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Optimal passive orthosis configuration for squat to stand assistance

Denis Mosconi[1,2] **and Adriano A. G. Siqueira**[2]

[1] Federal Institute of Science, Education and Technology, Industry Department, Catanduva, São Paulo, Brazil - denis.mosconi@ifsp.edu.br

[2] Mechanical Engineering Department and Center of Engineering Applied to Healthy, São Carlos School of Engineering, University of São Paulo, São Carlos, São Paulo, Brazil

Abstract: In this work we used computational simulation to determine the best configuration of a passive orthosis modeled as a spring and used to assist the squat to stand movement. Two configurations were considered: knee and hip-knee-ankle assistance. The optimal value of spring stiffness was also determined using. The simulations were carried out using OpenSim Moco and a musculoskeletal model. The results obtained demonstrated that the best choice is orthosis that assists only the knee, with a stiffness of 66 N.m/rad, , as it promotes a reduction in muscle activations, ensuring the execution of the movement in a smooth and continuous way. Despite the hip-knee-ankle configuration promoting a reduction in muscle activation when compared to the movement performed without the orthosis, such reduction was lower than that obtained with the orthosis applied only to the knee.

Keywords: Passive orthosis, Computational biomechanics, OpenSim Moco

INTRODUCTION

The squat-to-stand movement is a very common task for the human activities of daily living, but highly complex from a biomechanical point of view. It requires the lower limb muscles to work together and in an orderly manner, performing an exact sequence of biomechanical steps in a finite time, ensuring dynamic standing balance and resulting in a closed-kinetic chain movement on a small base of support (Rosenberg and Edelstein, 2018).

Individuals with some motor limitation due to paraplegia, spinal cord injury, stroke or old age experience difficulty or disability in rising to a standing position, at the risk of falling and suffering injuries that can further worsen their health status. Assistive devices like passive orthosis (Rosenberg and Edelstein, 2018), weight-support device (Hong et al., 2015) and powered exoskeletons (dos Santos et al., 2017) can help impaired people to perform the squat-to-stand with success and safe.

In this work we used computational simulation to evaluate the influence of a passive orthosis, modeled as a spring, on the squat-to-stand movement performed by a neuromusculoskeletal model representing a healthy person. We also used optimization to determine how many joints to assist (only knee or hip-knee-ankle) as well as finding the best stiffness for the spring.

MATERIALS AND METHODS

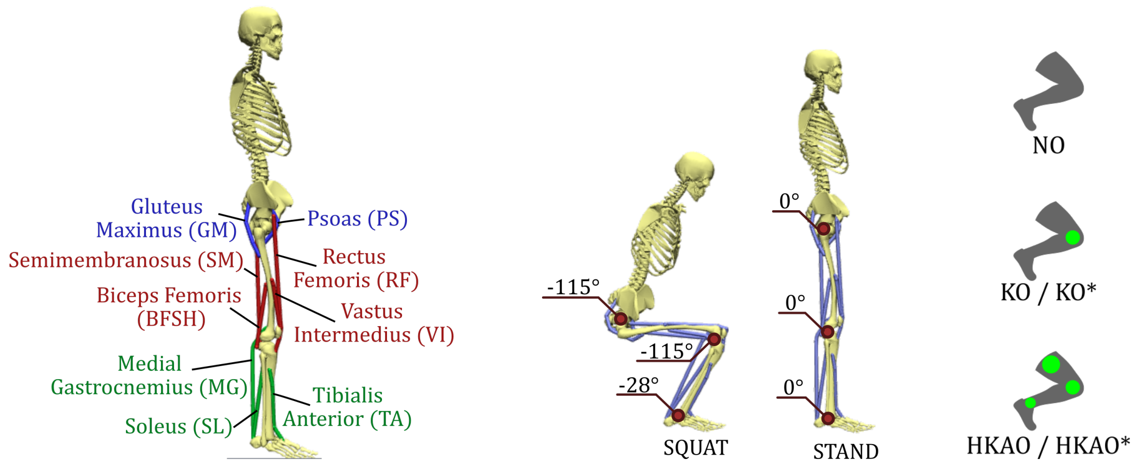
To determine the best passive orthosis configuration for the squat-to-stand movement, we resorted to computational simulations using the OpenSim Moco and a neuromusculoskeletal model. The OpenSim Moco is an easy-to-use, extensible and customizable software toolkit developed by Dembia et al. (2020) able to solve optimal control problems with OpenSim biomechanical models, using the direct collocation method.

The neuromusculoskeletal model used is the *squatToStand_3dof9musc* provided by the OpenSim Moco (Fig. 1a), and has a torso and a leg with 9 muscles and 3 degrees of freedom. As the model has only a single leg, its muscles strengths were doubled in order to ensure mediolateral symmetry (Dembia et al., 2020). The simulations were performed with the model starting in the squatting position (Fregly et al., 2015) and ending in a standing position (Fig. 1b).

