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Technical note

The effect of speed on leg stiffness and joint kinetics in human running

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Abstract

The goals of this study were to examine the following hypotheses: (a) there is a difference between the theoretically calculated (McMahon and Cheng, 1990. Journal of Biomechanics 23, 65–78) and the kinematically measured length changes of the spring–mass model and (b) the leg spring stiffness, the ankle spring stiffness and the knee spring stiffness are influenced by running speed. Thirteen athletes took part in this study. Force was measured using a "Kistler" force plate (1000 Hz). Kinematic data were recorded using two high-speed (120 Hz) video cameras. Each athlete completed trials running at five different velocities (approx. 2.5, 3.5, 4.5, 5.5 and 6.5 m/s). Running velocity influences the leg spring stiffness, the effective vertical spring stiffness and the spring stiffness at the knee joint. The spring stiffness at the ankle joint showed no statistical difference ($p < 0.05$) for the five velocities. The theoretically calculated length change of the spring–mass model significantly ($p < 0.05$) overestimated the actual length change. For running velocities up to 6.5 m/s the leg spring stiffness is influenced mostly by changes in stiffness at the knee joint.

Keywords: Running; Spring-mass model; Joint moments; Mechanical power

1. Introduction

In the literature the stiffness of the lower extremities for both humans and animals is often approximated using a spring constant from a spring–mass model (Greene and McMahon, 1979; Blickhan, 1989; McMahon and Cheng, 1990; He et al., 1991; Farley et al., 1993; Farley and González, 1996; Dalleau et al., 1998; Heise and Martin, 1998). In a couple of studies (He et al., 1991; Farley et al., 1993), it was reported that leg spring stiffness is independent of running velocity. Other researchers (Luhtanen and Komi, 1980; Mero and Komi, 1986) report a positive correlation between running velocity and leg spring stiffness.

The leg spring stiffness can be altered by changing the stride frequency (Farley and González, 1996). The running velocity influences the stride frequency (Mero and Komi, 1986) and the maximum ground reaction force (Munro et al., 1987). These findings support the idea that it is possible to alter the leg spring stiffness by altering the running velocity and that the differences between the results found in the literature (Luhtanen and Komi, 1980; Mero and Komi, 1986; He et al., 1991; Farley et al., 1993) could be due to differences in the calculation methods. Luhtanen and Komi (1980) as well as Mero and Komi (1986) used only kinematic data for the calculation of leg spring stiffness. He et al. (1991) and Farley et al. (1993) measured the ground reaction force and calculated theoretically the length change of the spring–mass model. The leg spring stiffness is dependent on the work strategy of the lower extremities. Until now the effect of increasing running velocity on the spring stiffness at the ankle and knee joints has not been reported.

The goals of this study were to examine the following hypotheses: (a) there is a difference between the theoretically calculated (McMahon and Cheng, 1990) and the kinematically measured length changes of the spring–mass model and (b) the leg spring stiffness, the ankle spring stiffness and the knee spring stiffness are influenced by running speed.

2. Methods

Thirteen runners (height: 1.83 ± 0.03 m, mass: 80.68 ± 4.99 kg) participated in this study. They were instructed to run over a "Kistler" force plate at five different given velocities (approx. 2.5, 3.5, 4.5, 5.5 and 6.5 m/s). Running velocities were controlled during the

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trials using two photocells (distance 5.13 m). The photocells were positioned before and after the force plate. Force was measured at 1000 Hz. The athletes were also filmed using two high-speed video cameras (120 Hz). To improve the quality of the video analysis reflective markers (radius 10 mm) were used to mark joint positions. The markers were placed on the lateral surfaces of the joints. The kinematic data were smoothed using a fourth-order low-pass Butterworth filter with a cut-off frequency of 8 Hz. Light-emitting diode (LEDs) were used to synchronise the two video cameras. The same signal (+ 5 V) was used for the force data trigger. The human body was represented using a 15 segment, two-dimensional human body model (see Arampatzis and Brüggemann, 1998). The masses of the segments were taken from the regression equation from Clauser et al. (1969) and the inertial moments were calculated from Hanavan's model (Hanavan, 1964).

The leg spring stiffness (K_{leg}) and the effective vertical spring stiffness (K_{vert}) were calculated as follows:

$$K_{leg} = \frac{F_{z\,max}}{\Delta L}, \quad K_{vert} = \frac{F_{z\,max}}{\Delta y},$$

where $F_{z\,max}$ is the maximum vertical ground reaction force, and ΔL the length change of the spring–mass model, and Δy the vertical length change of the athlete's centre of mass.

