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Towards optimal trajectories for knee flexion-extension training

Denis Mosconi * **Melkzedekue Moreira** * **Adriano A. G. Siqueira** **

* *Mechanical Engineering Department, São Carlos School of Engineering, University of São Paulo, São Carlos, Brazil (e-mail: denis.mosconi@usp.br)*
** *Center of Engineering Applied to Healthy, São Carlos School of Engineering, University of São Paulo, São Carlos, Brazil (e-mail: siqueira@sc.usp.br)*

Abstract: The knee is a very complex joint, extremely important for the movement of the lower limbs, so the rehabilitation of its functions after trauma or stroke is essential. Flexion-extension movements are largely used in the rehabilitation exercises. In this work we used OpenSim Moco to carry out predictive simulations to study some trajectories about this type of movement, as well as determine the best one to be used in rehabilitation exercises, improving the range of motion and reducing muscular fatigue. We have successfully achieved an optimal trajectory that can be used in knee rehabilitation therapies without the need for drastic changes in exercise.

Keywords: OpenSim Moco, predictive simulation, optimal control, biomechanical simulations, knee rehabilitation.

1. INTRODUCTION

The knee is the largest and probably the most complex synovial joint of the human body, being composed by three articulations: one between the femur and patella and two between the tibial plateaus and femoral condyles. It supports most of the body weight and is essential for the lower limbs movements such as squad-to-stand, jumping and gait. Therefore, when the knee motor skills are compromised by an accident or stroke, the rehabilitation of this joint becomes extremely necessary, especially to restore the gait abilities (McGinty et al., 2000).

Without rehabilitation, the range of motion of the knee may decrease, impacting the motor functions of the entire lower extremity, affecting the ankle and hip, altering the gait pattern and limiting the movements needed for squatting, climbing stairs and sitting (Shah, 2008). There are several exercises for knee rehabilitation (Malone et al., 1980) and those involving flexion-extension movements are among the most important (Akdoğan et al., 2009). With these exercises, it is possible to regain the range of motion (ROM) as well as improve the joint function, ensuring strength, control and stability of the knee (Shelbourne et al., 2007).

The isolated knee flexion-extension movement (Fig. 1) is a rehabilitation exercise of the Open Kinetic Chain (OKC) type, as the joint is free to move on the sagittal plane without causing movement in the other joints (e.g. hip and ankle) (McGinty et al., 2000). The efficiency of this exercise is scientifically proven, so it is recommended by several rehabilitation protocols (Keeling et al., 2021; Kubota et al., 2021; Wilk et al., 2021; Noehren and Snyder-Mackler, 2020).

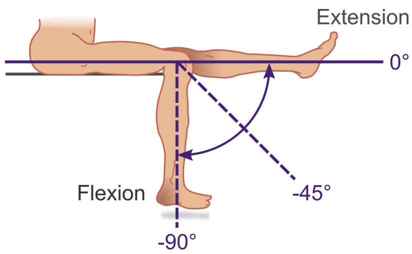

Figure 1. Knee flexion-extension movement performed by a person in a seated position

Despite being a relatively simple movement, there are several possible trajectories that can be performed between fully flexed and fully extended positions. In this work, we used predictive simulations to study some possible trajectories, as well as determine the best one for a knee flexion-extension rehabilitation exercise according to a specific anthropometry. The best trajectory considered is the one whose movement has the greatest amplitude at the lowest cost (that is determined from muscle activations), which contributes to increasing the ROM without, however, causing excessive stress on the muscles involved.

This paper is organized as follows: Section 2 presents the methodology, describing the computational models used and the simulations performed. Section 3 contains the

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results and their discussions. Finally, the Section 4 presents the conclusions achieved through this work.

2. METHODOLOGY

To study some possible flexion-extension trajectories, as well as determine the best one, we used a computational model of the human neuromusculoskeletal system together with predictive simulations. The resources used and the analyzes performed are presented in detail in the following subsections.

2.1 The Human Neuromusculoskeletal Model

To simulate the human lower limbs musculoskeletal system, an adaptation of the computational neuromusculoskeletal (NMS) model *gait2392* provided by OpenSim [1] was used (Fig. 2). Such adaptation represents a subject in a seated position and has less muscles than the original model, namely: the extensors rectus femoris (RF), vastus lateralis (VL), vastus medialis (VM) and the flexors biceps femoris (BF) and semitendinosus (SM). To define the sitting position, as well as reduce computational cost during the simulations, the hip and ankle joints of the right and left legs were locked at 90 and 0 degrees, respectively and the left knee was locked at -90 degrees, remaining free to move only the right knee joint, which was used to study the flexion and extension movement.

