Stiffness and work contributions of the windlass in human feet

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1 Summary

In human feet, toe dorsiflexion induces a midfoot torque that makes the midfoot longitudinal arch more pronounced. This windlass-like mechanism relies on the plantar fascia that spans across the longitudinal arch from heel-to-toe (fig. 1a). The windlass mechanism induces a torque that counters forefoot ground forces that tend to flatten the arch and is considered crucial for human feet to withstand large propulsive forces during push-off [1, 2]. However, there is conflicting evidence on whether the windlass mechanism increases midfoot stiffness [1, 3], and how the elasticity of the plantar fascia affects windlass function during locomotion is also debated [4]. We performed static three point bending tests on cadaveric feet at different toe dorsiflexion angles to characterize the windlass mechanism's influence on midfoot stiffness. We found that the primary effect of engaging the windlass was to left-shift the load-displacement curve of the foot rather than stiffen it. Using a sagittal plane model of the foot, we show how such functionality arises and analyze its implications for locomotion.

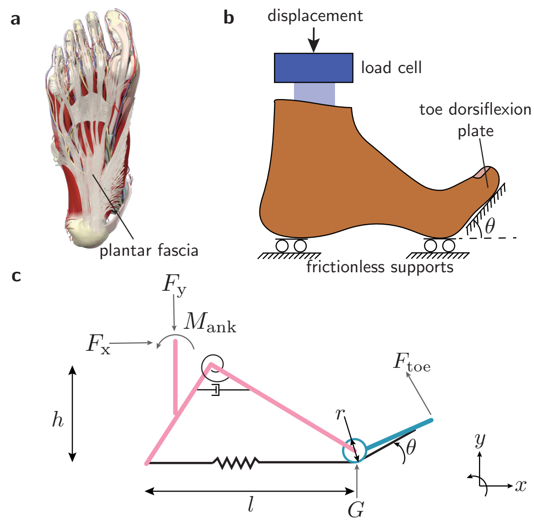

Figure 1: Windlass mechanism of the foot and a simplified model of its function. **a**, Skeleton of the foot showing the plantar fascia and its points of attachment at the calcaneus and the toes. **b**, Sketch of the loading apparatus for cadaveric three-point bending tests. **c**, Free body diagram of the whole foot with forces F_x,F_y and torque M_{ank} acting at the shank, lumped torsional spring and damper at the midfoot, and an extension spring modeling the plantar fascia.

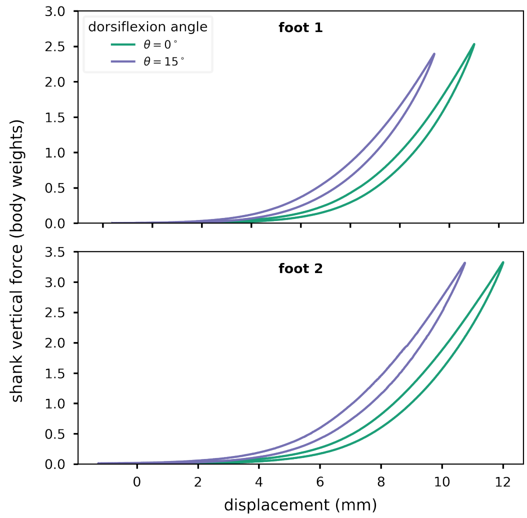

Figure 2: Experimental results. Force vs displacement curves from three point bending experiments on two cadaveric foot specimens.

2 Methods

Two fresh frozen cadaveric feet from 55 and 64 year old female posthumous donors weighing 1023 N (foot 1) and 596 N (foot 2), respectively, were amputated at the mid-tibia and loaded in a materials testing machine (Instron) with the proximal tibia potted in resin (Bondo, 3M) (fig. 1b). The forefoot rested on a lubricated flat surface in neutral posture and the heel rested on a lubricated antero-posterior slider. These boundary conditions, widely used in foot three-point bending tests, approximate those experienced by the foot during push-off [5, 6]. The tibia was moved downward at 1 mm/s until the load reached around 3× bodyweight. The response settled into a steady state within 10-15 cycles. A ground-mounted constraint set the toes at 0° and 15° of dorsiflexion to engage the windlass. The load and displacement at the transected tibia were recorded and analyzed.

3 Results and discussion

3.1 Cadaveric load testing experiments

The three point bending tests show that the effect of toe dorsiflexion is a horizontal shift in the load-displacement curve of the foot without much change in the slope or shape of the curve (fig. 2). Thus the windlass has little effect

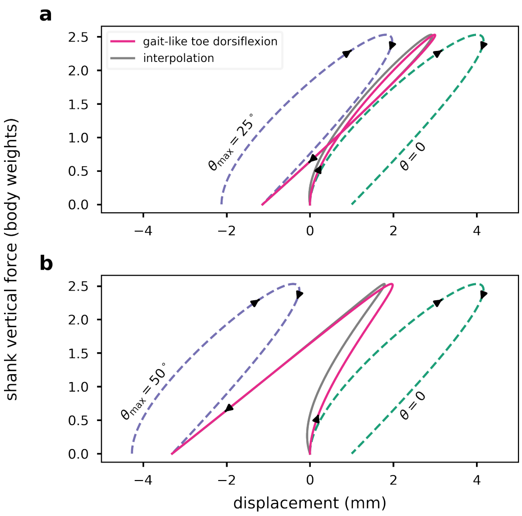

Figure 3: Modeling results. **a** Force vs displacement curves predicted by the windlass model under cyclic loading and gait-like variation in toe angle, and the shifted curves corresponding to zero and maximum toe dorsiflexion. **b** Curves for the same parameters but with a larger maximum toe dorsiflexion. Arrows show direction of loading.

on stiffness but alters the neutral geometry of the foot. A mechanical interpretation of this effect is that of an active spring whose free length can be modulated.

