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BIPEDAL HUMAN-EXOSKELETON MODEL FOR SIMULATIONS OF SQUAT-TO-STAND MOVEMENT

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Abstract. *Exoskeleton-type robots have been increasingly used in the fields of medicine, industry, military and domestic, in order to promote rehabilitation, assistance and human empowerment. However, movements considered simple by a human being can be very complex for a robot to perform, so it is important to study the human-exoskeleton interaction for the most diverse possible movements. One of these movements is the squat-to-stand, which can be performed many times during the day to perform tasks, lifting weights and loads, getting out of bed when waking up or from a chair after a meal. One way to study the human-exoskeleton interaction is through the use of computational simulations, with interaction models that can represent the human neuromusculoskeletal system interacting with actuators representing those of an exoskeleton. Thus, the objective of this work was to propose a model of human-exoskeleton interaction, bipedal, with foot-ground interaction through contact forces, focused on simulations of squat-to-stand movements, useful for understanding the robot's interaction with the user in this type of movement, allowing to understand how occurs the muscle recruitment, the application of torque by the robot and the movement of the joints, during the entire displacement of the user between the two poses (squat and stand). Predictive simulations were performed and the results obtained were the movement performed, the torque applied by the exoskeleton and muscle activations. Such results allowed inferring that the model is feasible, useful for squat-to-stand simulations and capable of allowing the understanding of human-robot interaction for this type of movement.*

Keywords: *Biomechanical simulation, predictive simulation, optimal control problem, neuromusculoskeletal model*

1. INTRODUCTION

Exoskeleton-type robots have been increasingly used, whether in the health field (Walsh, 2018), in the industrial (Bogue, 2018) and military areas for human empowerment (Dembia *et al.*, 2017) or even in domestic use to assist elderly or people with reduced mobility (Grimmer *et al.*, 2019). Thus, it is extremely important to study the human-robot interaction in order to ensure that such devices are developed and controlled effectively, fulfilling the purpose for which they were created, without compromising the physical integrity of the user.

One way to study the human-exoskeleton interaction is through the use of computational simulations, with interaction models that can represent the human neuromusculoskeletal system interacting with actuators representing those of an exoskeleton. Such simulations allow the study and understanding of human-robot interaction, allowing a comprehension of the possible influence of the exoskeleton on the user, in addition to providing bases for the design and development of both the robot and its controls. Another advantage of using computer simulations is the flexibility, which allows several conditions to be simulated, and the agility in their preparation and execution, which tend to consume less time and resources than physical tests with robots and humans, in addition to not putting them in danger.

Several works have used computational simulations to study the human-exoskeleton interaction in order to analyzing the assistance of an exosuit for human walking (Firouzi *et al.*, 2021), find torque profiles that ideal devices must to apply to assist an user during walking with heavy loads in order to reduce metabolic cost (Dembia *et al.*, 2017), develop human-centered adaptive controls applied to rehabilitation robot (Shi *et al.*, 2021), obtain the hip and knee moments related to gait (Zhang *et al.*, 2021) and develop robot control based on kinetic motor primitives (Nunes *et al.*, 2020). This type of approach is of great importance, since movements considered simple by human beings can be much more complex for a robot. One of these movements is the squat-to-stand, which can be performed many times during the day to perform tasks, lifting weights and loads, getting out of bed when waking up or from a chair after a meal. In this way, it is necessary to understand the interaction and effects of the robot on the user, since this movement involves strength, balance and stability, and if performed even minimally wrong, it can lead the user to fall or to get hurt damage due to poor weight distribution.

Dembia *et al.* (2020) proposed a model for squat-to-stand simulations performed with OpenSim Moco, an easy-to-use freely available software that allows to perform predictive simulations by solving optimal controls problem applied to neuromusculoskeletal models. Although the simulation was successfully performed, showing satisfactory results, the proposed model is limited: it has only one leg, not two, it has a passive actuator only on the knee, which does not represent well the active actuators of an exoskeleton and the connection between the foot and the ground is through a welded joint, which does not represent well the foot-ground interaction of a human being.

An evaluation of the human and lower-limb exoskeleton interaction during sit-to-stand was carried out by Bottin-Noonan and Sreenivasa (2021), through computational simulation using MATLAB. However the researcher just evaluated the human and robot torques produced, not taking account the muscle activations.