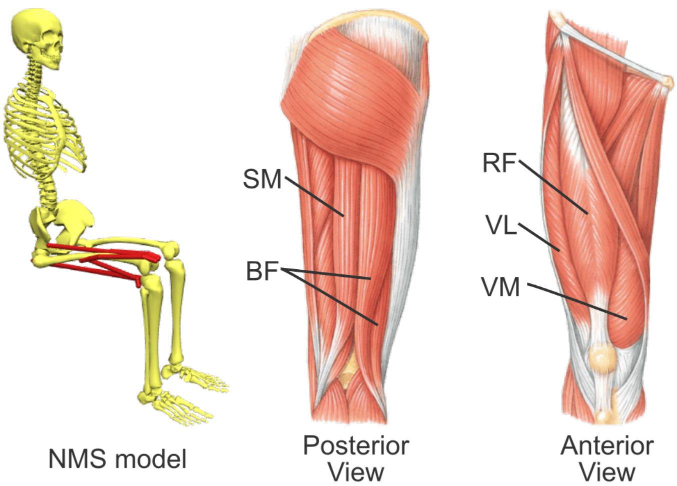

Figure 2. *gait2392*-based human neuromusculoskeletal model and the indication of the muscles considered in this work

The *Scale Tool* from OpenSim was used to fit the NMS to the anthropometry of a healthy male 29-year-old subject with 1.77 m height and 84 kg mass.

2.2 Predictive Simulations with OpenSim Moco

In the biomechanical field, predictive simulations are a type of simulation where the biomechanical model performs a movement without tracking a desired trajectory, that is usually defined from experimental data. As there is no reference to be tracked, the model performs a movement in order to minimize some specific functional cost, respecting a set of constraints. Thus, a predictive simulation basically consists of solving an optimal control problem, finding a set of optimal states and controls for the model, according to the given conditions. This approach is reasonable for the study of biomechanics, since the human movement is assumed to be performed by optimizing some performance criteria (Groote et al., 2016).

Predictive simulations have been successfully used in the context of biomechanics, such as to study pedaling movement (Park et al., 2022), influence of lower limb exoskeleton (Bianco et al., 2022), assessment of different metabolic cost calculations of gait (Koelewijn et al., 2019) and analyze loaded and inclined walking (Dorn et al., 2015). In this work we used the predictive simulations to determine an optimal trajectory for the knee flexion-extension movement as well as to produce optimized movements around predefined trajectories.

Recently, Dembia et al. (2020) developed the OpenSim Moco, a software toolkit that solves optimal control problems, allowing the execution of predictive simulations with OpenSim biomechanical models. The Moco has the MocoTrack and the MocoStudy packages, being the first related to predictive simulations where a reference trajectory is provided and the last is related to fully predictive simulation. It is useful to emphasize that MocoTrack does not perform a tracking simulation, but a predictive simulation based on a motion, with optimization of the controls and states involved. In this work, MocoTrack was used to study the predefined trajectories and the MocoStudy was used to determine the optimal one.

The first trajectory studied was determined by the sinusoidal function expressed by Equation (1) (Peña et al., 2019). This function represents a movement time interval of 8 seconds and that starts with a flexion of $-90°$, followed by an extension to $0°$ and then finished with a new flexion to $-90°$ (Fig. 3).

$$\theta^d = 45sin(0.7854t - \frac{\pi}{2}) - 45 \tag{1}$$

Where θ^d is the desired trajectory to be simulated, in degrees, and t is the time in seconds.

