Musculoskeletal Modeling as a Tool for Biomechanical Analysis of Normal and Pathological Gait

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1 Introduction

Musculoskeletal Models have been used successfully in many applications such as injuries analysis, surgeries evaluation, and Biomechanical analysis to determine Forces and Torques.

The main importance of the musculoskeletal model is that allows us to predict muscle-tendon activity without having to use patients which would imply using invasive Electromyography Sensors (EMG), because non-invasive EMG has a low sensitivity to discriminate between voluntary motor activity and deep muscleactivity involved during limb movement. However, invasive EMG is not feasible due ethic conflict with the international guidelines of biomedical investigation with human beings [1]. On the other hand, the model allows to include electronics sensors such as: Inertial Measurement Units (IMU), force sensors or encoders,or using signals from third-party software.

The aim of this paper is to present a human lower limb modeling and simulation of multiple sclerosis disease. Furthermore, the model allows us not only to perform a biomechanical analysis for both normal and pathological gait but also kinematics and dynamics analysis for dimensioning and selection of actuators in order to develop rehabilitation mechanisms. Thus, the model will allow us to study differences in muscle synergies of a pathology and compare them with a normal gait which is crucial for the optimized mechanical design of powered lower limb robotic exoskeletons.

2 Material and Methods

The model presented in this work was created based on the anatomical dataset reported by Arnold et al. [2] and Ward et al. [3], and have been implemented using Musculoskeletal Modeling Software (MSMS). MSMS has the advantage that the model can be exported directly to Simulink allowing us to generate Functional Electrical Stimulation (FES) signals for muscle-driven and send these signals to MSMS via UDP. On the other hand, the model allows to include electronics sensors such as Inertial Measurement Units (IMU), force sensors or encoders, using signals from motion analysis systems such as Cartesian Optoelectronic Dynamic Anthropometer (CODA) or other third-party software

Musculoskeletal Model

The model is composed of 44 muscle-tendon actuators per leg, each actuator was modeled as a 3-element Hill-Type muscle-tendon unit [4]. For muscle-tendon with complex geometry (Adductor magnus, gastrocnemius, gluteus maximus, gluteus medius, gluteus minimus) the whole muscle was divided into multiple segments and the constraint of the muscle-tendon path was modeled by moving points and wrapping objects.

The model has 6 joints (hip, knee, ankle, subtalar, metatarsophalangeal, patellofemoral) allowing 10 degrees of freedom (DoF) per leg. The hip joint was modeled as a spherical joint allowing 3 DoF. The knee, ankle, metatarsopha-langeal and subtalar were modeled as a revolute Joints, allowing one degree of freedom per Joint. The Range of Motion (ROM) were taken from Kapandji [5] and Arnold et al. [2]. The cadavers from which muscle-tendon architecture parameters were measured [3] had an average weight of 82.7±15.2 kg and height of 168.4±9.3 cm,the complete model is depicted in Fig. 1.