To facilitate the analyzes, the muscles were grouped according to the main joint they move: gluteus maximus (GM) and Psoas (PS) for the hip, semimembranosus (SM), rectus femoris (RF), biceps femoris short head (BFSH) and vastus intermedius (VI) for the knee, medial gastrocnemius (MG), tibialis anterior (TA) ans soleus (SL) for the ankle.

In this work we simulated the passive orthosis as a torsional spring. Then we carried five simulations in order to determine the best configuration of the orthosis (number of joints assisted) as well as the optimal stiffness of the spring. Each simulation is detailed next: **Simulation NO:** Model with no orthosis, being actuated only by the muscles. **Simulation KO:** Knee orthosis with 50 N.m/rad stiffness. **Simulation HKAO:** Hip-knee-ankle orthosis with 50 N.m/rad stiffness in the three joints. **Simulation KO*:** Knee orthosis with optimized stiffness. **Simulation HKAO*:** Hip-knee-ankle orthosis with optimized stiffness in the three joints. A illustration of the different orthosis configurations used in the simulation is presented in the Fig. 1c.

To determine movement between the start and end positions, as well as the best orthosis configuration and optimal



(a) Musculoskeletal model (b) Squat-to-Stand angles (c) Configurations

Figure 1 – The *squatToStand_3dof9musc* model (a), the angles related to the initial and final positions (b) and the different configurations with and without orthosis (c)

stiffness, an optimal control problem (OCP) was defined, so that the combination between the movement performed and the orthosis configuration sought to minimize the sum of the absolute values of muscle activations, according to the cost function described by Eq. (1).

$$\frac{1}{d}\int_{t_i}^{t_f}\sum_{c\in C} w_c|u_c(t)|^{\rho}\,dt \tag{1}$$

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

The objective function must be minimized subject to the system multibody dynamics (Eq. 2), the kinematic constrains (Eq. 3), the boundary constrains (Eq. 4), the path constrains (Eq. 5) and the initial and final states and controls (Eq. 6).

$$M(q,p)\ddot{q} + G(q,p)^T\lambda = f_{app}(t,y,u,p) - f_{inertial}(q,\ddot{q},p) \tag{2}$$

$$0 = \phi(q,p) \tag{3}$$

$$V_{L,k} \leq V(t_0,t_f,y_0,y_f,u_0,u_f,\lambda_0,\lambda_f,p) \leq V_{U,k} \tag{4}$$

$$g_L \leq g(t,y,u,\lambda,p) \tag{5}$$

$$\begin{aligned} y_{0,L} \leq y_0 \leq y_{0,U} \quad & y_{f,L} \leq y_f \leq y_{f,U} \\ u_{0,L} \leq u_0 \leq u_{0,U} \quad & u_{f,L} \leq u_f \leq u_{f,U} \end{aligned} \tag{6}$$

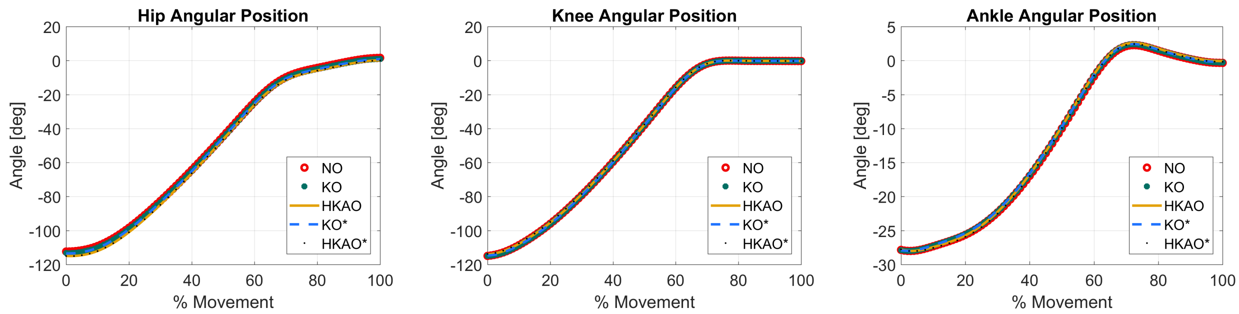
Where $M(q,p)$ is the mass matrix, q and $\ddot{q}$ are the joint position and acceleration, respectively, $G(q,p)$ is the Jacobian matrix whose transpose converts the Lagrange multipliers λ into generalized forces along the system's degrees of freedom, $f_{app}(t,y,u,p)$ are the applied forces from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

This OCP was solved for the optimal motion, muscles activations and spring stiffness through the direct collocation method: the CasADi library Andersson et al. (2018) embedded in OpenSim Moco was used to transcribe the continuous optimal control problem above into a finite dimensional nonlinear programming (NLP) which was then solved by the open-source solver IPOPT using gradient-based methods.

The simulations were performed on a computer with Intel®Core™i7-10510U 2.30 GHz processor, 20 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.