The length change of the spring–mass model (ΔL) was first calculated using the change in the position of the centre of mass (CM) in relation to the point of force application and then by using the following formula presented by McMahon and Cheng (1990).

$$\Delta L = \Delta y + L_0(1 - \cos\theta),$$

where L_0 is the athletes standing CM position, θ is the angle of the spring–mass model with respect to the vertical axis at the beginning of the support phase ($\theta = \sin^{-1}(ut_c/2L_0)$), u the horizontal CM velocity, and t_c the ground contact time.

The stiffness at the joints of the lower extremities was estimated using two rotational springs at the ankle and knee joints. The spring stiffness was calculated as follows:

$$K_{Ankle} = \frac{2W^{-}_{Ankle}}{\Delta\theta_{A^2}}, \quad K_{Knee} = \frac{2W^{-}_{Knee}}{\Delta\theta_{K^2}},$$

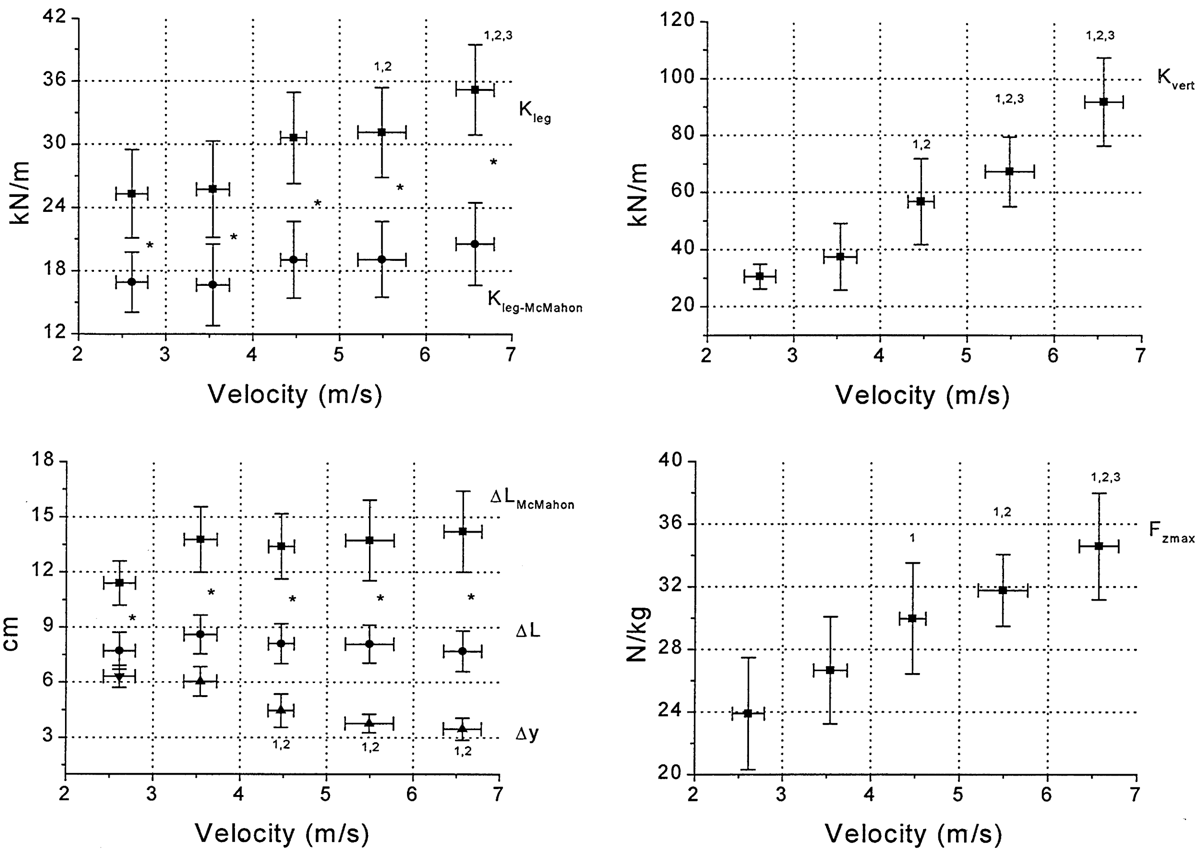

Fig. 1. Leg spring stiffness (K_{leg}, $K_{leg\text{-}McMahon}$), effective vertical spring stiffness (K_{vert}), length change of the spring–mass model (ΔL, $\Delta L_{McMahon}$), vertical length change of the spring–mass model (Δy) and maximum ground reaction force (F_{zmax}) in relation to running velocity ($n = 13$).