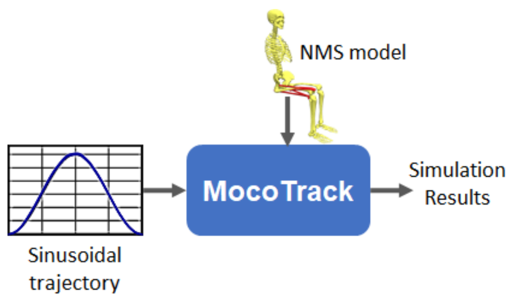

Figure 3. Sinusoidal trajectory simulation

The second trajectory studied was obtained from a experimental procedure conducted with a subject in a seated position, performing knee flexion-extension movements according to the sinusoidal trajectory presented above (which was shown to him through a computer screen). The knee angular position was measured using a series elastic

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

actuator (SEA) designed by dos Santos et al. (2017). Such measurement was then used as the reference to the predictive simulation (Fig. 4). Thus, it was possible to study the knee flexion-extension movement relative to a sinusoidal trajectory, both from a theoretical and experimental point of view.

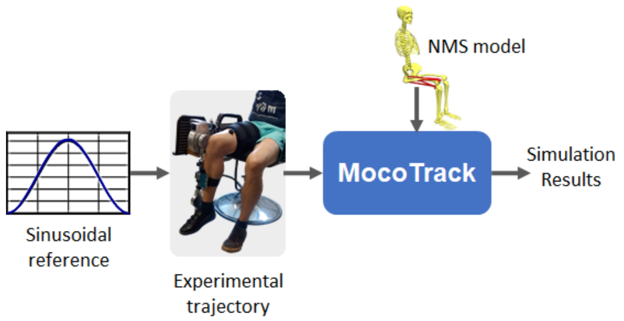

Figure 4. Experimental trajectory simulation

Finally, we used the predictive simulation combining MocoStudy and MocoTrack to determine and study the optimal trajectory for knee flexion-extension movement (Fig. 5). Such trajectory was expected to have the widest possible range of motion ($-90°$ to $0°$ in this case) with the lowest levels of muscle activation. In this case, there is no input reference trajectory, but three points: the start point at $t = 0$ s and $\theta^d = -90°$ (flexion), the intermediate point at $t = 4$ s and $\theta^d = 0°$ (extension) and the end point at $t = 8$ s and $\theta^d = -90°$. Through the MocoStudy, the optimal trajectory that passes through these points was determined. Then, MocoTrack was used to perform fine adjustments to the optimal trajectory and determine the muscle activations and knee torque related to it.

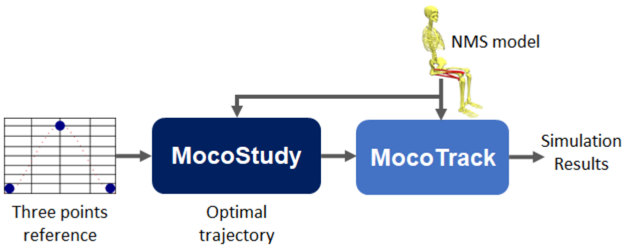

Figure 5. Optimal trajectory simulation

The term **simulation results** presented in figures 3-5 consists of the optimized quantities: position, velocity, torque and muscle activations, that were analyzed and compared to each other.

2.3 The Optimal Control Problem Formulation

As mentioned above, to perform a predictive simulation is the same as to solve an optimal control problem (OPC). Then, the first step is to define the OPC, by choosing a cost function and selecting a set of constraints.

In this work the cost function is defined by (2). The term J_s, defined by (3), is used to minimize the difference between the movement performed by the neuromusculoskeletal model ($\hat{\theta}$) and the one determined by the trajectory studied (θ^d). The term J_c, seeks to minimize the value of the controls, that here are the muscle activations. Minimizing such activations is important to reduce the human effort avoiding fatigue and reducing the biological cost. The scalars α and β are the weight for each term and their values are 10 and 1, respectively.

$$J_T = \alpha J_s + \beta J_c \tag{2}$$

Where

$$J_s = \int_{t_0}^{t_f} \sum_{i=1}^{N} (\theta_i^d - \hat{\theta}_i)^2 dt \tag{3}$$

$$J_c = \frac{1}{d} \int_{t_0}^{t_f} \sum_{c \in C} w_c |u_c(t)|^\rho dt \tag{4}$$

With d being the displacement of the system, C the set of control signals, w_c the weight for control c (unitary in this work), $u_c(t)$ the control signal c and ρ the exponent (2 in this case).

