Contribution of the plantar aponeurosis to locomotion efficiency in bipedal walking and running

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Summary

This study aimed to evaluate the mechanical contribution of the plantar aponeurosis (PA) during walking and running. Using a detailed foot model and a motion analysis system, we quantified the PA power and energy released during the stance phase in six healthy adults. The peak power was higher in running, but the total energy released by the PA was comparable between the walking and running. Furthermore, the relative contribution of PA energy to overall metabolic energy expenditure per distance was significantly greater during walking compared to running. These findings suggest that the PA plays a relatively larger role in reducing energy consumption during walking, challenging the prevailing view that the PA primarily evolved to enhance running efficiency.

Introduction

The human PA is an elastic band that spans the longitudinal arch of the foot, contributing to locomotion efficiency by storing and releasing elastic energy. It is traditionally believed that the PA primarily enhances running economy by reducing muscular effort and metabolic cost. However, the extent of its contribution to walking and running has not been quantitatively evaluated. This study investigated the role of the PA in human locomotion by comparing its mechanical contribution during walking and running.

Methods

Six healthy adult males participated in this experiment. To quantify the dynamics of the PA during walking and running, we used a seven-segment foot model incorporating anatomically detailed PA morphology [1]. In this foot model, the PA was modeled as a broom-shaped bundle of five tension-only linear springs connecting the origin and insertions via intermediate points (PA1–5, from medial to lateral) based on CT data. The participants walked and ran along 12 m walkway at a self-selected speed. The trajectories of 20 infrared-relative markers attached to their right feet were collected using a motion analysis system (Vicon Nexus 2.12.1, Vicon, Oxford, UK) at 200 Hz with 20 infrared cameras. To create the subject-specific model, the PA on the generic foot model was warped onto the motion-captured foot in quiet standing using markers attached to the foot surface. Each of the PA landmarks was represented in an adjacent segment local coordinate system to estimate the PA behaviors during movements. The natural lengths of the PAs were assumed to be 98% of the PA lengths during quiet standing [1]. The spring constants of the PAs were estimated based on the studies reporting that the strain of PA at the time of push off during walking was approximately 0.07 and the force generated by the PA was approximately 1.5 times the body weight [2,3]. Thus, the time change in the PA strain, force, and power can be calculated. The elastic energy released by the PA during the stance phase was calculated as the sum of positive work done by the five PAs from the time of foot contact to foot off. To evaluate the contribution of the PA to the energy consumption in walking and running, the percentage of mechanical energy generated by the PA relative to the net metabolic energy was calculated. The net metabolic energy per distance was estimated from the gait speed based on the experimentally obtained regression equations [4].

Results and Discussion

Mean and standard deviation of the stride length, speed, and net metabolic energy per distance in walking and running were 1.51 ± 0.20 m and 3.19 ± 0.27 m, 1.49 ± 0.17 m/s and 5.58 ± 0.31 m/s, and 3.3 ± 0.05 J/(kg.m) and 3.6 ± 0.1 J/(kg.m), respectively. The peak strain and force were not largely different between walking and running, but the peak contracting velocities was significantly larger for running ($p < 0.01$). Therefore, the peak power was significantly larger for running than walking ($p < 0.01$) (Figure 1A). However, the energy released by the PA (green shaded region) was slightly lower than walking (orange shaded region) because the stance phase was less for running. The net metabolic energy per distance was similar between walking and running, but the stride length was longer for running. Consequently, the %PA contribution to net metabolic energy per distance was significantly greater in walking than running ($p < 0.01$) (Figure 1B). This finding suggests that the PA more contributes to reducing energy consumption for walking than running, challenging the conventional understanding of its role.

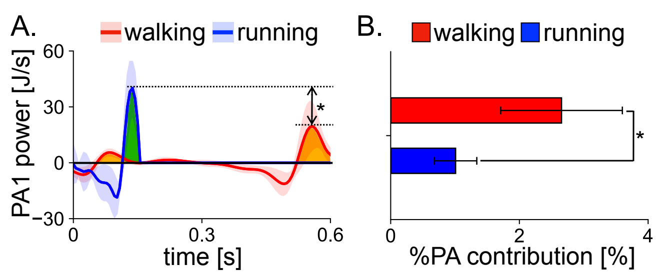

Figure 1: (A) Mean PA power profile;
(B) The %PA contribution to net metabolic energy per distance

Conclusions

The elastic energy released by the PA more contributes to enhancing walking efficiency, indicating that the PA evolved as an adaptation to walking rather than running.

References

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