Laschowski *et al.* (2021) analyzed the human-exoskeleton interaction considering the lower-limb joint mechanical power during stand-to-sit movements using inverse dynamic simulations. The objective of the research was to estimate the biomechanical energy available for electrical regeneration. Here, once again, the simulations proved to be effective in treating the problem addressed, however, as in de Bottin-Noonan and Sreenivasa (2021) work, the muscle activations were not analyzed, considering only the magnitudes of torque and energy involved.

Thus, the objective of this work was to propose a model of human-exoskeleton interaction, bipedal, with foot-ground interaction through contact forces, focused on simulations of squat-to-stand movements, useful for understanding the robot's interaction with the user in this type of movement, allowing to understand how occurs the muscle recruitment, the application of torque by the robot and the movement of the joints, during the entire displacement of the user between the two poses (squat and stand). Understanding the human-exoskeleton interaction for such movement will allow engineers to have more resources for developing controls applied to exoskeletons.

2. METHODOLOGY

The human-exoskeleton model developed in this work consists of a neuromusculoskeletal model of the human lower-limbs in whose hip, knee and ankle were attached coordinate actuators in order to represent the ones of the exoskeleton. Contact forces were also established between the feet and ground, in order to represents the human-ground interaction. Simulations with the model were carried out, in order to evaluate if it is consistent and able to represent a human performing squat-to-stand movements assisted by exoskeleton. More details about the model, the simulations and the analysis of the results are presented below.

2.1 Bipedal Human-exoskeleton Model

The neuromusculoskeletal model used in this work is the *gait10dof18musc* provided by OpenSim[1] (a freely available and open source environment for modeling, simulation and analysis of human movement developed by Delp *et al.* (2007)). Such a model is composed by trunk, pelvis and leg segments and has 10 degrees of freedom actuated by 18 muscles (9 in each leg), being allowed to perform movements only in the sagittal plane. In the standard version, it represents a human with mass of 75.16 kg and height of 1.8 m. A description of the primary functions of the muscles in the joints of the model is presented below:

- **Gluteus Maximus (GM):** Extension of the hip;
- **Iliopsoas (IP):** Flexion of the hip;
- **Hamstrings (HS):** Extension of the hip and flexion of the knee;
- **Rectus Femoris (RF):** Flexion of the hip and extension of the knee;
- **Vastus Intermedius (VI):** Extension of the knee;
- **Biceps Femoris Short Head (BFSH):** Flexion of the knee;
- **Gastrocnemius (GT):** Flexion of the knee and foot plantar flexion;
- **Soleus (SL):** Foot plantar flexion;
- **Tibialis Anterior (TA):** Foot dorsiflexion;

As mentioned above, to simulate the exoskeleton we attached to the hip, knee and ankle joints of the neuromusculoskeletal **coordinate actuators**. This is a type of virtual actuator from the OpenSim library that applies a generalized force (or torque) to the joint where it is attached. In this work we used this type of actuator inspired in the ExoTAO, introduced by dos Santos *et al.* (2017) (Fig. 1b), which is a modular lower-limbs exoskeleton able to assist a human to perform movements on the sagittal plane. The equation that describes the dynamic of the coordinate actuator used is:

$$\tau = u \cdot \tau_{optm} \tag{1}$$

[1] https://opensim.stanford.edu/

Where τ is the torque applied by the actuator, u is the input signal (that can be generated by some control) and τ_{optm} is the maximum torque that the actuator can apply. Some simplifications were considered: the actuators are massless, with no response delay or losses, the axes of the robot and user joints are collinear and the torque is applied directly to the human joint in question.

The foot-ground interaction was ensured by using contact geometries and forces of the type Hunt-Crossley Forces (Seth *et al.*, 2011; Hunt and Crossley, 1975; Hertz, 1882). The parameters of the contact forces are: stiffness factor 1000 kN/m, dissipation factor 1, static friction factor 800.10^3, dynamic friction coefficient 400.10^3, viscous friction coefficient 400.10^3 N.s/m.

The Fig. 1a depicts the bipedal human-exoskeleton interaction model proposed in this work.

