ADAPTATION OF RUNNING KINEMATICS TO SURFACE AND FOOTWEAR

E.C. Hardin[1], J. Hamill[1], and A.J. van den Bogert[2]
[1]Department of Exercise Science, University of Massachusetts, Amherst MA
[2]Department of Biomedical Engineering, Cleveland Clinic Foundation, Cleveland OH
E-mail: bogert@bme.ri.ccf.org

INTRODUCTION

Runners change their leg stiffness inversely to surface stiffness in order to maintain similar whole body movement on different surfaces (Ferris et al., 1998). It is generally thought that such adaptations mainly involve changes in knee joint angle, e.g. an increased knee flexion would lead to decreased leg stiffness (Frederick 1986; McMahon et al., 1987). Direct evidence of kinematic changes is scarce, however. This may be due to the fact that the changes are small (McNair and Marshall, 1994), though potentially important.

Running impact occurs at small flexion angles. The leg stiffness is therefore initially large and may be sensitive to changes in knee angle (McMahon et al., 1987). The purpose of our work was, then, to experimentally determine changes in sagittal plane kinematics during the stance phase of running as a function of shoe and surface and to interpret these changes as to their effect on overall leg stiffness.

METHODS

Twelve male subjects ran at a speed of 3.4 m s^{-1} on a treadmill with adjustable surface compliance. Six different combinations of surface and shoe stiffness were created and all measurements were done when the subjects were at metabolic steady state. Sagittal plane kinematic data were collected at 200 Hz with reflective markers placed on the humeral head, greater trochanter, femoral condyle, lateral malleolus, calcaneus and fifth metatarsal. Marker paths were digitally filtered at 12 Hz and hip, knee and ankle joint angles were calculated. Mean values were calculated from 10 randomly selected stance periods for joint angle at contact, maximum joint angle and peak joint velocity. A two-way repeated-measures ANOVA was used to test for surface and midsole differences ($p<0.05$).

A two-segment model (McMahon et al., 1987) was used to establish theoretical force-length relationships of the lower extremity. If the segments have length L, the knee joint has rotational stiffness k, and heel strike occurs at knee angle φ_0, the force F depends on the joint angle φ as follows:

$$F = \frac{k(\varphi - \varphi_0)}{L \sin \frac{\varphi}{2}}$$

Length change as a function of joint angle is:

$$\Delta = 2L\left(\cos\frac{\varphi_0}{2} - \cos\frac{\varphi}{2}\right),$$

resulting in nonlinear spring properties for the leg as shown in Fig. 1.

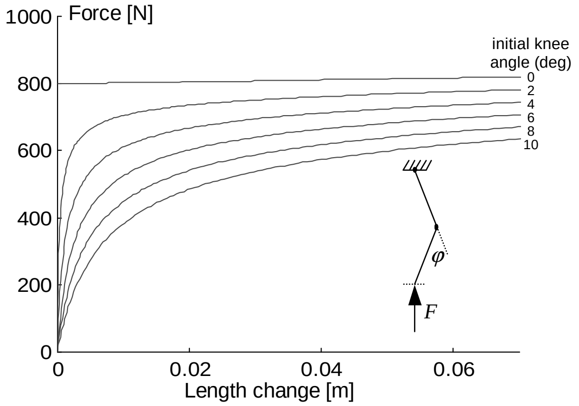

Figure 1: Force-length curves for the leg model with k=200 Nm/rad and L=0.5 m.

RESULTS AND DISCUSSION

Experimental results are presented in Table 1. As surface stiffness increased, knee flexion at touchdown decreased ($p<0.05$), peak knee angle remained the same ($p>0.05$) and peak joint velocity of the hip, knee and ankle increased ($p<0.05$). Effects of midsole hardness were smaller.

"Increased knee flexion" has been proposed as a mechanism for adaptation to running on hard surfaces (Frederick, 1986; McMahon et al., 1987; Ferris et al., 1998) but it is unclear whether this term refers to flexion angle at impact, at midstance, or a larger change in angle between these two events. Our results clearly show that, for this range of surface stiffness, runners impacted with more extended knee on a harder surface while the peak flexion angle did not change. Consequently, knee flexion velocity increased with increasing surface stiffness. These results are consistent only with the third interpretation of "increased flexion."

The two-segment model qualitatively shows the effect of initial knee angle. When impacting with a more extended knee the short-range stiffness (slope of the force-length curve) quickly decreases, whereas an initially more flexed knee leads to a *greater* short-range stiffness at the same stage of leg deformation. This “buckling” behavior, when initial flexion angle is small, may regulate the magnitude of impact force. Limitations of the model are assumptions of constant joint stiffness and muscle activation. Both rise during knee flexion and would result in a larger force than predicted. However, the striking effect of geometry remains.

We conclude that runners modify their lower extremity geometry to adapt to surface stiffness. These adaptations may reflect adjustments in leg stiffness. Leg stiffness varies rapidly during impact, thus models with constant stiffness may not provide insight into impact-related questions.

REFERENCES

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McMahon TA et al. (1987) *J Appl Physiol* **62**:2326-2337.

McNair PJ, Marshall RN (1994) *Br J Sports Med* **28**:256-260.

Ferris DP et al. (1998) *Proc R Soc B* **265**:989-994.

Table 1. Mean sagittal kinematic variables during running stance. Significant differences noted by a superscript: a = 100>200>350; b = 100 & 200 >350; c = 100<200<350; d = midsole effect.

	Midsole		40 Shore A			70 Shore A	
	Surface	100 kN·m^{-1}	200 kN·m^{-1}	350 kN·m^{-1}	100 kN·m^{-1}	200 kN·m^{-1}	350 kN·m^{-1}
Touchdown angle (°)	Hip[a]	22.5	20.0	14.7	23.7	20.4	15.5
	Knee[b]	9.8	8.2	4.6	10.9	8.4	4.4
	Ankle	-1.2	-3.2	-1.4	-2.4	-3.8	-2.3
Maximum flexion/ dorsiflexion (°)	Hip[b, d]	26.4	25.8	22.9	27.4	27.1	24.3
	Knee	41.0	41.7	42.3	42.1	42.6	42.5
	Ankle	21.0	19.5	22.0	20.5	19.2	21.0
Maximum flexion velocity (°·s^{-1})	Hip[c, d]	87.9	121.3	154.3	86.1	138.1	169.0
	Knee[c]	446.3	498.1	542.6	444.0	515.1	572.7
	Ankle[c, d]	351.7	394.5	414.2	378.3	415.8	470.1