[1,2,3,4]: Statistically significant ($p < 0.05$) difference at various velocities.

*: Statistically significant ($p < 0.05$) difference between K_{leg} und $K_{leg\text{-}McMahon}$ and between ΔL and $\Delta L_{McMahon}$.

Table 1
Maximum joint moment values and mechanical power at the ankle and knee joints at the five running velocities ($n = 13$)

Parameter	Velocity 1 (2.61 ± 0.18)	Velocity 2 (3.55 ± 0.19)	Velocity 3 (4.47 ± 0.15)	Velocity 4 (5.60 ± 0.41)	Velocity 5 (6.59 ± 0.24)
$M_{\text{Ankle-max}}$ (N m/kg)	2.45 (0.46)	2.79 (0.42)	2.99 (0.50)	3.18 (0.46)[1]	3.43 (0.49)[1,2]
$M_{\text{Knee-max}}$ (N m/kg)	– 1.97 (0.45)	– 2.57 (0.46)[1]	2.64 (0.53)[1]	– 2.74 (0.47)[1]	– 2.98 (0.37)[1,2]
$P_{\text{Ankle-min}}$ (W/kg)	– 3.26 (1.79)	– 4.58 (2.03)	– 5.87 (3.67)	– 8.66 (4.03)[1]	– 12.24 (4.96)[1,2,3]
$P_{\text{Ankle-max}}$ (W/kg)	6.59 (2.80)	10.15 (3.07)	12.35 (3.07)[1]	16.39 (4.82)[1,2]	20.97 (4.91)[1,2,3]
$P_{\text{Knee-min}}$ (W/kg)	– 7.71 (2.46)	– 11.97 (3.75)	– 13.17 (4.32)[1]	– 14.16 (5.10)[1]	– 16.81 (4.66)[1]
$P_{\text{Knee-max}}$ (W/kg)	4.29 (1.78)	5.61 (1.78)	7.20 (2.53)	10.05 (3.18)[1,2]	10.76 (3.60)[1,2,3]

[1,2,3,4]: Statistically significant ($p < 0.05$) difference at various velocities.

where W^{-}_{Ankle} is the negative mechanical work in the ankle joint, W^{-}_{Knee} the negative mechanical work in the knee joint, $\Delta\theta_{\text{A}}$ the change in the ankle angle, and $\Delta\theta_{\text{K}}$ the change in the knee angle.

The joint moments and the mechanical power of the joint moments were calculated as follows (see Hof, 1992):

$$M_j = -M_{\text{F}} - (r_j \times F) - \sum_{i=1}^{n} (r_{ji} \times G_i) + \sum_{i=1}^{n} (r_{ji} \times \dot{p}_i) + \sum_{i=1}^{n} \dot{H}_i,$$

where M_j is the jth joint moment, M_{F} the frictional moment, F the ground reaction force, r_j the position vector between jth joint and the point of force application, r_{ji} the position vector between jth joint and centre of mass of ith segment, G_i the force of gravity on the ith segment, $\dot{p}_i$ the first derivative of the ith segment impulse, $\dot{H}_i$ the first derivative of the ith segment angular momentum, and n the number of segments.

$$P_j = Mj \cdot \omega_j,$$

where P_j is the mechanical power of the jth joint moment, and ω_j the angular velocity of the jth joint.

The differences between the chosen parameters (leg spring stiffness, length change of the spring–mass model, joint moments, mechanical power, ankle and knee spring stiffness) over the five velocities were determined using repeated measurements of one-way analysis of variance (ANOVA, post-hoc test Tukey). The level of significance was set at $p < 0.05$.

3. Results

Clear differences in leg spring stiffness were seen for all velocities between the different calculation methods (Fig. 1). The leg spring stiffness calculated using the formula from McMahon and Cheng (1990) was significantly lower than the actual value. Running velocity influences the leg spring stiffness, the effective vertical spring stiffness and the maximum vertical ground reaction force (Fig. 1). The leg spring stiffness calculated using the method from McMahon and Cheng (1990) shows no significant difference for the five given velocities (Fig. 1). The maximum moment and mechanical power values at the ankle and knee joints were influenced by running velocity (Table 1, Fig. 2). Running velocity also influences the spring stiffness at the knee joint and the change in the angle at the knee joint (Fig. 3). The spring stiffness at the ankle joint showed no significant difference for the five given velocities (Fig. 3).