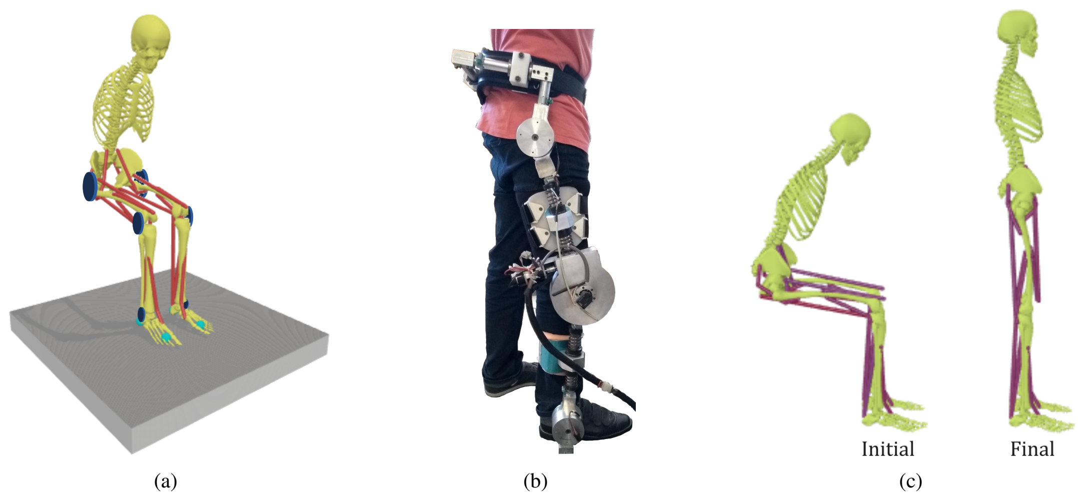


Figure 1. (a)Human-exoskeleton interaction model (the red lines are the muscles, the blue discs are the coordinate actuators and the green balls in the foot are the foot-ground contact surfaces), (b) the exoskeleton ExoTAO, (c) the initial and final poses of the squat-to-stand movement simulated

2.2 Predictive Simulations

Computational simulations were carried out with the proposed model performing a squat-to-stand movement, beginning in an initial squat pose and moving until a final stand position in a time of 2 seconds (Fig. 1). The hip, knee and ankle starting angles were 80, -80 and 0 degrees, respectively while the final angles were 0 degrees for all the joints. So it is expected an extension both for the hip and the knee and no movement to the ankle.

No predefined reference trajectory between the initial and final poses was tracked, so the simulation performed is called *predictive simulation*, in which the model executes the movement not following a trajectory, but rather trying to minimize a certain functional cost.

In this work, the predictive simulation was based on the solution of an optimal control problem (OCP), through which we tried to determine the states and controls to move the model from the initial pose to the final one, within the determined time, seeking to minimize the muscular activations and the torque applied by the robot. This approach is based on the fact that the movement performed must be the one that promotes the lowest metabolic cost on the part of the human and the lowest energy consumption on the part of the robot, in order to avoid human fatigue and guarantee greater robot autonomy (mainly for the case in which the robot it is powered by batteries). To minimize both the muscle activations and torque actuator, the OCP was formulated with the cost function expressed by Equation (2) , where T is the period (2.0 s), a_i is the activation of the ith muscle, m is the number of muscles (that is, $m = 18$), τ_j is the torque of the jth actuator, n is the number of actuators (that is, $n = 6$)

$$J = \frac{1}{T}\left[\sum_{i=1}^{m}\int_{t_0}^{t_f} a_i^2(t)dt + \sum_{j=1}^{n}\int_{t_0}^{t_f} \tau_j^2(t)dt\right] \tag{2}$$

In order to ensure solutions from the simulation that are physically possible, the optimal control problem was complemented by constraints related to related to the dynamics of the neuromusculoskeletal model (Equation (3)), path constraints on the states (Equation (4)), muscles activations (Equation (5)) and robot actuator torques (Equation (6)) and boundary constraints on the time (Equations (7)) and initial and final states (equations (8) - (9), respectively). The symbols in bold represent vectors.

