# Study of the Risk of Ankle Injury During Impact on the Ground and Definition of Support Orthoses

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*Abstract* — **This work studies the effect of different orthoses on preventing injuries in the ankle-foot joint. It was carried out using OpenSim and the available ankle-foot musculoskeletal model and AFO orthoses models. The motion situation assessed is related to placing the foot on the ground. It is also analyzed how a passive ankle-foot orthosis, muscles reflexes and muscle coactivation influence the risk of injury, namely during ankle inversion. Results indicate that muscle coactivation and the use of an AFO can reduce injury risk. Thus, an average stiffness AFO is best suited for preventing ankle injuries.**

## I. INTRODUCTION

Ankle injuries are very frequent and can occur to anyone as a result of physical activity practice sports, or even during a run or walk. Ankle sprains are probably the most common injury in the universe of musculoskeletal injuries. It is estimated that 15-25% of all musculoskeletal wounds are of this type [1]. About 85% of ankle sprains occur on the lateral part of the foot [2] [3], during an ankle inversion movement. In this type of injury, ligaments that restrict ankle inversion can be damaged, namely the calcaneal-fibular ligament and the anterior talofibular ligament. When the angle of inversion exceeds 25°, it is considered that there is an injury causing pain and inflammation [4] [5].

The movement of the foot through the subtalar joint (articular synovial joint located between the inner face of the talus and the upper face of the calcaneus) can be modeled by representing the ankle as a spheroid joint [6]. The angle between the talus bone and the calcaneus bone is known as the "subtalar angle". This angle determines the degree of inversion/eversion of the ankle. One way of preventing this type of injury is using orthoses.

Orthoses are commonly used even by those who do not practice sport, since they offer protection, stabilization and discharge of weight, and can even be used in everyday life because they are a great aid to injuries. An ankle-foot orthosis (AFO) is an orthosis whose support aims to control the position and movement of the ankle, compensate for weaknesses and correct deformities [7].

One intrinsic muscular feature that also provides some level of prevention to injuries is muscle co-activation. During movement, Muscle coactivation occurs whenever agonist and antagonist muscles surrounding a joint contract simultaneously to provide joint stability. Muscle coactivation allows muscle groups around a joint to become more stable [8]. This is caused by the contraction of both muscles at the same time, which produces compression in the joint. The joint may become more rigid and more stable due to this action [9]. Therefore, the motion is steadier and more constant, without abrupt instantaneous changes.

## II. METHODS

In order to study the effects caused on the ankle by the ground impact, an OpenSim model ("ToyLandingModel") available at http://opensim.stanford.edu/ was used. This model consists of a flat platform and a skeletal muscle model. The skeleton consists of a torso, a pelvis, and two legs with a total of 23 degrees of freedom and 70 muscle–tendon actuators. Motion between the tibia and foot is described by two joints. The joints associated with the ankle of the right leg are ankle_r and subtalar_r. These represent respectively the talocrural (or "true ankle") joint and the subtalar joint. Contact spheres are attached to the feet to produce foot–floor contact forces.

The scheme from Figure 1, demonstrates the forward dynamics simulation utilized by OpenSim that was explored.

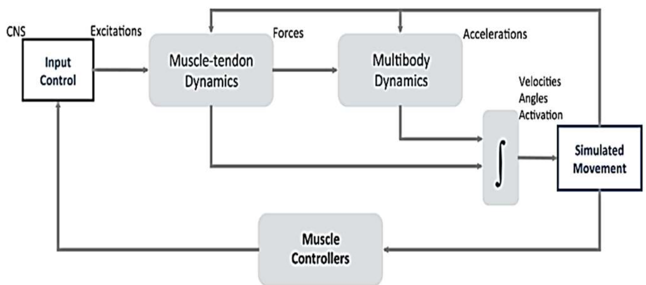


**Figure 1 – Scheme of forward dynamics simulation that was explored. *[10]***

In contrast to inverse dynamics where the motion of the model is known and the forces and torques that generated the motion are determined, in forward dynamics, a mathematical model describes how coordinates and their velocities change due to applied forces and torques (moments).

The forces in a musculoskeletal model are controlled by dynamics and have inputs that affect their behavior. In OpenSim, these inputs are called the controls of a model, which can be excitations for muscles or torque generators. Ultimately, controls determine the forces and/or torques applied to the model and therefore determine the resultant motion.

A simulation is the integration of the musculoskeletal model's dynamical equations starting from a user-specified initial state. After applying the controls, the activation rates, muscle fiber velocities, and coordinate accelerations are computed.

