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Leg stiffness and joint stiffness while running to and jumping over an obstacle

G. Mauroy, B. Schepens, P.A. Willems*

Laboratoire de physiologie et biomécanique de la locomotion, Institute of NeuroScience, Université catholique de Louvain, Place Pierre de Coubertin 1, B-1348 Louvain-la-Neuve, Belgium

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ABSTRACT

During running, muscles of the lower limb act like a linear spring bouncing on the ground. When approaching an obstacle, the overall stiffness of this leg-spring system (k_{leg}) is modified during the two steps preceding the jump to enhance the movement of the center of mass of the body while leaping the obstacle. The aim of the present study is to understand how k_{leg} is modified during the running steps preceding the jump. Since k_{leg} depends on the joint torsional stiffness and on the leg geometry, we analyzed the changes in these two parameters in eight subjects approaching and leaping a 0.65 m-high barrier at 15 km h^{-1}. Ground reaction force (F) was measured during 5–6 steps preceding the obstacle using force platform and the lower limb movements were recorded by camera. From these data, the net muscular moment (M_j), the angular displacement (θ_j) and the lever arm of F were evaluated at the hip, knee and ankle. At the level of the hip, the M_j–θ_j relation shows that muscles are not acting like torsional springs. At the level of the knee and ankle, the M_j–θ_j relation shows that muscles are acting like torsional springs: as compared to steady-state running, the torsional stiffness k_j decreases from ~1/3 two contacts before the obstacle, and increases from ~2/3 during the last contact. These modifications in k_j reflect in changes in the magnitude of F but also to changes in the leg geometry, *i.e.* in the lever arms of F.

1. Introduction

During running, the muscles–tendons units of the lower limb act like a linear spring storing and releasing elastic energy during contact (Alexander, 1992; Blickhan, 1989; Cavagna et al., 1988; McMahon and Cheng, 1990). When the running conditions are changing, the bouncing mechanism is adapted by adjusting the stiffness of the leg-spring system (k_{leg}) and the angle swept during contact. When the speed of progression increases, k_{leg} does not change but the angle swept increases (Farley et al., 1993; He et al., 1991; Morin et al., 2005). If at a given speed the step frequency is increased, k_{leg} increases and the angle swept decreases (Farley and Gonzalez, 1996); k_{leg} is also adapted when subjects are running on an uneven ground (Seyfarth et al., 2002; Grimmer et al., 2008) or when the softness of the surface is modified (Ferris et al., 1999, 1998).

Mauroy et al. (2012) have shown that when approaching an obstacle, k_{leg} and the angle swept are adjusted during the last two contacts before the jump. Two contacts before the obstacle, k_{leg} decreases whereas the angle swept increases slightly, and the *COM* is lowered and accelerated forwards. Then, during the last contact before the obstacle, k_{leg} increases whereas the angle swept decreases, and the *COM* is raised and accelerated upwards, while its forward velocity decreases.

During running and hopping on place, the lower limb can be assimilated to a multi-jointed system composed of 4 segments – foot, shank, thigh, head-arms-trunk – and 3 torsional springs – ankle, knee, hip (Fig. 1). The overall leg-spring stiffness, k_{leg}, depends (1) on the torsional stiffness, k_j, of the joints and (2) on the geometry of the leg at touchdown (Farley et al., 1998; Farley and Morgenroth, 1999). Torsional stiffness of a joint is defined as the slope of the relation between the net muscular moment and the angular displacement at that joint (Stefanyshyn and Nigg, 1998); k_j determines how much the joint angle changes in response to a given external moment. It depends on muscle activation, reflexes and joint angle (Agarwal and Gottlieb, 1977; Gottlieb and Agarwal, 1978; Hunter and Kearney, 1982; Nielsen et al., 1994; Sinkjaer et al., 1988; Weiss et al., 1988; Weiss et al., 1986a,b). If the lower limb joints are stiffer, they undergo smaller angular displacements during contact, resulting in less leg compression and higher leg-stiffness.