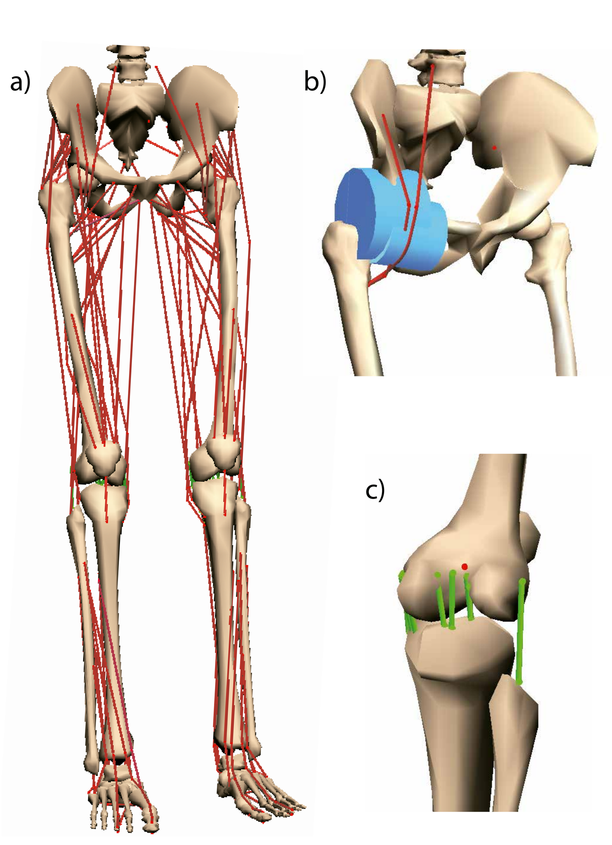

Fig. 1. Musculoskeletal model of the lower limb. a) Full model with the 44 Hill-type muscle tendon units, b) Example of 2 wrapping objects to constraint the muscle-tendon path, c) Ligaments of the right knee.

Simulink - MSMS Integration

One of the unique features of MSMS is the ability to export the model directly to Simulink. This represents a huge advantage because it allows: set activation signals (muscle-driven simulation), measure angles, speeds, accelerations, torques and forces in the joints, integrate sensors, as well as apply control strategies and integrate all the well-know MATLAB's toolboxes

Once the model was exported to Simulink, the muscle-tendon was excited by applying activation signals to them. The signals correspond to a 0 to 1 pulse train with a pulse width of 50%. An active delay between each signal is set in order to shift agonist-antagonist muscles interactions. The amplitude of the signals corresponds with the percentage of muscle activation (0% to 100%). That is, 100% for a healthy subject.

Fig. 2 shows the Simulink and MSMS Integration. The MSMS integration allow us to see the motion evolution in the avatar while the simulation is being performed. The communication between Simulink and MSMS is established viaUDP.

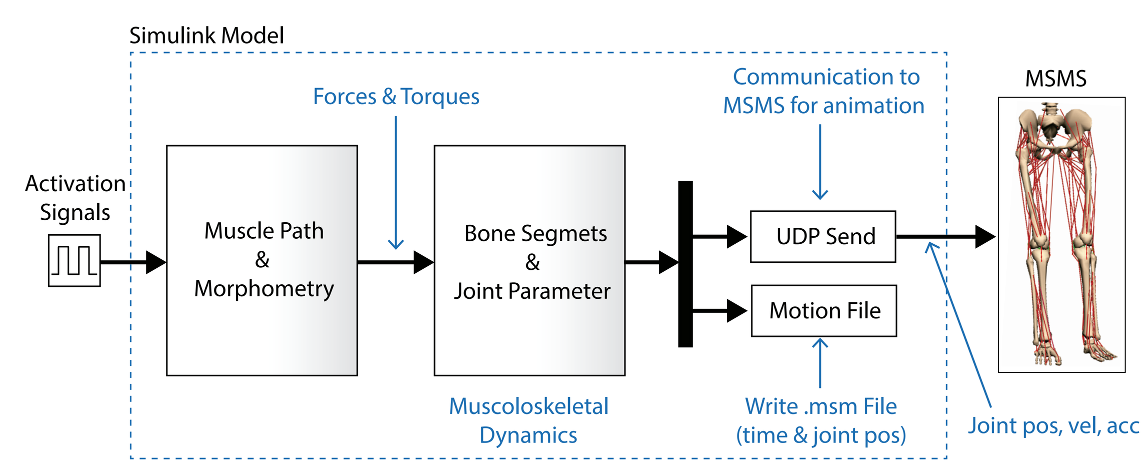

Fig. 2. Simulink block model & MSMS integration.

3 Results

In order to validate the model presented, several tests were performed, the muscle-tendon segments were activated simulating the functional electrical stimulation (FES). Then, the results obtained were compared with both results presented in the literature and experimental data.

Validation by Comparing with Previously Published works

The validation of the model was tested by comparing the obtained results (model predicted) to previously published works. Fig. 3 and 4 shows knee-flexion moment arms (obtained directly from MSMS) of muscles crossing the knee and compare the results predicted by Arnold et al. [2] model, and those obtained from experimental measurements by Buford et al. [6] and Spoor and van Leeuwen [7] with our model.

