Degeneracy in the Foot and Ankle Complex Enables Tibia Positioning During Locomotion

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Summary

We used biplanar videoradiography (BVR) to determine the extent to which the toes, arch, and ankle constrain the tibia's posture during walking and running. In contrast to the tibia's consistent posture, the distal joints were highly variable within and across people, even with an arch-supporting orthotic. This reveals a case of degeneracy, where structurally different components of a system exhibit variability while contributing to the same constrained function - a hallmark of robust, complex, and adaptive systems.

Introduction

We observed that during running and walking, the tibia's global orientation is consistent within and across people [1]. We previously predicted that removing arch motion might compromise the tibia's ability to go through its natural range of motion (ROM); however, if specific tibia postures are required for locomotion, we expect the system to compensate. In this study, we wanted to understand how the toes, arch, and ankle contribute to tibial tilt. We used BVR to quantify the contribution of each joint to overall tibia tilt. We applied an arch-supporting orthotic to determine if the joints can adapt to maintain a consistent tibial tilt. This work could elucidate the adaptability of the foot and ankle complex and help predict the system's response to footwear, disease, and treatment.

Methods

Seven healthy participants (3M, 4F/ 23.29 ± 2.76 years) were manually fitted for a set of stiff, arch-supporting orthoses by a pedorthist, and their right foot was CT scanned. Participants were asked to walk and run at self-selected speeds, with and without a stiff arch-supporting orthosis, while BVR images were acquired. The six-degree-of-freedom tibia, talus, calcaneus, navicular, hallux, and first metatarsal motion were tracked using previous methods (Autoscoper, Brown University). We computed sagittal angles and their variability. The angles were defined such that the contributions of the first metatarsal-phalangeal joint (MTPJ), arch, and ankle angles summed to tibia anterior tilt. The orthoses' effect on arch mobility was defined as the change in peak arch angle and arch ROM across conditions. We used mixed linear models, accounting for inter- and intra-subject variability as random effects to assess the effects of orthoses and the relationships between the motions of the observed joints (fixed effects). Post hoc tests determined differences in variability in the motion of the observed structures.

Results and Discussion

Across all participants and conditions, the variability in the tibial push-off angle is significantly lower than MTPJ, arch, and ankle angle at the same time point ($p<0.05$). Although the absolute value of the tibial angle at push-off differs between running and walking, both locomotor modes had relatively low variability (36.1 ± 2.5°) – indicating the global tibia posture is constrained through adjustments of the distal joints. The orthosis restricted arch motion during running, with every participant reducing average ROM while wearing the orthosis. Conversely, while walking, the orthotic did not consistently reduce arch ROM. We identified relationships between arch motion and the motion of the surrounding joints. For example, the more the foot pitched forward about the toe joint, the more arch recoil compensated by tilting the talus posteriorly (Figure 1) ($p<0.002$). During running, each joint had a significant compensatory relationship with the other two ($p<0.05$). While the patterns noted above were consistent across individuals, we did not see a dominant strategy to maintain tibia posture - numerous configurations of the toe, arch, and ankle achieved the same tibial tilt.

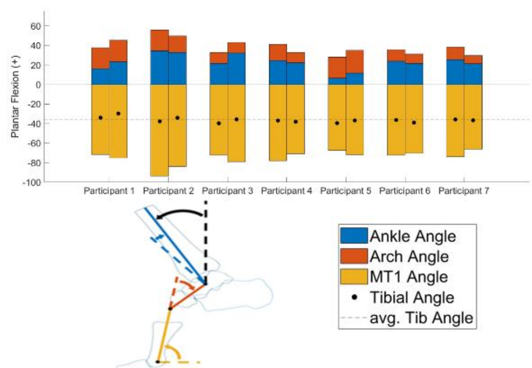

Figure 1: MT1, arch, and ankle contributions to tibial posture at push-off (Left: Minimal shoe, Right: Arch supporting orthotic). All joint angles are sagittal plane angles.

Conclusions

We found evidence that the foot and ankle exhibit degeneracy—different system elements vary in their contributions yet converge to achieve the same overall outcome. Despite the considerable variation in motion at each distal joint and restricted arch motion, the tibia remained consistent across all trials and conditions, suggesting that its posture is precisely tuned. We do not yet understand why the tibial angle appears to be controlled; however, understanding that the distal joints adapt to facilitate tibia posture provides a new framework for understanding and potentially predicting how the system will respond to footwear, clinical interventions, and pathological involvement that limit motion at the toes, foot, or ankle.

Acknowledgments

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References

[1] Welte et al. (2023), *Front. Bioeng. Biotechnol.* ***11**:1155439*