The Forward Dynamics Tool uses the same model and actuator set used in CMC, together with the initial states and controls computed during the CMC step, to run a muscle-driven forward dynamic simulation that aims to reproduce the same motion tracked by CMC [10].

In all the simulated scenarios the following setup was used:

- Platform angles: rotation: (20º; 0º; 0º); translation: (0; -0.5m; 9); All four coordinates of the platforms were locked, which means that the platform will be static during the impact;
- The simulation time was 0,4 seconds;

The scenarios simulated were:

### *A. Free fall simulation without assistance*

Firstly, an unassisted free fall was simulated. In the following simulations there were attenuating factors (muscular coactivation and/or AFO).

### *B. Free fall simulation with the assistance of a soft AFO on a slope*

In this simulation we used the model ToyDropLanding_AFO. The difference between this model and the previous one is the fact that this one has an AFO that is constituted by two segments: a footplate and a cuff, that stands on the tibia. These two segments are linked by bushings.

Our setup and simulation procedure are the same as the last one. The translational stiffness of the medial and lateral bushings was set to a value of 10000 Nm in all directions.

### *C. Free fall simulation with the assistance of a stiff AFO on a slope*

It was used the same simulation model as the previous simulation. The translational stiffness of the medial and lateral bushings was set to be ten times stiffer than the soft AFO, which means, it was set to a value of 100000 Nm in all directions.

### *D. Study of the effects of muscular coactivation*

The model that was used is equipped with two controllers that are used to control the levels of muscular excitation on the evertors and inverters that are deactivated by default. When the controllers are activated, it is possible to study the effects of muscular coactivation in the ankle inversion ankle.

## III. RESULTS AND ANALYSIS

Figure 2 shows the variation of the ankle inversion angle during the free fall. The angle reaches a peak of 50 degrees, which largely exceeds the reference angle of 25 degrees.

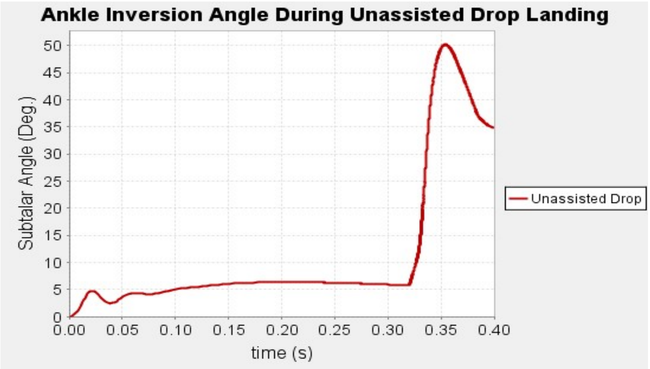


**Figure 2 – Variation of the ankle inversion angle during the fall without assistance.**

The ankle inversion angle is comparatively lower than the fall without assistance, however it still exceeds the reference angle of 25 degrees.

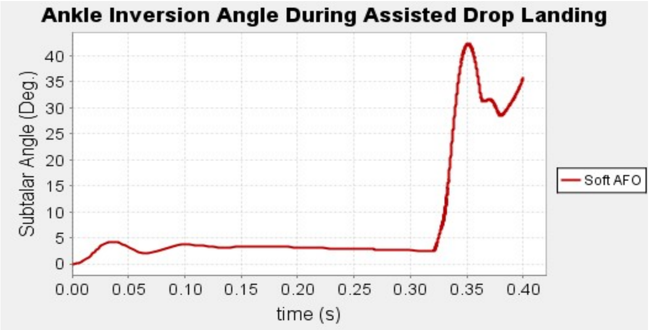


**Figure 3 – Variation of the ankle inversion angle during the fall with assistance of a soft AFO.**

Analyzing Figure 4, the ankle inversion angle is below 22,5 degrees, which is lower than the reference angle, that is, it is enough to mitigate the injury risk.

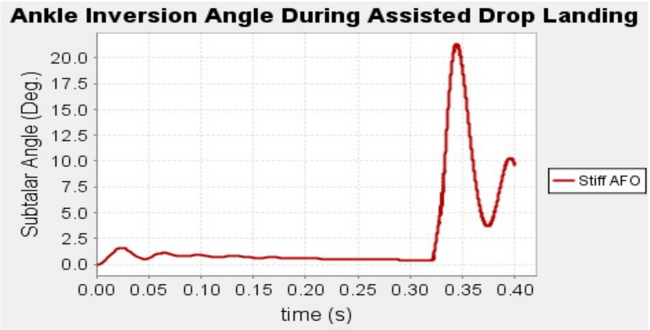


**Figure 4 – Variation of the ankle inversion angle during the fall with assistance of a stiff AFO.**

As expected, the graph represented in Figure 5 shows that there was a reduction on the ankle inversion angle compared to the simulation where the muscular coactivation controller was turned off. Despite the reduction, the maximum obtained angle is still above the reference, therefore, it is necessary to combine the muscular coactivation mechanism with an AFO.