$$\dot{x}(t) = f(\boldsymbol{x}(t), \boldsymbol{u}(t), t) \quad (3)$$

$$\boldsymbol{x}_{min} \leq \boldsymbol{x}(t) \leq \boldsymbol{x}_{max} \quad (4)$$

$$0 \leq \boldsymbol{a}(t) \leq 1 \quad (5)$$

$$\boldsymbol{\tau_{max}} \leq \boldsymbol{\tau}(t) \leq \boldsymbol{\tau_{min}} \quad (6)$$

$$0 \leq t_0 \leq t_f \leq 0.75 \quad (7)$$

$$\boldsymbol{x}_{0,L} \leq \boldsymbol{x}(t_0) \leq \boldsymbol{x}_{0,U} \quad (8)$$

$$\boldsymbol{x}_{f,L} \leq \boldsymbol{x}(t_f) \leq \boldsymbol{x}_{f,U} \quad (9)$$

The optimal control problem was solved using OpenSim Moco[2] which is a software toolkit developed by Dembia *et al.* (2020) focused on solution of OCP applied to neuromusculoskeletal models. The OpenSim Moco has an embedded CasADi library (Andersson *et al.*, 2018) which is used to transcribe the continuous optimal control problem into a finite dimensional nonlinear programming (NLP) which is then solved by the open-source solver IPOPT using gradient-based methods.

2.3 Analysis Procedure

We analyzed the results by considering the trajectory, muscle activations and torque applied by the robot obtained with the simulations. It was evaluated whether the model was able to perform the movement with feasible and coherent states, whether the simulation converged and whether the human-robot interaction occurred properly with regard to levels of interaction torque and assistance in producing the movement.

The simulations were performed considering the biomechanics of a healthy subject. The simulations were performed on a computer with Intel® Core™i7-10510U 2.30 GHz processor, 20.00 GB of RAM, 2.00 GB dedicated video card, 512 GB SSD PCIe 3.0 x2 NVMe (M.2 2280) and Windows 10 Pro 64 bits. The OpenSim version 4.4, and the MATLAB R2017b were the platforms where the simulations took place. OpenSim Moco is currently available bundled with OpenSim 4.4.

3. RESULTS AND DISCUSSION

In this section, the results obtained in the simulations are presented and discussed. For the graphs, the solid and dotted lines indicate the averages of the values obtained with the simulations, the shaded region indicates the standard deviation. Five simulations were performed.

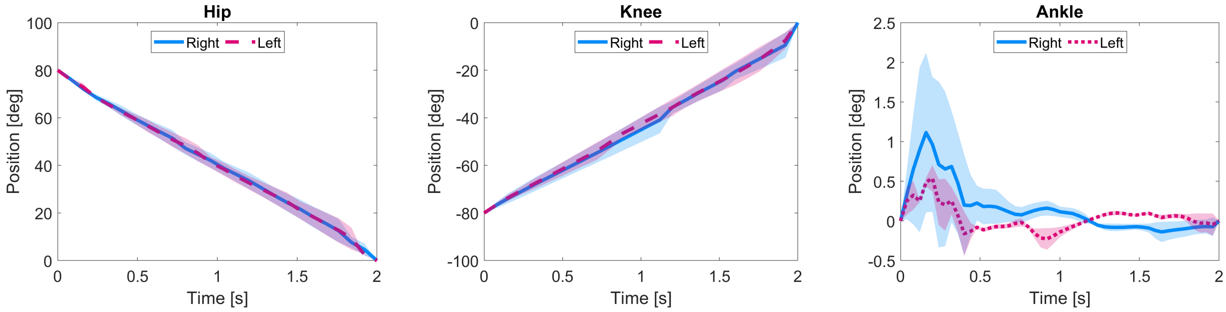
Observing Fig. 2, it is possible to verify that the movement was executed meeting the initial and final position requirements for all joints. Small movement variations can be identified for the hip and knee, however they are acceptable variations and that did not compromise the equilibrium and performance of the movement. It is also noted that for these joints the movements of the right and left sides are similar, which results from the symmetry of the model.

The ankle joint, despite meeting the initial and final position requirements, was the joint that showed the most variation. Considering that for such a joint the initial and final values of the angular position are the same, it could be expected at first that there would be no movement of the joint, however this was not what was obtained, as can be seen in the graph in Fig. 2c. This is due to the fact that the joint assists in maintaining the balance of the model during movement, preventing it from falling. It also can be seen that the right ankle had greater dorsiflexion than the left, a movement that was reflected in the right knee, which presented greater flexion on average than the left, as shown in Fig. 2b.

