FES-Aid Walking For Paraplegic Patient By Using Musculoskeletal Modeling Software And Matlab

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Abstract— **This paper shows how the simulation of FES-aid walking for paraplegic patient is possible using MSMS (Musculoskeletal Modelling Software) and MATHLAB®. Concept, significance and factors of FES-aid walking have been detailed. It presents how the complexity of biomechanics related to walking in paraplegic patient can be implemented with MSMS and MATLAB/SIMULINK®. It can also be used for further development of a prototype of the FES system for walking for paraplegic patients having lower extremity disorders. The proposed model of lower limb includes 12 leg virtual muscles which shows its accuracy due to consideration of the coordinating position, Mass, Inertia used for rigid body segment, and Joint Type, Rotational Axes used for lower limb joints for walking event. The result of FES-aid walking generated by MSMS and MATLAB® for proposed modelling has been presented. Merits and demerits of proposed walking have also been discussed.**

Keywords— **Biomechanics, FES, Gait cycle, virtual muscles.**

I. INTRODUCTION

Disability is challenging especially for those who have been energized before spinal cord injury and are currently disabled. Spinal cord injury (SCI) can produce total or partial paralysis. The person who has one of these conditions may be not capable to move parts of his or her body. Paraplegia is usually the result of Spinal Cord Injury. The area of the spinal cord which is affected in paraplegia is either the thoracic, lumbar, or sacral regions. Paraplegia describes complete or incomplete paralysis affecting the legs but not the arms. A paraplegic is a person whose lower extremities are affected and has usually no control in his lower extremities. FES is a hopeful way to restore mobility to SCI by sending electrical signals to restore the function of paralyzed muscles. In this technique, low-level electrical current is applied to an individual with an SCI disability so as to enhance that person's ability to function and live independently. It is important to understand that FES is not a cure for SCI, but it is an assistive device.

Beginning of a walking event by one limb and continuing until the event is repeated again with the same limb is called gait cycle. The single gait cycle is divided into two phases called Stance phase (~ 60%) and swing phase (~ 40%). In stance phase, given limb is in contact with the ground. A stance phase of gait is divided into four periods called: Initial contact, loading response, mid stance, terminal stance. In swing phase, given limb is in the air. A Swing phase is divided into four periods called: pre swing, initial swing, mid swing, and terminal swing.

A model is a representation of a physical system that may be used to predict the behavior of the system in some desired respect. Models of the lower extremity musculoskeletal system [1, 2] have made achievable a wide range of biomechanical investigation especially for paraplegic patients with lower extremity disorders after spinal cord injury (SCI) or multiple sclerosis (MS). For example, Models of the musculoskeletal system facilitate individual to study neuroprosthersis, evaluate athletic performance, and to study muscular coordination of walking, jumping, sitting [3], standing [4] and cycling [5]. Here, modelling of the human lower limb is prepared in MSMS and FES-aid walking is achieved in MATLAB/SIMULINK®.

II. METHODS FOR LOWER LIMB MUSCULOSKELETAL MODELLING IN MSMS

MSMS (Musculoskeletal Modeling Software) [6] is open-source software that allows users to develop, analyze, and visualize models of the musculoskeletal system, and to create dynamic simulations of movement. MSMS is used to build a standard model of a lower limb musculoskeletal modelling. Skeletal geometry integrates rigid models of the pelvis, femur, tibia, fibula, patella, talus, calcaneus, metatarsals, and phalanges that were shaped by digitizing a set of bones from a male adult subject with an approximate height of 1.8 m and an approximate mass of 75 kg. The model consists of 7 rigid body segments and includes the lines of action of 12 virtual muscles. For slanting the coordinate systems of each bone segment so that in the anatomical position the X-axis points anteriorly, the Y-axis points superiorly, and the Z-axis points to the right. Figure 1 (A) illustrates proposed leg model in MSMS window. Left side of the window shows rigid segments, joints and 12 virtual muscles used in the model and right side of the window shows the complete right leg model.