RESULTS AND DISCUSSIONS

Observing the Fig. 2 it is possible to see that the desired initial and final positions have been reached. In addition, all movements between these positions are coincident, so that the different configurations of the passive orthosis as well as the variations in the stiffness values did not change the trajectory of the joints, all of them being similar to the trajectory performed by the model without the orthosis. The movement performed is smooth and continuous, which guarantees comfort and safety to the individual.

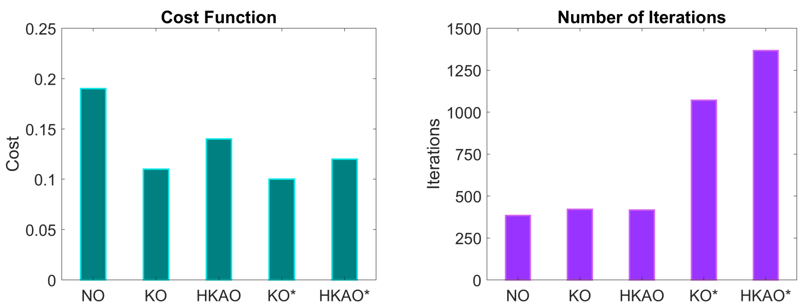


(a) Hip (b) Knee (c) Ankle

Figure 2 – Angular positions of the hip, knee and ankle for the five simulations

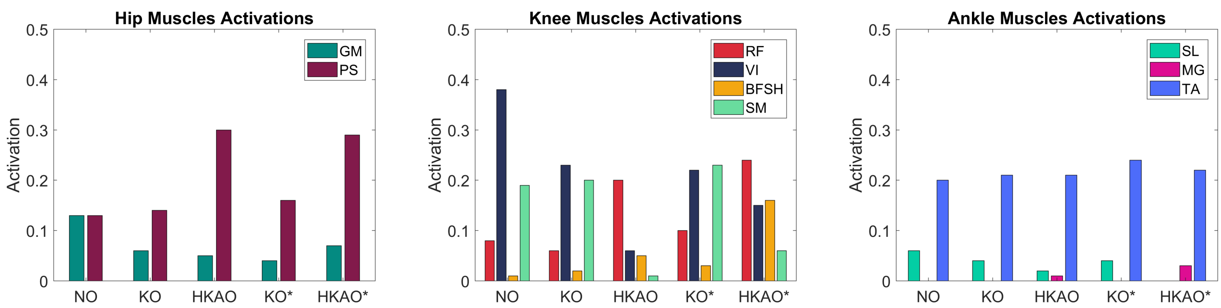
The values of the cost function (Eq. (1)) are compared in the Fig. 3a. The highest cost was obtained with the movement performed without orthosis (NO). The lowest costs were obtained with the knee orthosis (KO and KO*), being the one related to the KO* the lowest of them, with optimized stiffness equal to 66 N.m/rad. The configurations HKAO and HKAO* resulted in costs lower than the one obtained without orthosis but greater than the ones obtained only with knee orthosis. The optimal stiffness of the HKAO* are 47, 48 and 38 N.m/rad for the hip, knee and ankle, respectively.

To solve the optimal control problem more iterations were needed for the stiffness optimization (Fig. 3b), which is reasonable, since in this case there was necessary to optimize both the movement and the orthosis stiffness. None of the five simulations took more than twelve minutes to complete.



(a) Cost (b) Iterations

Figure 3 – Cost function value and iterations for the five simulations



(a) Hip (b) Knee (c) Ankle

Figure 4 – Muscle activations RMS related to the hip, knee and ankle for the five simulations

A comparison between the root mean square (RMS) values of the muscle activations is presented in the Fig. 4. For all cases, the orthosis caused a reduction in gluteus maximus activations and an increase in psoas activations (Fig. 4a).

Without the orthosis and for the KO and KO* configurations, the vastus intermedius worked more than the rectus femoris. As the rectus femoris antagonistically interferes with hip extension, it is more interesting that the vastus intermedius has more participation in the movement than the rectus femoris, showing once again that the orthosis applied only to the knee is more interesting than an orthosis applied to the three joints. With the KO and KO* orthosis configuration, the semimembranosus worked more than the biceps femoris short head, which is interesting, since the semimembranosus contributes positively for the hip extension, that is desired for the squat-to-stand movement. The same not occurs with the HKAO and HKAO* configurations (Fig. 4b).

The medial gastrocnemius causes the plantarflexion of the ankle, but also contributes for the knee flexion, which is undesirable in this case: a greater involvement of the soleus muscle is preferable. Observing the (Fig. 4c) it is possible to see that the HKAO and HKAO* configurations cause activation of the medial gastrocnemius. The high RMS value for the tibialis anterior is due the fact that this muscle starts highly activate at the beginning of the squad-to-stand movement, because the ankle is in a dorsiflexion position.

Considering the results obtained it is possible to conclude that the knee orthosis configuration with optimized stiffness (KO*) is the best choice to be made. This is advantageous, because a hip-knee-ankle orthosis is more expensive to produce and maintain that a knee orthosis. With the optimized knee orthosis, the squat-to-stand movement becomes safer, requiring less biological effort and minimizing the muscle fatigue.

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