The torques applied by the exoskeleton actuators are shown in Fig. 3. It is possible to verify that the highest levels of torque were applied to the ankle, which is consistent, since this joint moves the greatest mass in relation to the other joints. There is also a difference between the torque applied in the left and right ankles, a fact that contributed to the difference between the movements of these joints, as observed in Fig. 2c. For the hip and knee joints, values oscillate around the zero torque line (except for the hip at instant 0.8 s, which has a greater extension torque on both sides), this means that the torques applied by the exoskeletons seek only to assist the movement and not perform it by the user.

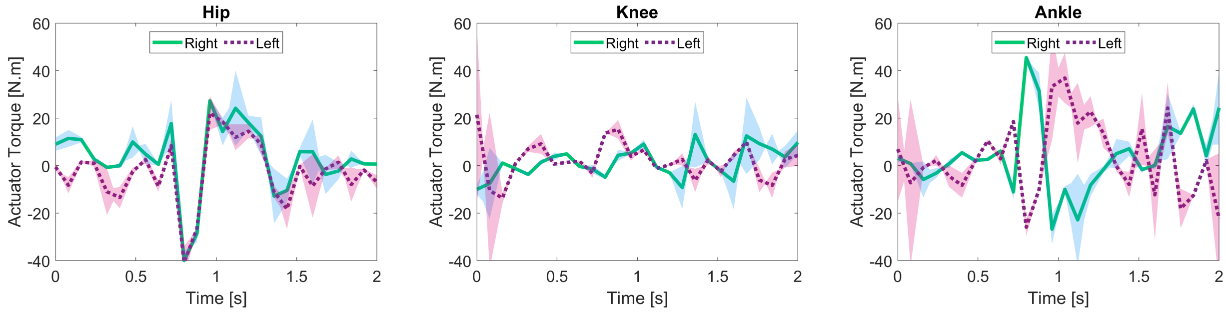
Although the applied torques showed some consistency, it is important to note that at instant 0.8 s there was a sudden variation in the torque applied to the hip, as well as at instants 0.8 and 1.0 seconds for the ankle. These sudden variations are undesirable, as they cause discomfort for the user. In addition, sudden variations in opposite directions can even lead to injury. Thus, although the torque obtained through the simulation is physically possible and contributes to the minimization of the cost function, it is necessary that improvements are made in the robot control, in order to guarantee smooth transitions as well as to avoid sudden variations in the torque applied by the exoskeleton. Therefore, new restrictions in OCP must be considered for future simulations, in order to avoid such variations.

[2]https://opensim-org.github.io/opensim-moco-site/



(a) (b) (c)

Figure 2. Angular position of the lower limbs joints



(a) (b) (c)

Figure 3. Torques applied by the actuators on the lower limbs joints

Observing the muscle activation graphs shown in Fig. 4, it is possible to verify that the activations of the muscles on the right side coincide with those of the muscles on the left side. This allows inferring that any asymmetry of movement between the sides was included by the torque applied by the robot, which confirms the fact that such control must be improved.

The gluteus maximus (Fig. 4a) muscle showed activation levels greater than 0.4 during the entire movement, that is, this muscle performed contraction. As the hip joint moved in extension, and the GM is responsible for this type of movement, it turns out that there was a concentric contraction of the muscle. At the end of the movement, the activation of this muscle did not become null, which is important, as this is necessary to maintain the final pose, however, from the moment the final pose has been reached, the joint must remain stationary and stabilized, that is, the muscle must undergo isometric contraction.

Observing the activations of the iliopsoas muscle (Fig. 4b), it can be seen that it also underwent contraction, despite being a muscle whose primary function is to promote hip flexion, a movement that was not performed. Thus, the contraction of this muscle is eccentric in order to control the movement, ensuring stability. After reaching the final pose, this muscle remains activated in order to, together with the gluteus maximus, perform an isometric contraction that ensures permanence in the pose, stability and balance, increasing the stiffness of the joint.