3.2 Mathematical model

The goal of the model is to find a relationship between the vertical shank force F_y, the midfoot height h, and the toe dorsiflexion angle θ. We assume a linear elastic spring for the plantar fascia and a hinged connection between rigid rear and forefoot segments with a linear lumped-parameter torsional spring and damper that model the sagittal-plane viscoelasticity of the midfoot (fig. 1c). The plantar fascia connects the heel to the toe and has a moment arm r about the ball of the foot. When the forefoot pushes on the ground and the heel is lifted up, the foot experiences ankle forces F_x and F_y and torque M_{ank}, and ground reaction forces G and F_{toe} at the ball of the foot and toes, respectively (fig. 1c). With the foot in equilibrium, static torque balance about the midfoot relates the net external load on the foot to midfoot moment and tension in the plantar fascia. The kinematic relationship between plantar fascia length l, and the midfoot and toe dorsiflexion angles gives rise to another governing equation. These kinetic, kinematic, and spring constitutive equations yield a single equation relating F_y, h, and θ. To approximate *in vivo* loading observed during locomotion [7] we use these governing equations to solve for midfoot height due to a cyclic load on the shank F_y at (i) different constant values of θ, and (ii) continuously varying toe dorsiflexion observed during locomotion. Because the locomotion cycle is dynamic, we additionally include viscous damping.

Varying engagement of the windlass due to changing toe dorsiflexion during a single stance cycle results in more positive work output by the foot compared to a fixed toe angle (pink versus either dashed loop in fig. 3). Furthermore, features found in experimental data such as self intersections emerge when range of toe dorsiflexion is small ($\theta_{\text{max}} = 25°$), and net positive work is done for larges ranges ($\theta_{\text{max}} = 50°$).

Dorsiflexing the toes induces an increase in the unloaded midfoot height Δh, which we capture by shifting the zero-dorsiflexion load-displacement curve by Δh along the abscissa to obtain the maximum dorsiflexion curves (green and purple dashed curves in fig. 3). Linear interpolation between the two shifted curves, with the actual toe angle as the interpolating variable accurately captures the true load-displacement curve in this model (gray curves in fig. 3).

4 Conclusions

The predictions of our model are consistent with measured *in vivo* foot load-displacement curves during locomotion [7]. Our results suggest that the effect of the windlass is to change the neutral geometry of the foot, rather than its stiffness. When the foot is under load, a change in its neutral geometry requires net work to be done on the foot. This additional work is visualized as an increase in the net area under the load displacement curve of the foot (fig. 3). Since the ground cannot perform work on the foot, this work must come from more proximal joints such as the ankle and the knee. Thus, we hypothesize that the *in vivo* role of the windlass is to extract additional work from proximal leg joints, which can then contribute to propulsion. What benefits there may be to having net positive work at ground contact remains to be explained. Finally, the accuracy of the linear interpolation of the shifted load-displacement curved provides a means for future studies to test the hypothesized *in vivo* windlass function. Foot load-displacement curves measured in standing or sitting subjects can be used to predict the load-displacement curves during locomotion.

References

[1] JH Hicks. The mechanics of the foot: II. The plantar aponeurosis and the arch. *Journal of Anatomy*, 88(Pt 1):25, 1954.

[2] Nicholas B Holowka and Daniel E Lieberman. Rethinking the evolution of the human foot: insights from experimental research. *Journal of Experimental Biology*, 221(17):jeb174425, 2018.

[3] Lauren Welte, Luke A Kelly, Glen A Lichtwark, and Michael J Rainbow. Influence of the windlass mechanism on arch-spring mechanics during dynamic foot arch deformation. *Journal of the Royal Society Interface*, 15(145):20180270, 2018.

[4] Lauren Welte, Luke A Kelly, Sarah E Kessler, Daniel E Lieberman, Susan E D'Andrea, Glen A Lichtwark, and Michael J Rainbow. The extensibility of the plantar fascia influences the windlass mechanism during human running. *Proceedings of the Royal Society B*, 288(1943):20202095, 2021.

[5] R. F. Ker, M. B. Bennett, S. R. Bibby, R. C. Kester, and R. McN. Alexander. The spring in the arch of the human foot. *Nature*, 325:147–149, 1987.

[6] Madhusudhan Venkadesan, Ali Yawar, Carolyn M Eng, Marcelo A Dias, Dhiraj K Singh, Steven M Tommasini, Andrew H Haims, Mahesh M Bandi, and Shreyas Mandre. Stiffness of the human foot and evolution of the transverse arch. *Nature*, 579(7797):97–100, 2020.

[7] Nicholas B Holowka, Alexander Richards, Benjamin E Sibson, and Daniel E Lieberman. The human foot functions like a spring of adjustable stiffness during running. *Journal of Experimental Biology*, 224(1), 2021.