Biomechanical analysis of human grounded running

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1. Introduction

Human walking is generally defined as a gait in which there is a double-support phase and characterized by utilization of the so-called inverted pendulum where the mutual exchange of potential energy (PE) and kinetic energy (KE) takes place to conserve energy [1]. On the other hand, running is usually defined as a gait in which there is an aerial phase and characterized by the so-called mass-spring mechanism where the PE and KE stored in the form of elastic energy are released for the subsequent step is utilized as an energy saving mechanism [2]. In human locomotion, phase shift from walk to run occurs discontinuously as speed increases [3]. However, in avian and non-human primate locomotion, such transition occurs continuously by adopting grounded running defined as a gait utilizing spring-like running mechanics even though there is a double-support phase [4]. Answering why humans do not adopt grounded running may provide profound implications for understanding the evolution of human bipedalism. In this study, therefore, we biomechanically analyzed walking, running (with aerial phase) and grounded running gaits in humans to clarify the mechanism underlying the absence of grounded running in human locomotion.

2. Methods

Seven participants (mean age 24.6 ± 4.8 years old, mean height 171.0 ± 5.1 cm, and mean weight 65.0 ± 9.1 kg) walked, ran, and grounded ran across two force platforms (EFP-S-1.5KNSA13; Kyowa Dengyo, Japan) set in a 10-m long wooden walkway (Figure 1). They were asked to walk at a self-selected speed (approx. 5 km/h), but to run at a relatively low speed (approx. 10 km/h) due to limitations of space. The speed of grounded running was self-selected at approx. 10 km/h. They were also instructed to land on two foot strike patterns; fore-foot strike and rear-foot strike. This experiment was approved by the Ethics Committee of the Faculty of Science and Technology, Keio University and an informed consent was obtained from the participants.

Three components of the ground reaction force (GRF) vectors generated by both foot were recorded at 1000 Hz by a universal recorder (EDX-100A; Kyowa Dengyo, Japan) and low-pass filtered at 40 Hz. The body kinematics of the participants was simultaneously measured at 200 Hz using 9-camera motion-capture system (MAC3D; Motion Analysis Cooperation, USA). A total of 12 reflexive markers (6 on each side) were attached to: 1) acromion, 2) greater trochanter, 3) lateral epicondyle of the femur, 4) lateral malleolus of the fibula, 5) head of the fifth metatarsal, and 6) calcaneal tuberosity. The motion-captured marker trajectories were low-pass filtered at 7 Hz.

A total of 30 gait cycles (5 trials x 2 foot strike patterns x 3 gaits) were analyzed per participant. Using the obtained data, we calculated cycle duration, stance-phase duration and duty factor. We also computed the Froude number (Fr), defined as $Fr = v^2/gL$, where v is the velocity, g is the gravitational acceleration, and L is the leg length, defined as the mean distance between the hip and the metatarsal head during stance phase.

To estimate leg stiffness during walking, running, and grounded running, the body center-of-mass (COM) position was calculated based on the kinematic data and virtual leg length, defined as the distance between the COM and the position of center-of-pressure (COP) was calculated at the foot-contact midstance, and toe-off (l_{FC}, l_{MS}, and l_{TO}, respectively). The leg stiffness, k, was computed using the vertical GRF at the midstance F_{MS} and the leg lengths as $k = F_{MS} / \Delta l$, where $\Delta l = l_0 - l_{MS}$ and $l_0 = (l_{FC} + l_{TO})/2$. Since the vertical GRF in human walking gait exhibits a characteristic two-peaked profile and the force magnitude gets substantially smaller at the midstance, F_{MS} of walking gait was calculated by averaging the vertical GRFs at the 20 %, 50% and 80% of the stance phase. To facilitate comparison, the dimensionless leg stiffness k' was calculated as $k' = k\, l_0 / mg$.

To quantify the percentage of energy recovery via the inverted pendulum mechanism during walking, running and grounded running, %Recovery was calculated as

$$\%Recovery = \frac{\Delta PE + \Delta KE - \Delta TME}{\Delta PE + \Delta KE} \tag{1}$$

where ΔPE, ΔKE and ΔTME are the increments of PE, KE and TME (total external mechanical energy; = PE + KE) of the body COM over one gait cycle [1]. The KE was calculated by differentiating the displacement profile of the COM.
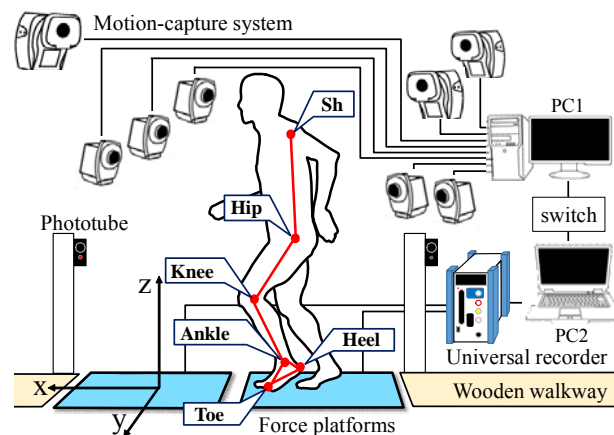