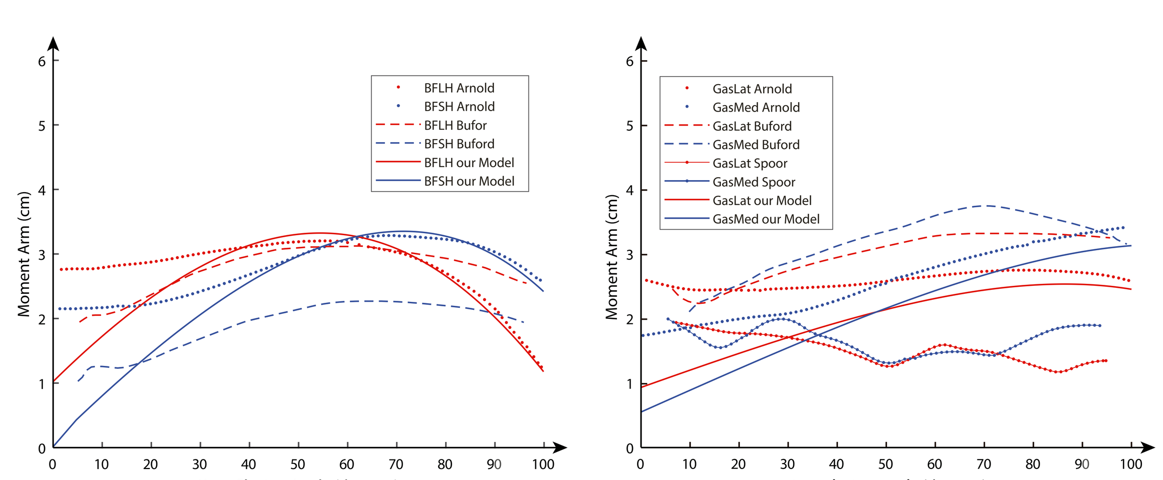

Fig. 3. Bicep Femoris and Gastronecmius moment arm.

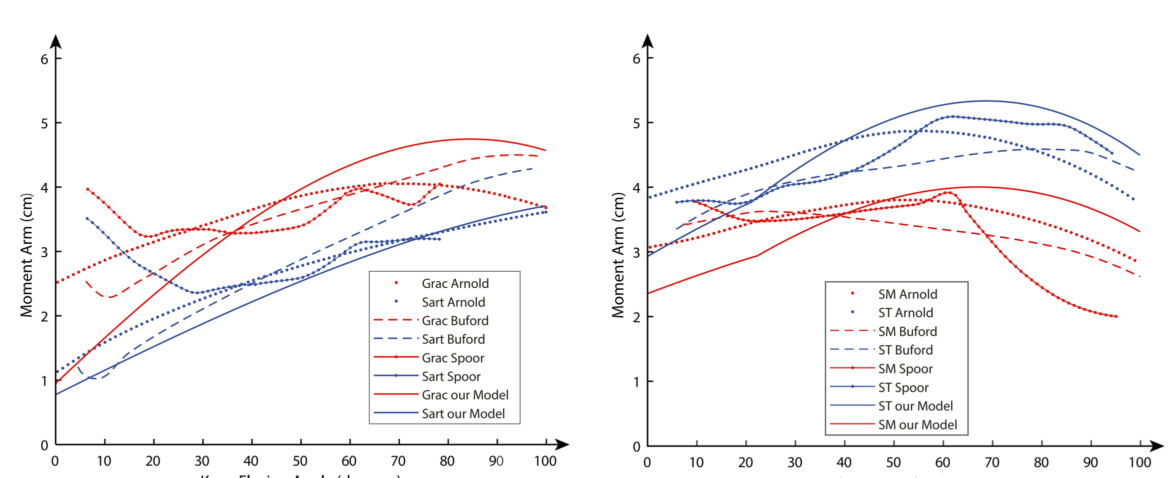

Fig. 4. Gracilis, semimembrasus and semitenidosus moment arm.

Validation by Comparing with Real Data

The model was also tested over a gait cycle for both normal and pathological gait. For normal gait, the functional electrical stimulation (FES) signals applied to the muscles of the model (Simulink) over the gait cycle were selected according to medical literature.