The hamstring muscles also started for hip extension (Fig. 4c), thus presenting greater activations than those developed by the iliopsoas and with a profile similar to that of the activations of the gluteus maximus. However, the hamstring also causes knee flexion, so the rectus femoris (Fig. 4e) and vastus intermedius (Fig. 4f) muscles had to work together, both to resolve the knee flexion caused by the hamstring and to perform joint extension. This made the variability of both hamstring and vastus intermedius activations greater. In addition, the vastus intermedius showed greater activation than the rectus femoris, since this muscle also tends to cause hip flexion. The participation of the biceps femoris (Fig. 4d) in knee extension is similar to that of the iliopsoas for the hip: stabilizing the movement and ensuring permanence in the final pose.

The gastrocnemius (Fig. 4g), soleus (Fig. 4h) and tibialis anterior (Fig. 4i) muscles worked to maintain the ankle's position, allowing it to move during the displacement between poses to guarantee the individual's balance, however satisfying the initial and final pose conditions. The tibialis anterior was more activated than the soleus and the gastrocnemius since it is the muscle responsible for dorsiflexion, which is characteristic of the 0 degree position for the ankle, imposed in the simulations performed. The gastrocnemius also causes knee flexion as a secondary task, a factor that also contributed to the vastus intermedius reaching the highest activations among all the muscles studied.

Thus, considering the results obtained through the simulations, one can to affirm that the bipedal human-exoskeleton proposed for squat-to-stand simulations is feasible and able to perform coherently the movement studied. With this

