INFLUENCE OF STIFFNESS OF AN ANKLE-FOOT ORTHOSIS ON GAIT
A PREDICTIVE SIMULATION STUDY

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INTRODUCTION

An ankle-foot orthosis (AFO) is often prescribed to patients with instability or weakness in the lower leg to assist plantarflexion or dorsiflexion [1]. A limited number of studies focuses on the optimal stiffness of the AFO. It is known that excessive AFO stiffness introduces buckling in the knee [1]. It would be desirable to have the ability to predict the effect of an AFO on the gait of a specific patient. This would make customized prescriptions possible and reduce the need for trial and error. Bregman et al. used a simplified gait model and found that patient energy cost might be reduced by choosing the correct stiffness [2]. However, this model did not have muscles.

In the present study, a dynamic musculoskeletal model will be used to predict the effect of the stiffness of the AFO on gait parameters. We hypothesize that less muscular effort is required in the lower leg with an increased stiffness in the AFO due to the higher moment generated in the AFO.

METHODS

Predictive simulations of gait were performed with a sagittal plane model having nine degrees of freedom and 16 muscles. An open loop optimal control problem was formulated to find a gait cycle that minimizes a weighted sum of muscular effort and deviation from normal gait kinematics. The model and solution method were identical to [3], but a full gait cycle was simulated. Also, tracking was not performed on the ankle where the AFO was applied, since this could make the muscles "fight" the orthosis.

The optimal control problem was solved for an able-bodied system with and without an AFO. The AFO was modelled as a rotational spring that was applied to one of the ankle joints. The stiffness of the AFO ranges from 50 to 400 Nm/rad, similar to the range of stiffnesses that were tested in [2].

RESULTS AND DISCUSSION

Figure 1 shows the ankle moment and muscle forces in the lower leg of the predictive simulations. The color of the line gets lighter with an increased stiffness. The black line shows the result without an AFO.

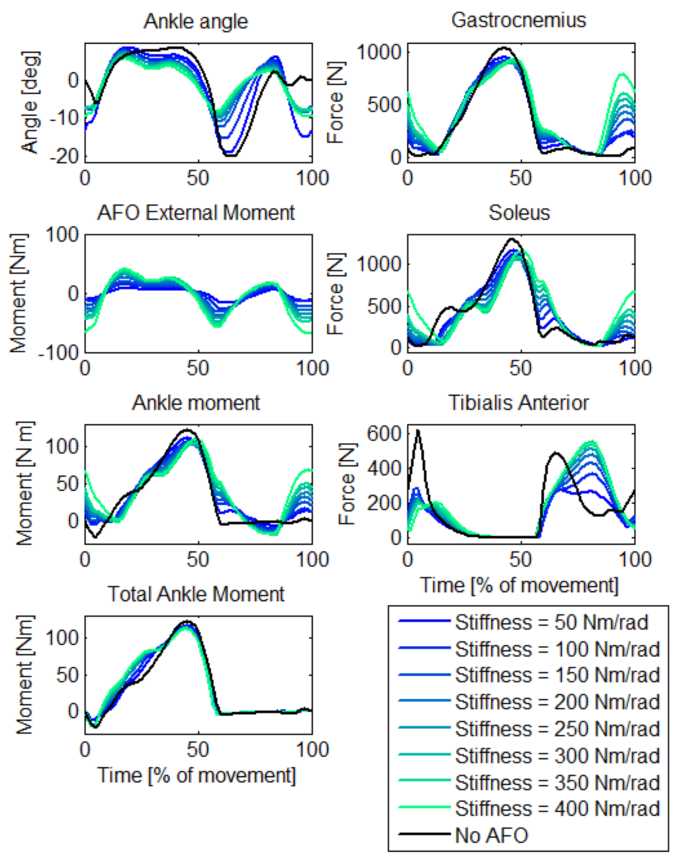

Figure 1: Results of the predictive simulations of gait with and without an AFO.

Figure 1 shows that the AFO decreases the force required in the Tibialis Anterior during initial stance significantly. However, there is little benefit of having a higher stiffness, since the decrease is much higher between the no-AFO simulation and any simulation with AFO. Also, the stiffness does not have an effect on the size of the peak Gastrocnemius and Soleus force during stance. Both are lower than in gait without AFO, but there is no significant effect of the stiffness.

It was found that this is due to the timing of the moments that are generated by the AFO. During push-off, the ankle angle is almost zero, so the AFO is not able to provide much assistance during this phase. However, during the stance phase, when the ankle angle is larger, the total ankle moment increases with AFO stiffness.

The AFO stiffness has a significant effect on the Tibialis Anterior force during the swing phase. The muscle is counteracting the AFO to provide sufficient toe-clearance, for which a dorsiflexion angle is required. This suggests that a too large stiffness is not beneficial, since it increases the necessary force in the Tibialis Anterior.

There is also a significant effect of the stiffness of the AFO on the Gastrocnemius and Soleus during the initial and final phase of the swing phase. It was found that this was due to the tracking of the vertical ground reaction force, which requires a nonzero ankle angle during the swing phase, yielding a moment in the AFO. The Soleus and Gastrocnemius were activated to reduce the total ankle moment to 0. Further research is necessary to find if this behavior is also present in reality, or if it is an artifact of the cost function that was used in the optimal control problem.

Studies on impaired patients walking with and without an AFO confirm our finding that there is no decrease in peak muscle force in the Gastrocnemius and Soleus muscle [4]. Balmaseda et al., in a study on healthy subjects, reported a reduction of the mean stance phase duration of 4.83% with an AFO compared to without an AFO [5]. This reduction is confirmed by this study, which also yielded a reduction in the stance phase of approximately 5%.

CONCLUSIONS

The hypothesis that an increase in AFO stiffness yields a decrease in muscular effort was not confirmed. It was found that there was only little effect of the stiffness of the AFO on the peak force in the Gastrocnemius and Soleus.

Future studies should include a verification of these results using a subject study, for example to see if humans also increase their force in the Gastrocnemius and Soleus during the swing phase. If it is found that this is an artifact of the optimal control problem, such results can be used to further improve the formulation of suitable cost functions.

REFERENCES

[1] Yokoyama, O., et al. "Kinematic effects on gait of a newly designed ankle-foot orthosis with oil damper resistance: A case series of 2 patients with hemiplegia." *Arch. Phys. Med. Rehabil.* 86.1 (2005): 162-166.

[2] Bregman, D. J. J., et al. "The effect of ankle foot orthosis stiffness on the energy cost of walking: A simulation study." *Clin. Biomech.* 26.9 (2011): 955-961.

[3] Van den Bogert, A. J., et al. "Predictive musculoskeletal simulation using optimal control: effects of added limb mass on energy cost and kinematics of walking and running." *Proc Inst Mech Eng, P: J of Sports Eng Technol* 226.2 (2012): 123-133.

[4] Ohata, Koji, et al. "Effects of an ankle-foot orthosis with oil damper on muscle activity in adults after stroke." *Gait & posture* 33.1 (2011): 102-107.

[5] Balmaseda Jr, M. T., et al. "Ground reaction forces, center of pressure, and duration of stance with and without an ankle-foot orthosis." *Arch. Phys. Med. Rehabil.* 69.12 (1988): 1009-1012.

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