The normal gait was also registered by our own wireless gait capture system (Fig. 5) that consist of three wireless 9-axis inertial measurement unit (IMU) modules, each module consists of a high precision 3-axis gyroscope, 3-axis accelerometer, 3-axis geomagnetic sensor, and a 32 bits high performance MCU. Furthermore, the normal gait was registered using the Cartesian Optoelectronic Dynamic Anthropometer (CODA) professional software at Physiotherapy School ONCE in Madrid.

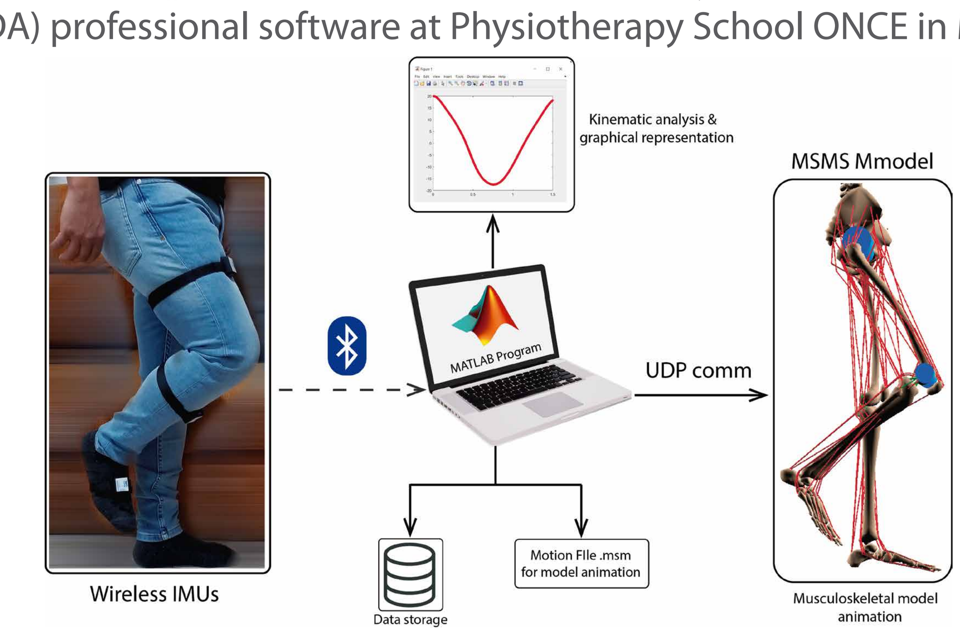

Fig. 5. Our own Wireless gait caption system

For pathological gait, the muscle level activation profile for each muscle-tendon unit used in our model was selected according to the literature and those muscle-tendon activation reported by Lencioni et al. [8], and correspond to persons with Multiple Sclerosis (PwMS). Furthermore, the gait cycle for a PwMS was obtained using CODA software at Physiotherapy School ONCE in Madrid.

The results for the hip flexion/extension (HFE), knee flexion/extension (KFE), and ankle flexion/extension (AFE) for a healthy are shown in Fig. 6. whereas Fig. 7 shows the results for persons with Mutiple Sclerosis. The gray area corresponds to values obtained by CODA software for fifteen subjects.