A second factor influencing k_{leg} is the *touchdown leg geometry* (Farley et al., 1998; Farley and Morgenroth, 1999), *i.e.* the position of the joints relative to the ground force vector when landing. For a given ground reaction force and a given k_j, if the joints are more flexed during contact, the lever arms and thus the net external

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* Corresponding author. Tel.: +32 10 47 44 32; fax: +32 10 47 31 06.
E-mail address: patrick.willems@uclouvain.be (P.A. Willems).

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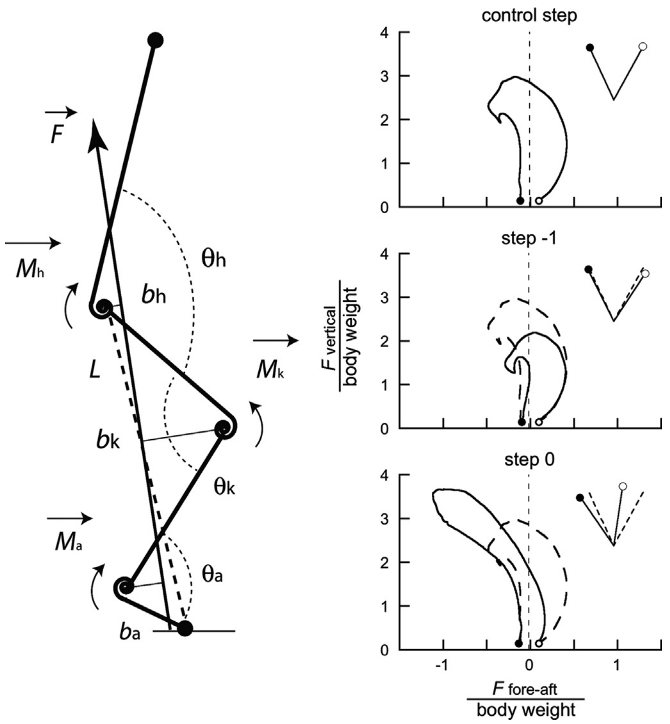

Fig. 1. Left: model used to evaluate the torsional stiffness at the lower limb joints during contact of steps preceding the jump over a 0.65 m-high barrier while approaching at ~15 km h^{-1} Right: magnitude and direction of the ground reaction force (F) during contact of *control steps*, *step*-1 and *step* 0. In the left panel, F is the ground reaction force; L is the distance between the great trochanter and the head of the fifth metatarsal bone; θ_h, θ_k and θ_a are the angular displacement at the hip, knee and ankle; b_h, b_k and b_a are the lever arms of the ground reaction force F (*i.e.* the distance between F and the hip, knee and ankle joints) and M_h, M_k and M_a are the net muscular moment at the hip, knee and ankle joints, computed by the inverse dynamic method. The curved arrows represent the direction in which the joint rotates under the action of the extensor (plantar-flexor) muscles. In the right panels, the vertical and fore-aft components of F are normalized as a function of body weight. Note that the fore-aft scale is two times greater than the vertical. During contact, the point of application of F moves on the average of 0.26 ± 0.02 m (mean ± SD, n=96), *i.e.* from the back to the front of the foot. Each curve is the average of curves obtained on all trials across subjects: *step* 0 correspond to the contact phase of the impulse before the barrier, *step*-1 to the contact before *step 0* and *control step* to the steps recorded in steady-state running. The filled and open circles correspond to touchdown and takeoff, respectively. The interrupted curves in the middle and bottom panels are replications of the average curve of the *control steps*. The inset in the panels represents the average orientation of the leg at touchdown and takeoff.

moments are greater. In turn, the angular displacement of the joint and thus the compression of the overall leg-spring are increased. In such a situation, k_{leg} is reduced. This statement is confirmed by the results of Greene and McMahon (1979): bouncing on a compliant board with greater knee flexion leads to lower the leg stiffness. Similarly, when humans run with exaggerated knee flexion, k_{leg} is lower than during normal running (McMahon et al., 1987); and when humans land from a jump, k_{leg} during landing decreases as the knee flexion at touchdown increases (Devita and Skelly, 1992).