Figure 6 shows the variation of the ankle inversion angle during the fall with the combined effects of muscular coactivation, plus a soft AFO. The setup of the coactivation controller stayed the same.

The ankle inversion angle that was obtained in this simulation (Figure 6), was inferior to the angle obtained when only using a soft AFO due to the muscular coactivation effects. The angle obtained was inferior to 35 degrees, but still above the reference angle.

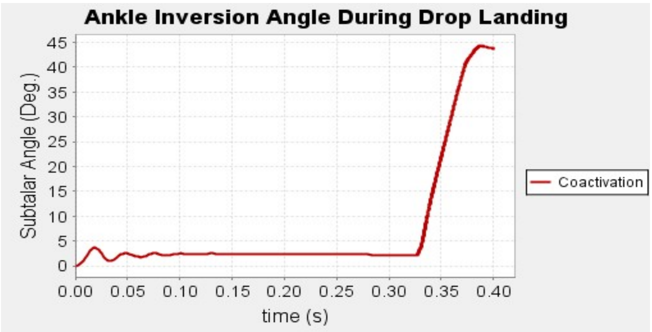


**Figure 5 - Variation of the ankle inversion angle during the fall without assistance and with muscle coactivation.**

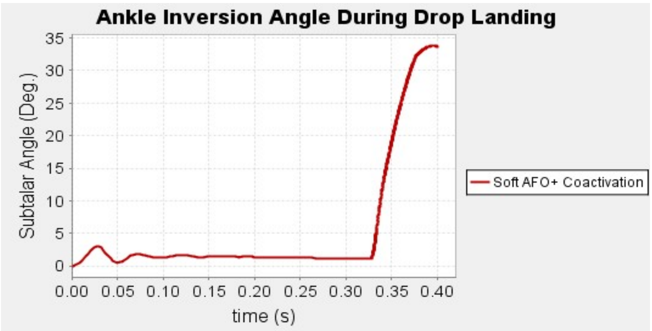


**Figure 6 - Variation of the ankle inversion angle during the fall with soft AFO and with muscle coactivation.**

Figure 7 shows the graph obtained through simulation with a stiff AFO and muscle coactivation. In this case (Figure 7), the maximum ankle inversion angle was inferior to 10,5 degrees. Since this angle is lower than the reference, there's some margin to try and reduce the AFO's stiffness, which results on a more comfortable AFO and in the reduction of the production cost [11].

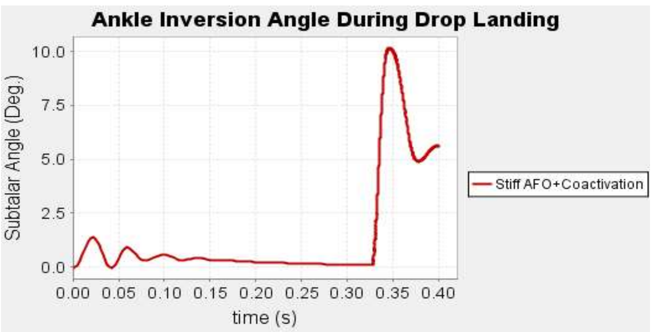


**Figure 7 - Variation of the ankle inversion angle during the fall with a stiff AFO and muscle coactivation**.

*Design of the most efficient AFO*

In order to decrease the AFO stiffness, several simulations were made using both AFOs (of medium stiffness) and muscular coactivation. Three different AFO stiffnesses were tried (Figure 8). The first one had translational and medial bushings set to a value of 20000 (blue line) in all directions. The second one had 30000 (purple line) and the third on 40000 (green line). All the results were organized in Figure 8.