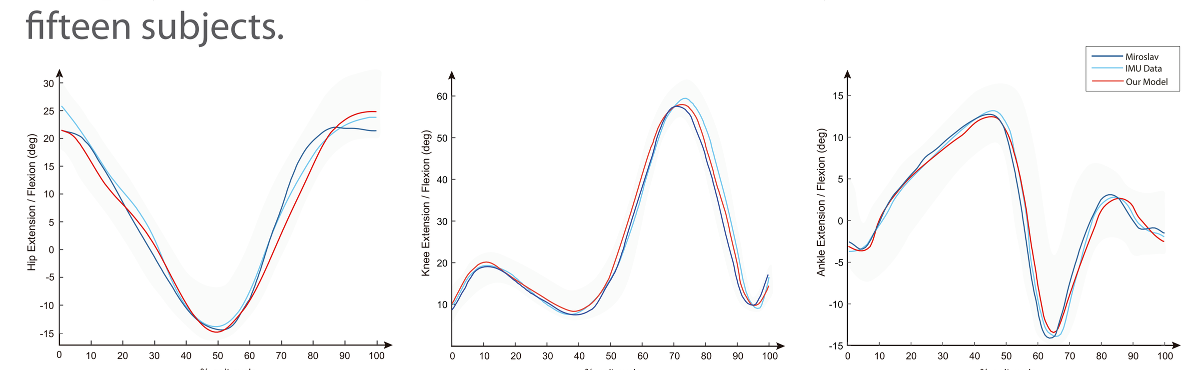

Fig. 6. Hip flexion/extension (HFE), knee flexion/extension (KFE) and ankle flexion/extension (AFE) angular position (degrees) during a normal gait cycle.

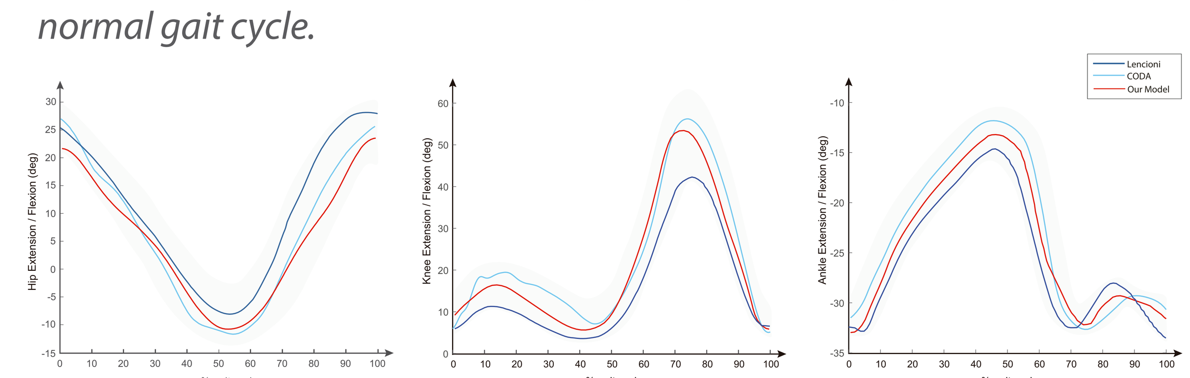

Fig. 7. Hip flexion/extension (HFE), knee flexion/extension (KFE) and ankle flexion/extension (AFE) angular position (degrees) for persons with multiple sclerosis.

The goodness-of-fit of our model was assessed using the root mean square error (RMSE) and the normalized mean square error (NMSE); the values of these indices suggest that the model estimated the kinematics and kinetics parameters of healthy and pathological gait successfully, Table I summarize the errors obtained by our model for both estimation, normal and pathological gait.

Table I. Root mean square error (RMSE) and normalized mean square error (NMSE) obtained by our model.

		Hip flex/etx		Knee flext/ext		Ankle flex/ext	
		RMSE (deg)	NMSE (%)	RMSE (deg)	NMSE (%)	RMSE (deg)	NMSE (%)
Healtht Subject	Miroslav	1.881	1.996	3.969	1.518	1.580	4.684
	Our Mode	2.222	2.743	2.793	0.752	0.961	1.736
PwMS	Lencioni	4.831	13.178	8.50	9.224	3.774	2.455
	Our Mode	2.542	3.650	3.685	1.733	1.828	0.576

4 Conclusions

According to the results for the gait cycle analysis, we can observe that the curves obtained by our model follow the reference data closely, better than previously published works, suggesting a satisfactory estimation, As we can see in Fig. 6 and Fig. 7, the model predicts successfully for both normal and pathological subjects. For instance, in the case of the hip flexion/extension the Normalized Mean Square Error (NMSE) was 2.74% for HS and 3.65% for PwMS, whereas for knee exion/extension the NMSE was 0.752% for HS and 1.73% for PwMS. Thus, the values obtained shown the goodness-of-fit of the model presented.

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