The goal of this study is to understand the mechanism by which k_{leg} is regulated when approaching and crossing an obstacle. Is k_{leg} modified during *step*-1 and *step* 0 because of a change in the joint torsional stiffness at the ankle, the knee and/or at the hip? What is the role of each of the joints in the modulation of k_{leg} when approaching an obstacle and which joint is developing the additional power necessary to cross the obstacle? Furthermore, at the approach of the obstacle, the general orientation of the leg-spring system (*i.e.* the angle between a line joining the foot and the hip and the vertical) is modified: at takeoff of *step*-1 and at touchdown of *step* 0, the leg-spring is more horizontal than during steady state running, and at takeoff of *step* 0, the leg-spring is more vertical (Mauroy et al., 2012). Is this change in orientation accompanied by a change in the leg geometry at the joints, and how does this change in orientation (if any) modify k_{leg}? To answer these questions, we examined the changes in the touchdown leg geometry, in the net muscular moment and power (by the inverse dynamic method) and in the joint torsional stiffness at the level of the hip, knee and ankle during the steps preceding the jump over an obstacle.

2. Methods

In this section, the methods and experimental procedure are only explained shortly. A detailed description the experimental setup and procedure and of the data analysis is proposed as Supplementary material online.

2.1. Subjects and experimental set-up and procedure

Experiments were realized on eight young male recreational runners. Written informed consent was obtained. Experiments were performed according to the Declaration of Helsinki and approved by the local ethics committee.

Subjects ran at 15 km h^{-1}, jumped over a 0.65 m-high barrier and continued to move at the same pace. Ground reaction forces were recorded using a 13 m-long force platform (Genin et al., 2010). A barrier was mounted 3 m before the end of the force-platform.

Two pairs of photocells placed at each end of the plates on the level of the neck measured the average running velocity. Traces were analyzed if the average velocity of the first step(s) before the barrier ranged between 14.5 and 15.5 km h^{-1}. Steps were numbered as follows: *step* 0 corresponded to the last contact before the obstacle and the following aerial phase over the obstacle, *step*-1 was the step before *step* 0, etc. *Control steps*, *i.e.* runs without any obstacle, were also recorded.

Reflective markers were glued on the skin at the level of the lower limb joints. Their position in the sagittal plane was measured each 5 ms by a high-speed video camera (BASLER A501k). Movements of the supporting leg were recorded during contact (three trials on *step*-1, three on *step* 0, six on *control steps*). Camera and force-plates were triggered by the photocells. Coordinates of the reflectors were measured using a semi-automatic tracking software (Lynxzone, Arsalis).

2.2. Data analysis

Data processing was performed using custom software (LABVIEW 10.0, National Instruments). The leg was assimilated to a simple linear spring with the *COM* located at its upper end. This leg-spring system swept on an arc during the contact and the overall stiffness (k_{leg}) generated by the lower limb muscles was estimated by computer simulation (Mauroy et al., 2012). The kinetic, potential and total energy of the *COM* was computed using the method of Cavagna (1975).

The net muscular moment (M_j), power (P_j) and work (W_j) at the ankle, knee and hip were evaluated in the sagittal plane by an inverse dynamic method (Elftman, 1939). The M_j, P_j, and W_j at each joint were computed on the limb in contact when F was greater than 10% of body weight. The net work (W_{net}) is the difference between the positive and negative work done during the contact at each joint. Throughout the text, the subscript j refers to any lower limb joint, the subscript a refers specifically to the ankle, k to the knee and h to the hip.

The torsional stiffness of each joint (k_j) was determined from the ratio of the change in net muscle moment to joint angular displacement in the sagittal plane ($\Delta M_j/\Delta\theta_j$) between the beginning of the ground contact phase and the instant when the joints were maximally flexed (Farley and Morgenroth, 1999; Kuitunen et al., 2002; Stefanyshyn and Nigg, 1998).

Results were grouped in classes according to the step number (*control step*, *step*-1 and *step* 0). A one-way repeated measures ANOVA (Bonferroni post-hoc) was performed to evaluate the effect of the step number on the variables studied.

3. Results

3.1. Leg-stiffness and joint stiffness during steady-state running

During steady-state running, the leg-spring is bouncing and sweeping forward in a symmetric way. The magnitude of angle between the leg and vertical (θ_L) at touchdown and at takeoff are about equal, the distance between the hip and the fifth metatarsal