The objective function must be minimized subject to the system multibody dynamics (5), the kinematic constrains (6) that lock the hip, ankle and left knee joints, the boundary constrains (7), the path constrains (8) and the initial and final states and controls (9). With these constraints, the knee ROM was limited to $[-90°, 0°]$, the muscles activations to $[0, 1]$ and the knee angular velocity to $[-40, 40]$ deg/s.

$$M(q,p)\ddot{q} + G(q,p)^T \lambda = f_{app}(t,y,u,p) - f_{int}(q,\ddot{q},p) \tag{5}$$

$$0 = \phi(q,p) \tag{6}$$

$$V_{L,k} \leq V(t_0, t_f, y_0, y_f, u_0, u_f, \lambda_0, \lambda_f, p) \leq V_{U,k} \tag{7}$$

$$g_L \leq g(t,y,u,\lambda,p) \tag{8}$$

$$\begin{aligned} y_{0,L} \leq y_0 \leq y_{0,U} \quad y_{f,L} \leq y_f \leq y_{f,U} \\ u_{0,L} \leq u_0 \leq u_{0,U} \quad u_{f,L} \leq u_f \leq u_{f,U} \end{aligned} \tag{9}$$

Where $M(q,p)$ is the mass matrix, q and $\ddot{q}$ are the joint position and acceleration, respectively, $G(q,p)$ is the Jacobian matrix whose transpose converts the Lagrange multipliers λ into generalized forces along the system's degrees of freedom, $f_{app}(t,y,u,p)$ are the applied forces from muscles and actuators, $f_{int}(q,\ddot{q},p)$ are the centripetal and Coriolis forces, y, u and p are the states, controls and parameters, respectively.

2.4 Analysis Procedure

To analyze the result obtained, we considered the trajectory and velocity of the movement, the torques and the muscle activations required to perform the motion. The optimal trajectory was considered the one with the largest range of motion that required less effort (i.e. less torque and, consequently, lower muscle activations, which reduces the biological cost).

The simulations were performed on a computer with Intel® Core™i7-10510U 2.30 GHz processor, 8.00 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.

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3. RESULTS AND DISCUSSION

Figure 6 presents a comparison between the trajectories obtained. It is possible to see that both the sinusoidal and the optimal trajectories reached the desired initial, intermediate and final points (-90, 0 and -90 degrees, respectively) in the interval of 8 seconds. The experimental trajectory did not reach these points, despite having been performed at the same interval as the others, resulting in a less amplitude movement. An interesting analysis can be made between the positions related to the sinusoidal and optimal trajectories: both have the same displacement, but the former has a larger area under the curve than the latter. Although the area under the position curve does not have a physical meaning, we can analyze this magnitude from a mathematical point of view: the curve with the smallest area (i.e. the optimal trajectory curve) had the smallest cost function, for the same range of movement.

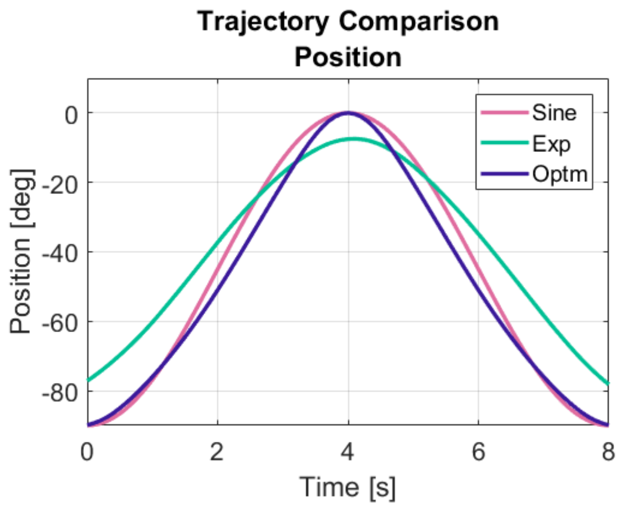

Figure 6. Comparison between the trajectories obtained in each simulation

A comparison between the knee angular velocities (Fig. 7) showed that all of them have an approximately sinusoidal behavior, with the highest absolute values occurring at 2 and 6 seconds for the sinusoidal and experimental trajectories and at 3 and 5 seconds for the optimal one. The sinusoidal trajectory has the major absolute value of velocity and the experimental trajectory has the minor one. This is not a surprise, since the experimental movement has a smaller range and is executed at the same time interval as the other movements. Although the velocity related to the optimal trajectory has absolute maximum values smaller than those of the sinusoidal trajectory, it varies rapidly between 3 and 5 seconds, which can cause some discomfort to the individual during the execution of the rehabilitation exercise.