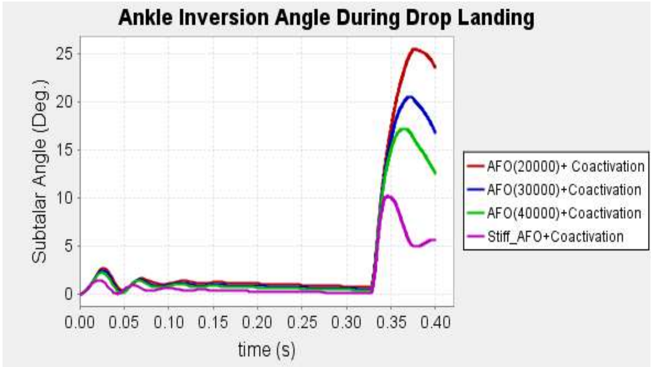


**Figure 8 - Variation of the ankle inversion angle during the fall with different AFO stiffnesses and muscular coactivation.**

The first AFO (20000) failed the task, because the angle surpassed the reference. The ankle angle in the first and second AFO were below the reference angle, but since the objective was to find the AFO that allied with the muscle coactivation factor would reduce injury risk while being comfortable (not too stiff), it was concluded that the AFO (30000) was the best suited.

With the ideal AFO the values of muscular coactivation were doubled. R-inverter was set to 0.2, while R-everter was set to 0.6.

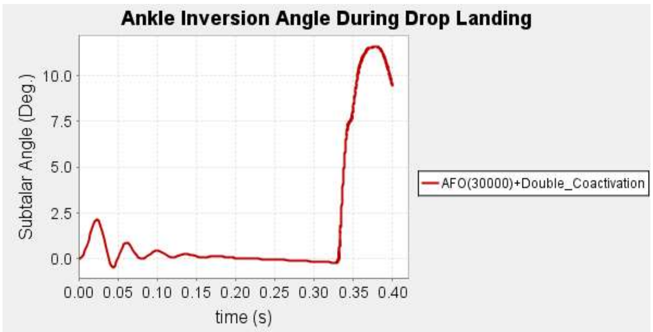


**Figure 9 - Variation of the ankle inversion angle during the fall with the ideal AFO stiffnesses and muscular coactivation doubled.**

Figure 9 shows that the maximum ankle inversion angle is lower than 12 degrees, which is a great improvement comparatively to the previous simulations where the values of muscular coactivation were 0.1 and 0.3. It is possible to conclude that the increase of muscular coactivation is one of the factors that can lead to the reduction of the maximum subtalar angle, therefore, it can reduce the injury risk. In table 1, it's possible to see a summary of the results obtained through simulation.

Finally, it is possible to choose a material that has characteristics that match the best suitable AFO requirements.

Carbon fibers are light, durable and resistant (mechanically and chemically) and are biologically inert. Metals (aluminum and steel) are considered the most used material for orthoses due to their resistance and durability, although it is important to say that metallic orthoses are heavy and esthetically unpleasant. Also, it is needed a material that allows both leg and ankle movement, in order to improve the orthosis versatility. It is recommended to use a material with some flexibility. Those are the reasons that make carbon fibers the best choice overall [12].

*Table 1 - Maximum inversion angle and the outcome in terms of ankle injury for each fall simulation type.*

| ***Simulation type*** | ***Maximum Inversion angle*** | ***Outcome*** |
|---|---|---|
| Without assistance | ~50.0º | Injury |
| Soft AFO | ~40.5º | Injury |
| Stiff AFO | ~22.5º | No injury |
| Muscle coactivation | ~44.8º | Injury |
| Muscle coactivation + Soft AFO | ~33.5º | Injury |
| Muscle coactivation + Stiff AFO | ~10.2º | No Injury |
| Ideal AFO+ muscle coactivation | ~20.5º | No injury |
| Ideal AFO+ double muscle coactivation | ~11.5º | No injury |

## IV. CONCLUSION

AFO stiffness and the muscle coactivation are inversely correlated with the maximum ankle inversion angle during the landing process.

To design the most effective strategy for the prevention of ankle injury, it is necessary to consider that (i) increasing AFO's stiffness will make it more expensive, less comfortable for the user and reduce the activity range; (ii) improving muscle coactivation and landing positions requires training that can bring costs and requires time commitment; (iii) versatility is also important, the AFO and training should be applicable in a variety of situations.

Based on the various results obtained it is concluded that the ideal strategy passes through an AFO of intermediate stiffness composed by carbon fibers combined with a training program to achieve greater muscular coactivation.

In the future, we could design an AFO suitable to prevent injuries in this conditions that also works in other scenarios without restraining user mobility and create an effective training program to increase muscle coactivation and improve landing technique.

## ACKNOWLEDGMENTS

OpenSim Community: open source software to create and analyze dynamic simulations of movement, available at http://opensim.stanford.edu/about/people.html.

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