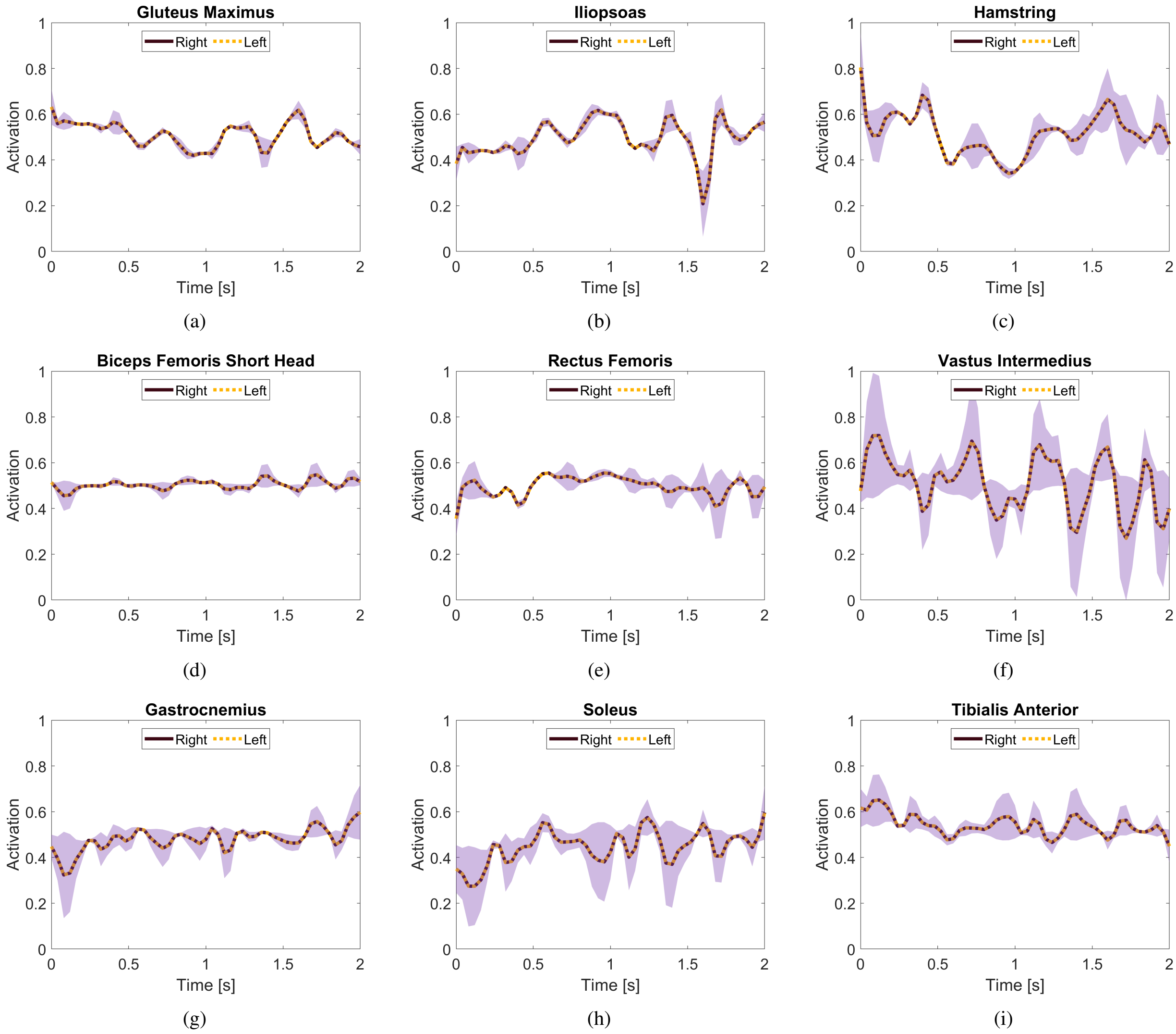


Figure 4. Muscles activations

model, was possible to understand the muscles behavior as well as the influence of the exoskeleton on the movement. The simulations allowed us to verify that the robot torques need to be improved since it presented sudden variations and inversions, a fact that, without the model and simulations, would take a reasonable amount of time to be identified and understood, in addition to causing damage to both the robot and the user in some physical test.

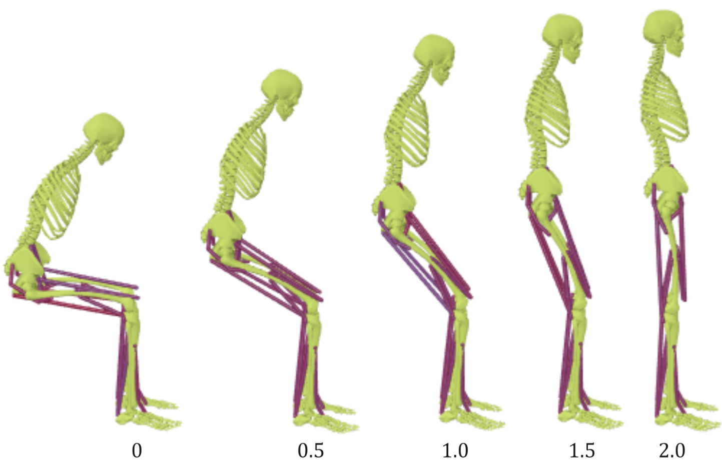


Figure 5. Illustration of the movement performed

The Fig. 5 illustrates the movement performed by the model for the times 0, 0.5, 1.0, 1.5 and 2.0 seconds. It is possible to verify that initially the trunk moves clockwise, accelerated by the hips, in order to position the center of gravity (CG) on the new support base formed by the feet fixed on the floor ($t = 0$ s). Then, there is a knee extension in order to raise the body. The hips remain flexed to ensure that the CG does not leave the support base (otherwise it would cause the subject to fall) ($t = 0.5$ s). Knee extension continues until the individual is fully standing. From a certain point onward, the hips extend again, in order to move the trunk in a counterclockwise direction, keeping the CG within the base of support ($t = 1.0$ s ~ 1.5 s). Finally the human is standing, supported solely on his feet. Now there is no more movement and the work of the muscles becomes maintaining the pose, through isometric contractions ($t = 2.0$ s).

4. CONCLUSIONS

In this work we proposed the development of a bipedal human-exoskeleton model for computational simulations of squat-to-stand type movements. The model represented the biomechanics of the lower limbs of a human being wearing an active assistive exoskeleton.

Computer simulations were conducted in order to assess whether the model is feasible and useful for what was proposed, a fact that was positively confirmed by the results obtained. In addition, the results allowed verifying that improvements must be made in the application of torque by the exoskeleton. This is an important factor, and it reaffirms the fact that the model and simulations are useful instruments for the development of more effective controls, applied to exoskeleton robots.

For future tests, it is intended to carry out simulations with the model representing a subject with hemiparesis, which is a condition resulting from neuromuscular diseases, such as stroke.

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