The torques applied in each movement are depicted in the Figure 8. All the torque curves are coherent with the movement performed by the neuromusculoskeletal model, as can be see comparing it with the time-position curves presented in Figure 6. The experimental trajectory produced a torque whose curve resembles a parabola arc, with continuous variation over time and with the highest absolute values when compared to the other curves. Thus, it is possible to conclude that, even for a movement of

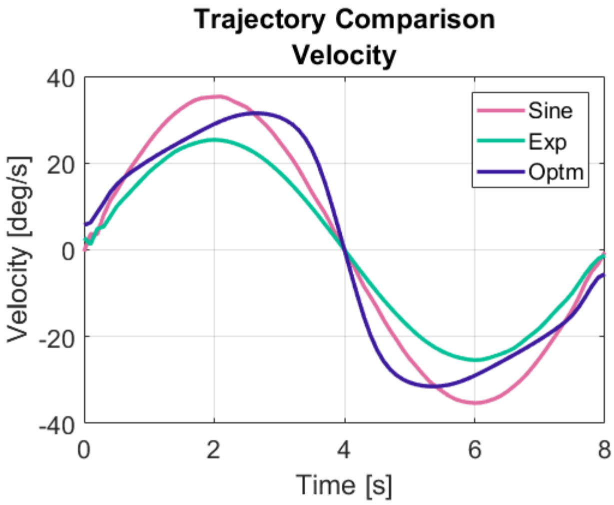

Figure 7. Comparison between the velocities obtained in each simulation

smaller amplitude, the individual had to perform more torque to follow the trajectory. Torque curves related to sinusoidal and optimal trajectories show a plateau at the instants when velocity decreases and changes its direction. Furthermore, the torque curves related to these trajectories are similar, with the same maximum values, but the optimal trajectory presented a narrower torque curve, with a smaller area for the same angular displacement of the knee.

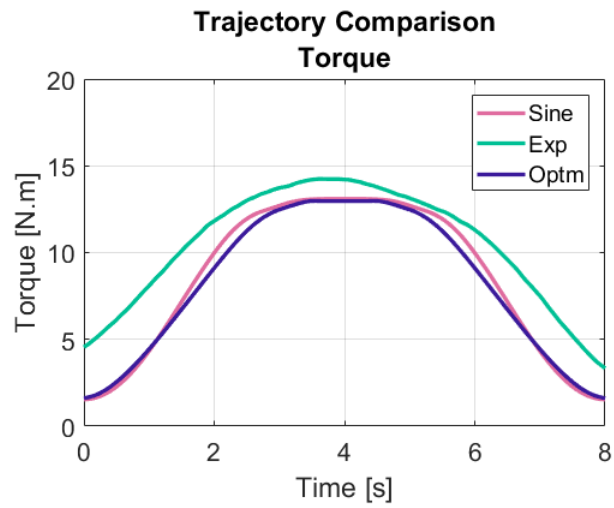

Figure 8. Comparison between the torques obtained in each simulation

The muscle activations of the model, needed to perform the movements, are presented in the figures 9-11. Remembering, the muscles of the model are: the extensors rectus femoris (RF), vastus lateralis (VL), vastus medialis (VM) and the flexors biceps femoris (BF) and semitendinosus (SM).

For all trajectories, we can notice that the extensor muscles demanded greater activation, which is expected, since due to the force of gravity, there is a permanent tendency for the shank to "descend", that is, for the knee to flex. Then, during the extension movement, the extensors have to work to overcome the force of gravity and to cause an acceleration that makes the leg move upward. On the other hand, during the flexion movement, these muscles must act as brakes, preventing the force of gravity from originating an acceleration that causes the leg to descend in an unplanned manner, which may incur instability and damage to the joint.

Comparing the activations between each trajectory, it is noticed that the movement relative to the sinusoidal trajectory demanded higher levels of activation while the movement relative to the optimal trajectory required the lowest levels. For the experimental trajectory, the activation values remain high all the time, although in relation to the other trajectories these values are intermediate, that is, here the muscles are constantly receiving a relatively high level of activation, which can result in a unwanted muscle fatigue. So, if we want a movement with less effort, avoiding the occurrence of muscle fatigue and striving for a reduction in biological cost, we need to use the optimal trajectory studied here as the reference for the movement.