In this model rigid body segments are used and coordinated that can be explored under "segments" block in "model explorer" (Figure 1 (A)). To model this rigid body segment we have considered pelvis as a ground segment. Subsequently we have constructed femur under pelvis by taking into consideration pelvis as a parent segment. Similarly by putting together a new rigid body segment (namely tibia, patella, and

foot) as a child segment just before its respective parent segment.
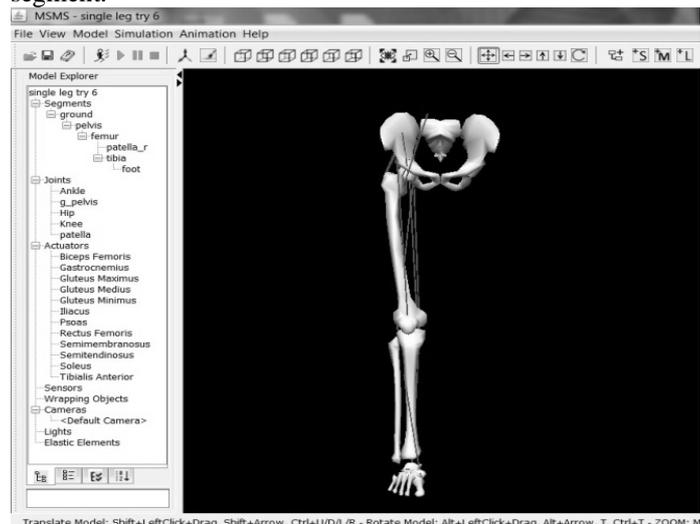

Figure 1 (A): Proposed right leg model in MSMS with rigid body segments, joints and 12 virtual muscles.

In addition to this proposed leg model has three joints with respect to ground pelvis. This can be explored below the "joint" block in the "model explorer" (Figure 1 (A)). Proposed leg model contains the same joint type as the natural leg, e.g. hip joint in this model has a ball and socket joint with three degrees of freedom such as flexion/extension, adduction/abduction, and internal/external rotation which is same as the natural leg.

Proposed right leg model contains 12 leg virtual muscles [7] which will help to achieve an equivalent response to a natural leg response in FES- aid walking. It can be explored below the "Actuators" block in the "model explorer". However, our ultimate goal is to achieve FES-aid walking by using 12 lower limb muscles. A table (A) shows gait cycle interval and 12 lower limb muscle activity during walking with respect to its joint. Joints DOF are limited in a proposed model as per table (B) to achieve nearly normally looking walk.

Table (A): Important Active Muscles During Gait Cycle		
Gait Cycle Interval	**Joint**	**Important Active Muscles**
Mid stance To Toe Off	Knee	Gastrocnemius.
	Ankle	Soleus.
Toe Off To Acceleration	Hip	Iliacus, Psoas.
	Knee	Gastrocnemius.
Acceleration To Heel Strike	Hip	Gluteus Maximus, Gluteus Medius, Gluteus Minimus, Semitendinosus, Semimembranosus, Biceps Femoris.
	Knee	Rectus Femoris.
Heel Strike To Mid stance	Hip	Gluteus Medius, Gluteus Minimus.
	Knee	Rectus Femoris.
	Ankle	Gastrocnemius, Soleus, Tibialis Anterior.

Table (B): Proposed Lower Limb Model's Joints DOF	
Joint Names	**DOF**
Hip	-9° to 9°
Knee	-15° to 0°
Ankle	-4° to 4°

III. FES-Aid Walking In MSMS And MATLAB/SIMULINK®

One of the major advantages of MSMS is that, it can generate a simulink model (.mdl) by using command "Save Simulation". This Simulink model represents the algorithms that can simulate the movement of the MSMS model in response to control excitations and external forces, This Simulink model can be opened and run in Matlab's Simulink environment which helps for further Biomechanics investigation. Here Figure 1 (B) shows a simulation model with pulse generator of a proposed leg model of MSMS. This Simulink model can be used in generating and simulating the complete lower extremity model having external electrical stimulus such as the one used in neuroprosthesis models. Figure 1 (C) shows the pulse sequence for each 12 muscles to achieve gait as per shown in table (A).
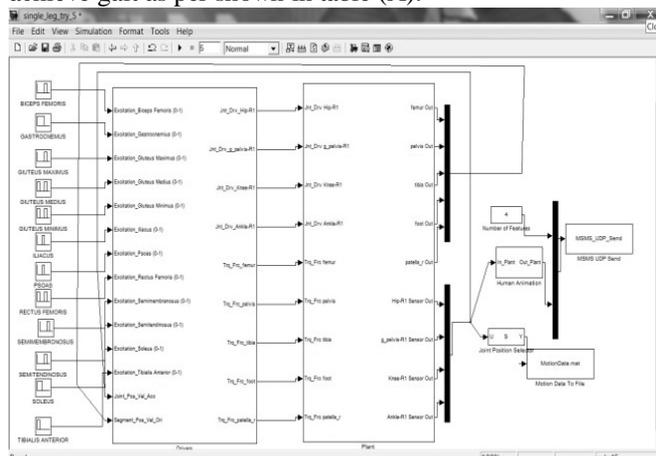

Figure 1 (B): Simulink model of proposed leg model in MATLAB/SIMULINK® with electrical stimulus.

