Step length influences compliance in the human walking leg

David V. Lee[1], Michael R. Isaacs[1], Tudor N. Comanescu[1]

(1) University of Nevada Las Vegas
School of Life Sciences
Las Vegas, NV 89154

Presenting Author:
David V. Lee
david.lee@unlv.edu
University of Nevada Las Vegas
School of Life Sciences
4505 S Maryland Pkwy
Box 454004
Las Vegas, NV 89154

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Abstract

Legs are traditionally considered to be compliant during running and rigid during walking. This construct derives from the paradigm of a compliant spring-loaded inverted pendulum (SLIP) mechanism during ‘bouncing’ steps of running and a rigid inverted pendulum mechanism during ‘vaulting’ steps of walking (Cavagna et al., 1977), Nonetheless, kinematic evidence indicates substantial compliance of human legs during both running and walking (e.g., Lee & Farley, 1998) and simulation studies show that both walking and running are achievable with energy conservative spring-loaded legs using a bipedal SLIP (B-SLIP) model (Geyer & Seyfarth, 2006; Rummel et al., 2010; Lipfert et al., 2012). Here we combine experimental step length manipulations in walking humans with a serial actuator-spring model of measured leg dynamics to determine changes in the modeled radial leg spring constant with step length. The optimal radial leg spring constant k_{rad} is that which minimizes the total actuator work expressed as fraction of total radial leg work, termed the actuation ratio (AR) (Lee et al., 2008).

Our serial actuator-spring model of the radial leg showed optimal spring constants k_{rad} ranging from 19.3 kN m^{-1} during running to 52.9 kN m^{-1} during the shortest step length condition, S = 0.6 (Figure 1A). It is notable that this 2.8 fold difference in k_{rad} occurred at the same excursion angle, psi ~ 43.5 degrees, hence, running and walking show distinctly different relationships of radial leg stiffness with excursion angle. Across walking step length conditions from S = 0.6 to S = 1.4, the radial leg spring constant k_{rad} decreased as reciprocal function of excursion angle psi. The equation of this curve fit,

$$k_{rad} = 19.5 + \left(187/\left(\psi - 38\right)\right), \qquad \text{(Equation 1)}$$

reveals a horizontal asymptote at 19.5 kN m^{-1}, which is approximately the radial leg spring constant k_{rad} of running (Figure 1A). This curve also shows a vertical asymptote at an excursion angle of 38 degrees, indicating that human legs become arbitrarily stiff as they approach excursion angles used by rigid-legged passive dynamic walkers (Figure 1A, dashed line; Garcia et al., 1998). Because passive dynamic walkers have infinitely stiff stance legs, the angle of declination (gamma) required to maintain walking is plotted instead of stiffness. Declination angle gamma is a proxy for cost of transport and increases roughly as a cubed function of excursion angle psi, hence, excursion angles of 38 to 40 degrees may represent an upper limit for passive dynamic walking and a lower limit for compliant-legged human walking.

According to the serial actuator-spring model, the radial leg spring stores and returns only ~20% of the mechanical work done by the leg during walking, compared to ~45% during running (Figure 1B). Human legs achieve walking at all but the shortest step lengths using a relatively modest 25-50% increase in radial spring constant, which does not support a qualitative change from a compliant mechanism to a rigid inverted pendulum mechanism at the step lengths and speeds typically used by human walkers. When using unnaturally short step lengths, however, humans show a confluence with rigid-legged passive dynamic walking machines in terms of both leg stiffness and excursion angle.

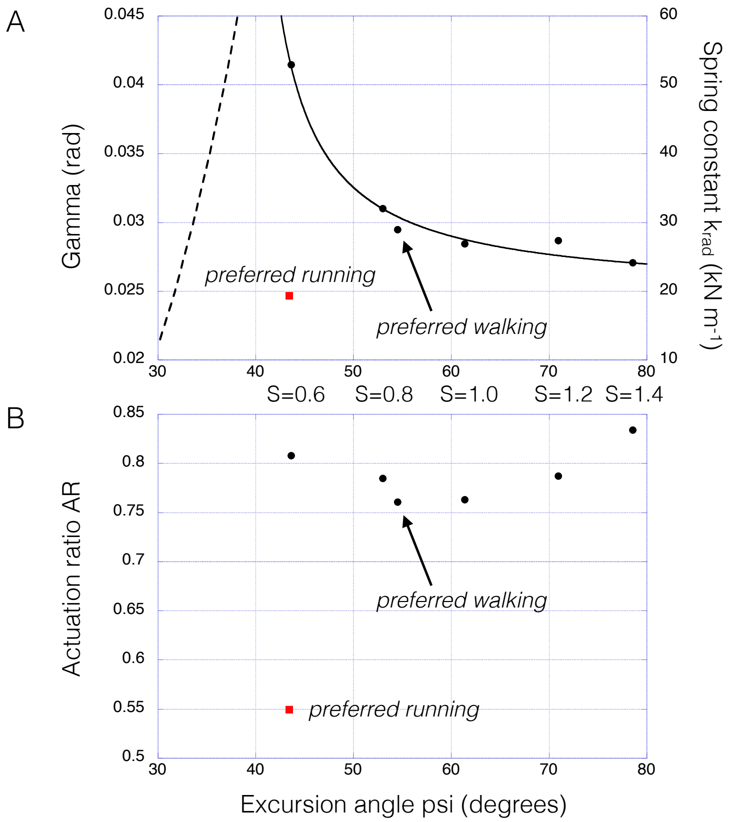

Figure 1. A) Gamma, radial leg spring constant k_{rad}, and B) actuation ration AR as functions of excursion angle psi. Walking data are black circles and running is a red square. The solid black curve fitted to k_{rad} for walking is a reciprocal function (Equation 1) and the dashed line is taken from the long-period solution for the simplest passive dynamic walker of Garcia et al. (1998).

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