEMENTS

“This paper was partly sponsored by the Centre of Graduate Studies UTHM, Office for Research, Innovation, Commercialization and Consultancy Management, UTHM and ATBU”.

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