4. Discussion

The leg spring stiffness is influenced by the running velocity. The leg spring stiffness values are between 25.29 ± 4.20 and 35.21 ± 4.30 kN/m at velocities from 2.61 ± 0.18 to 6.59 ± 0.24 m/s. These values are higher than those published in the literature to date (He et al., 1991; Farley and González, 1996; Dalleau et al., 1998; Heise and Martin, 1998). The difference in leg spring stiffness values is explainable by the different calculation methods used for determining the change in length of the spring–mass model. The theoretical calculations from McMahon and Cheng (1990) overestimate the actual distance change between the athletes CM and the force vectors point of origin. From this it is clear why no differences in leg stiffness with increasing velocity was seen (He et al., 1991; Farley et al., 1993). When using the McMahon and Cheng (1990) method in this study there was also no statistical significant difference among the different velocities. The effective vertical spring stiffness values in this study were similar to those reported by other studies (He et al., 1991; Farley and González, 1996; Heise and Martin, 1998).

Running velocity influences the joint moments and the mechanical power. Differences with respect to other studies (Devita and Skelly, 1990; Simpson and Bates, 1990; Derrick et al., 1998) can be seen in the knee joint moment. These studies reported an extension moment at the knee joint during the entire support phase. In the present study all athletes had a flexion moment at the knee at the

