Ankle plantar flexion drives talus posterior tilt during arch recoil

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Summary

We developed a computational model of the ankle joint to investigate how soft tissues contribute to the coordination of arch recoil and ankle plantar flexion. Our model showed that as the arch recoils, the talus posteriorly tilts relative to the first metatarsal because of contact forces from the tibia rather than from the arch. These findings provide a mechanistic understanding of arch-ankle coupling.

Introduction

The foot's arch-recoil and ankle plantar flexion are tightly coupled during locomotion. Kinematically, the recoiling arch removes some anterior talus tilt as the foot levers about the toes and the ankle plantar flexes [1]. We previously argued that arch-ankle coupling may help prevent the tibia from tilting too far forward and increases the effective range of motion of the ankle [1]. In this study, we questioned what forces drive arch-ankle coupling. We used biplanar videoradiography (BVR) to develop a computational model centered around the talus, the keystone of the arch and ankle. We estimated the cartilage contact and ligament contributions to talus motion to determine whether arch-ankle coupling was driven by the foot, the ankle, or both.

Methods

We used ArtiSynth, a combined rigid body, finite element (FE) modelling toolkit [2]. The bones were modelled as rigid bodies from CT scans of the participant, ligaments were modelled as spring-reinforced FE membranes, and cartilage as rigid bodies with elastic contact. The talus is only driven by passive tissues, so muscles were not included in the model. Muscle actions were inferred from adjacent bone kinematics. The simulation was driven by the 3D motion of the surrounding bones, measured with BVR (n = 1, M, 51, conditions: walking, running). The participant had tantalum beads previously implanted in their foot bones, providing highly accurate motion (error: ~0.1 mm, ~0.1°).

The material properties of the soft tissues were found by minimizing the mean square error (MSE) of the measured and modelled orientation of the talus during running using a response surface method (MSE: 1.5°/frame). We then applied the material properties to the model with walking kinematics to avoid overfitting (MSE: 2.1°/frame). The moments exerted by the individual soft tissues were extracted and transformed into the talus anatomical coordinate system to analyze which structures were driving posterior tilt.

Results and Discussion

As expected, there was a net anterior tilt moment on the talus during propulsion. Anterior tilt was driven by navicular and calcaneus cartilage and ligaments that insert on the navicular (Figure 1A). As the ankle plantar flexed, the tibia imparted an increasing posterior tilt moment on the talus, moving the centre of pressure of the contact posterior to the talus centre of mass and increasing the moment arm (Figure 1B).

Conclusions

Our results show that forces from the foot drive the global anterior tilt of the talus during propulsion, while the tibia opposes anterior tilt. This highlights the role of the tibia – and the weight of the body – in posteriorly tilting the talus. This suggests that the tibia contributes to the arch recoil during ankle plantar flexion, potentially explaining why arch recoil is linearly related to ankle plantar flexion during propulsion [1]. The ability of the tibia to move to the posterior part of the talocrural surface may be important for proper foot function. This is interesting when coupled with the recent finding that humans appear to target a specific tibia angle when locomoting [1], suggesting a further need for robust foot-ankle coordination during locomotion.

References

[1] Welte, L. *et al*. (2023). *Front bioeng biotechnol*, **11**.
[2] Lloyd, J. *et al.* (2012) *ArtiSynth*, Springer.

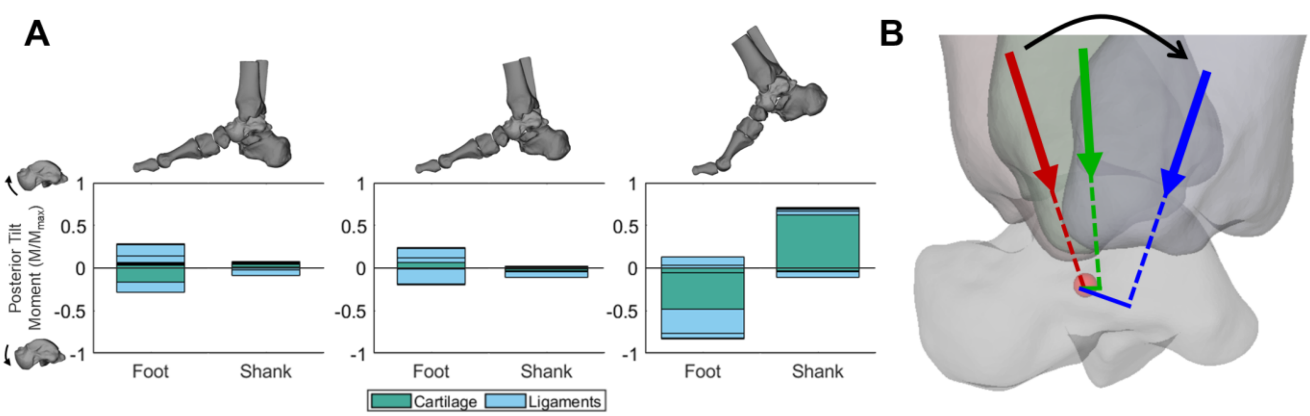

Figure 1: (A) The posterior tilt moment exerted on the talus by the individual cartilage and ligaments in the foot and shank at three points in stance: foot flat, as the heel comes off the ground, and as the metatarsal heads come off the ground. (B) The moment arm from the tibia cartilage contact force increases as the tibia moves backwards on the talocrural surface.