IV. Results And Conclusion

In this study, we formed a human lower limb model having 12 muscles to achieve FES-aid walking in MSMS and MATLAB/SIMULINK®. Figure 1 (D) shows the results of Gait cycle achieved in MSMS while applying electrical stimulus in MATLAB®.

Results achieved in MSMS are covering all gait cycle phases and resembles normal walking. The proposed system has some limitations such as it produces jerk at the start of simulation which can be limited by adding more number of muscles in proposed leg model. However, our FES-aid waking is currently open loop but in future we can make it closed loop with by validating it with experimental data.
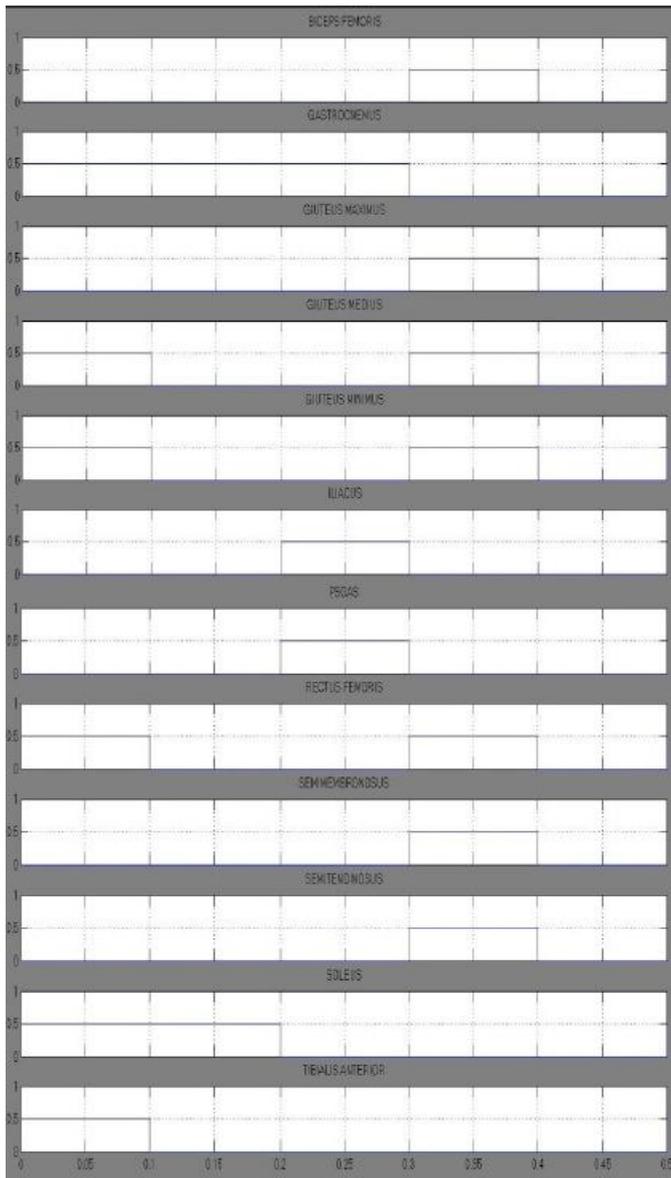
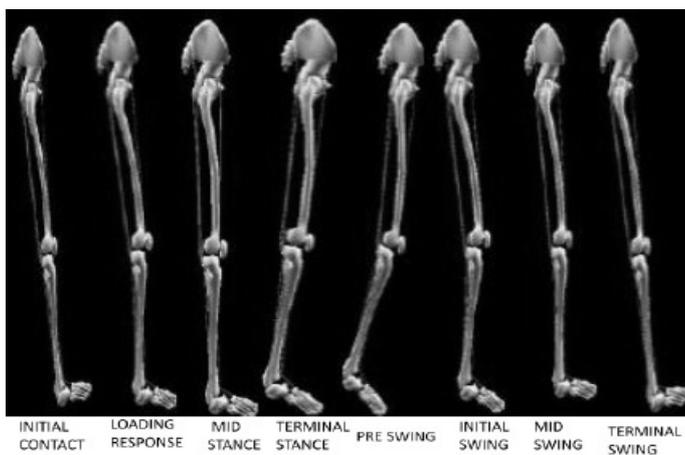Figure 1 (C): Pulse sequence given in MATLAB® for each 12 muscles to achieve gait as per shown in table (A).

Figure 1 (D): Achieved FES-aid walking in MSMS and MATLAB/SIMULINK®.

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