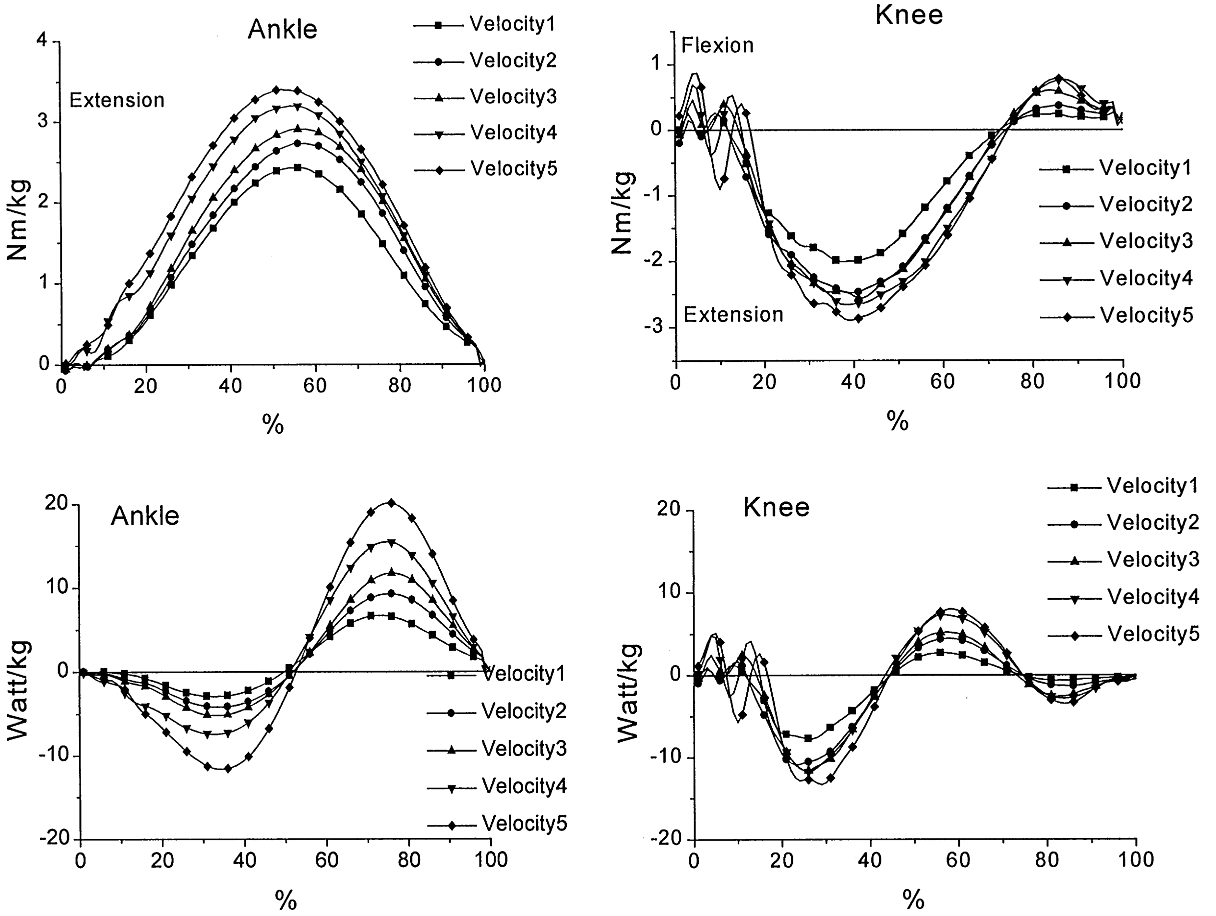

Fig. 2. Joint moment (upper diagram) and mechanical power (lower diagram) for the five running velocities ($n = 13$).

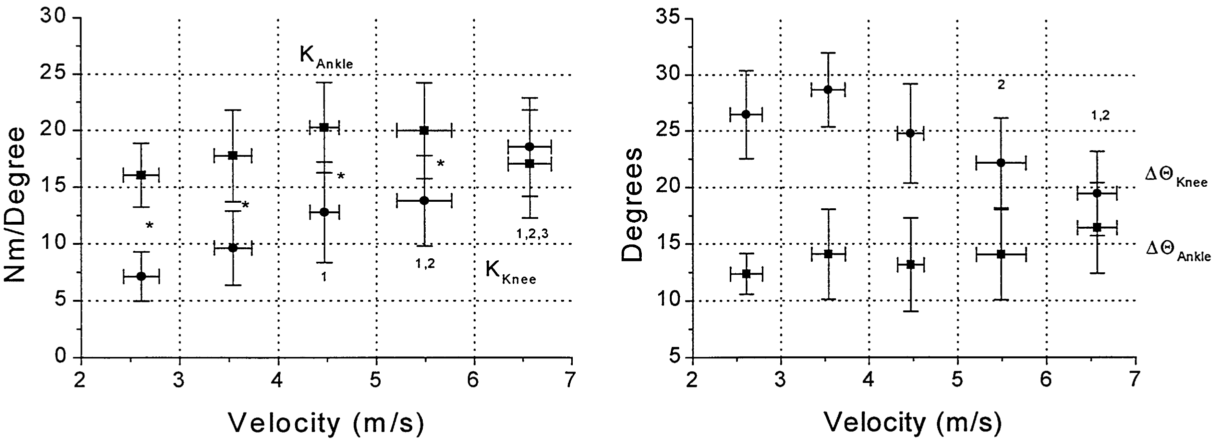

Fig. 3. Spring stiffness in the foot and knee joints (K_{Ankle}, K_{Knee}) and the change in ankle and knee angles ($\Delta\Theta_{Ankle}$, $\Delta\Theta_{Knee}$) with respect to the running velocities ($n = 13$).

[1,2,3,4]: Statistically significant ($p < 0.05$) difference at various velocities.

*: Statistically significant ($p < 0.05$) difference between K_{Ankle} und K_{Knee}.

end of the support phase. Similar flexion moment values at the knee were reported by Buczek and Cavanagh (1990) and Stefanyshyn and Nigg (1998).

With increasing velocity larger changes were observed in the spring stiffness at the knee joint than at the ankle joint. These findings indicate that the increase seen in leg spring stiffness is caused for the most part by the increase in knee spring stiffness. It appears that with increasing velocity the athletes alter the stiffness at the knee joint first. Derrick et al. (1998) and Stefanyshyn and Nigg

(1997) also reported greater changes at the knee joint. Derrick et al. (1998) reported that the stride length has a greater influence on the energy absorption at the knee joint in comparison to the ankle joint. Stefanyshyn and Nigg (1997) found greater differences in both energy absorption and energy production at the knee joint between running and sprinting. The leg spring stiffness and the effective vertical spring stiffness also affect running efficiency (Dalleau et al., 1998; Heise and Martin, 1998). It appears that the knee spring stiffness is important for efficient running and should be studied in the future.

In conclusion it is clear that running velocity influences the leg spring stiffness. The theoretical calculated length change of the spring–mass model (McMahon and Cheng, 1990) overestimates the actual length change. Up to a running velocity of 6.5 m/s the leg spring stiffness is mainly influenced by the change in knee spring stiffness.

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