Figure 1. Experimental setup

3. Results

Figure 2 compares the mean vertical GRF profiles of walking, grounded running and running gaits with fore- and rear-foot strikes. The vertical GRF profiles of walking and running gaits showed double- and single-peaked profiles, respectively as demonstrated previously. The vertical GRF of grounded running showed a single-peaked profile with a peak in early stance phase, and the force is much lower than that of running. The rear-foot strike caused large impact GRF in all gait patterns, but such impact force was absent in rear-foot strike gaits, but no clear differences were observed in the general force profiles between the two foot-strike patterns.

The duty factor and %Recovery were plotted against Fr. The Fr of grounded running was confirmed to be much larger than that of walking even though the duty factor was > 0.5. The comparison of the %Recovery demonstrated that the value was much lower in grounded running than in running, indicating that grounded running utilizes running mechanics even though no aerial phase was observed.

Figure 3 shows the comparison of the dimensionless leg stiffness among the three different gaits. The leg stiffness was much smaller in human grounded running than in human walking and running. The values were also compared with those of grounded running in Japanese macaques [5] and quails [6]. The leg stiffness values in
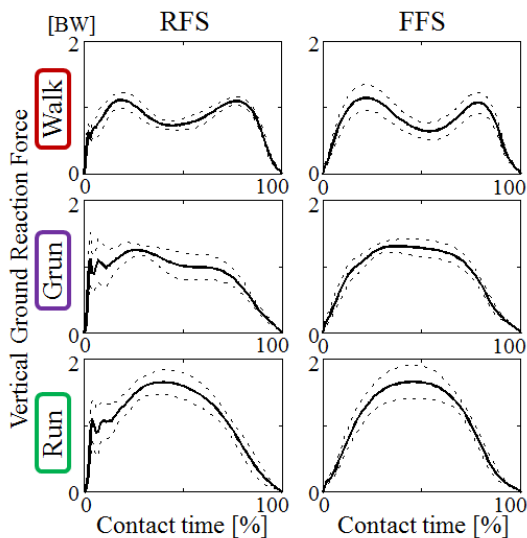

Figure 2. Comparisons of vertical ground reaction force profiles. RFS = rear-foot strike, FFS = fore-foot strike.
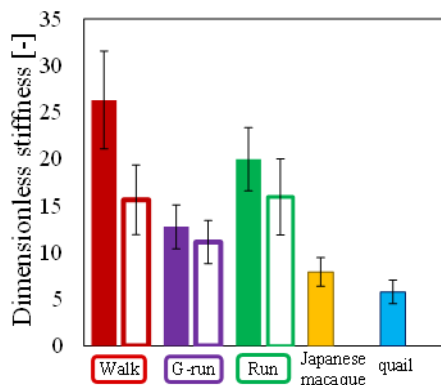

Figure 3. Comparisons of dimensionless stiffness. Solid bar = RFR. Solid bar = FS, open bar = FFS.

human locomotion were generally larger than those of macaques and quails.

4. Discussions

Although humans do not generally adopt grounded running, if they are asked to do so, they were actually be able to generate grounded running, gait utilizing spring-like running mechanics but the duty factor is > 0.5. However, generation of grounded running was actually much more tiring for the participants and hence difficult.

In order to generate grounded running, humans have to make the leg relatively compliant to increase the stance phase duration. However, this is possibly difficult for humans because the human leg is comparatively much stiffer than those of birds and macaques even in running (Figure 3). If the stiff leg tries to utilize the running mechanics, the stance phase duration should be short because the vertical GRF tends to get large if the leg is stiff. Therefore, maintaining long stance phase is difficult when the speed gets higher for humans, and with increasing speed, they discontinuously shift from walking gait with double-support phase to running gait with aerial phase without adopting grounded running.

The human leg is much stiffer than that of birds and macaques possibly because of more extend posture of the leg in humans. Human is a relatively large animal and large animals tends to take a more extended leg posture to decrease muscular forces to sustain weight [7]. Another possible explanation for the adoption of the stiff leg in humans is adaptation to efficient bipedal walking utilizing the inverted pendulum mechanism. In efficient bipedal walking, the body should vault over stiff supporting leg and the trunk is elevated at the midstance phase and lowered in the double-support phase. The structurally stiff leg is an advantage for minimization of metabolic cost of walking gait. Due to increased body mass and adaptation to erect bipedal walking in the course of the human evolution, grounded running is possibly absent in human bipedal locomotion.

References

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