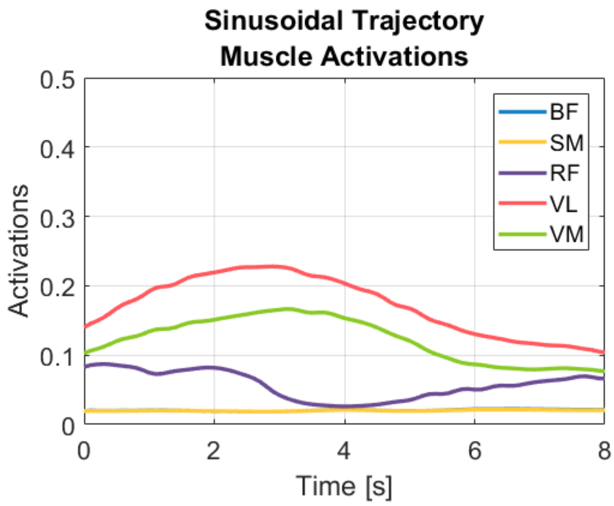

Figure 9. Muscle activations for the sinusoidal trajectory

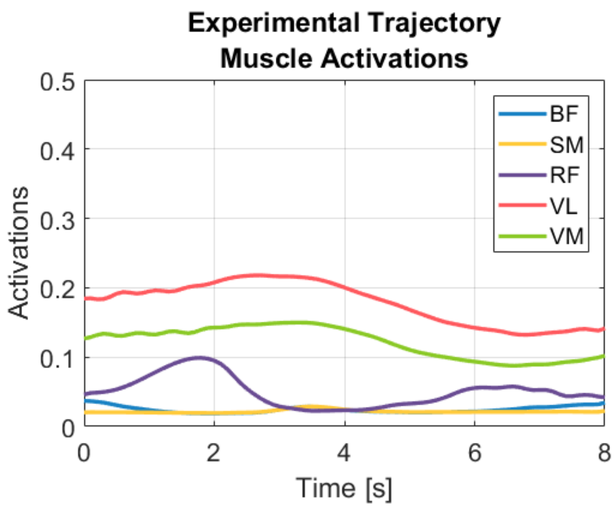

Figure 10. Muscle activations for the experimental trajectory

Each simulation took approximately 10 minutes to be prepared and about 7 minutes on average to be carried

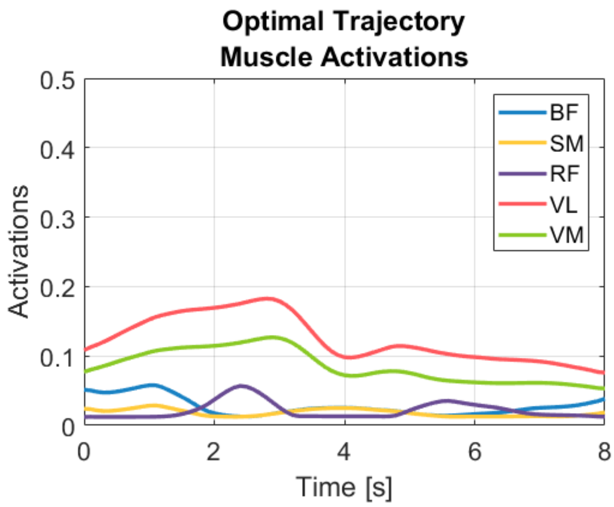

Figure 11. Muscle activations for the optimal trajectory

out, that is, in less than 1 hour we could produce a reasonable quantity of data, unable to be obtained without the predictive simulations.

A movie of the simulations carried out in this work can be found through the QR code below or by accessing the link `https://youtu.be/1Mw6X0Ta5Ew`.

4. CONCLUSION

The objectives of this work were to use predictive simulations to study some trajectories in the knee flexion-extension movement, as well as to determine an optimal trajectory for this type of movement.

The results showed that there is an optimal trajectory to be followed in the flexion-extension movement that, despite not showing gross differences in relation to a sinusoidal and sinusoidal-based experimental trajectory, its biomechanical results are better, with greater range of motion and less biological cost.

For future work, we intend to study the trajectories for the flexion-extension movement performed by a patient with muscle weakness and assisted by a lower limb exoskeleton robot.

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