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Original article

Effect of minimal shoes and slope on vertical and leg stiffness during running

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Abstract

Purpose: This study was designed to characterize and compare the vertical (k_{vert}) and leg (k_{leg}) stiffness measured during running in two different footwear conditions on negative, level, and positive slopes, using kinematic data only.
Methods: Fourteen male recreational runners (age 23.4 ± 4.4 years, height 177.5 ± 5.2 cm, and body mass 69.5 ± 5.3 kg) were tested on 2 separate days within 1 week. At each session, subjects ran seven 5-min trials on a treadmill at 10 km/h, interspersed with 5 min of sitting passive recovery. Each trial was performed on a different slope gradient, ranging from −8% (downhill) to +8% (uphill), assigned in a random order. Furthermore, each subject ran one 5-min trial wearing minimal shoes (MS) and the subsequent trial wearing traditional shoes (TS) in a counter-balanced randomized order ensuring that each slope was ran once in MS and once in TS. Kinematic data were collected using a photocell measuring system and high-speed video camera, with k_{vert} and k_{leg} stiffness being calculated from these data.
Results: Leg compression, contact times, and vertical displacement of the center of mass during running were significantly smaller in MS compared to TS across all slopes. In the two footwear conditions, step frequency significantly increased with a (positive) increase in slope. Kinematic analyses indicated that k_{leg} was greater when running in MS than TS and this between-footwear difference remained similar across slopes. On the contrary, k_{vert} did not change on the basis of footwear, but increased with positive increases in slope.
Conclusion: This study showed that k_{vert} and k_{leg} during running respond differently to change in footwear and/or slope. These two stiffness measures can hence provide a unique insight on the biomechanical adaptations of running under varying conditions and their respective quantification may assist in furthering our understanding of training, performance, and/or injury in this sport.

Keywords: Incline; Minimal shoes; Running; Spring-mass model; Stiffness

1. Introduction

The interest in barefoot and minimalist shoe (MS) running has exploded over the last decade with pretext that it is more natural than running in the modernized traditional shoe (TS). While offering more protection than barefoot, MS footwear has a lighter mass, greater sole flexibility, lower profile, and smaller heel elevation compared to the TS.[1,2] Given that the biomechanics of running in MS differ from TS to a smaller extent than those of barefoot running,[1,3] the shift towards MS in runners is more widespread.

Similar to barefoot, MS running is 1%−3% more efficient than running in TS in terms of energy cost (Cr) on level,[3−6] uphill and downhill terrain.[6] Although shown to result mostly from the lighter shoe mass,[4,5] this 1%−3% reduction in Cr has also been related to changes in running kinematics including decreases in contact times (t_c) and increases in step frequencies (f).[3,5,6] Furthermore, several studies have reported

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higher leg stiffness (k_{leg}) during barefoot than TS running[7–9] that, together with changes in running kinematics and foot strike patterns, may also contribute to lowering the *Cr* in barefoot or MS footwear compared to TS given that higher stiffness suggests greater ability to store and release elastic energy.[10]

Indeed, Kyröläinen and coworkers[11] have proposed that high muscle stiffness at the ankle and knee joints during the braking phase of running offers a suitable precondition for using the stretch-shortening cycle within muscle-tendon units, which enhances the mechanical efficiency, force potentiation and joint angular velocities and power during push-off at a negligible metabolic cost. While some authors have reported a lack of correlation between the leg stiffness and *Cr* values of runners,[12,13] most evidence supports that increased k_{leg} is associated to better running economy,[14,15] at least when running in TS or when comparing TS to barefoot running. Furthermore, the stretch-shortening cycle regulating stiffness does not only assist in decreasing the energetic cost of walking and running,[16] but it also potentiates muscle actions[17] and regulates the mechanical interactions between the body and the environment during the ground contact phase of locomotion.[18]

Although several articles provide insight on the relationship between running economy and lower extremity stiffness parameters − including muscle,[15] tendon,[19] leg,[14] and vertical[13] stiffness − these are moreover based on TS or barefoot than MS running. Even though MS approaches barefoot and offers a lightweight (∼150−180 g per shoe) no motion control alternative to the TS,[2] the MS conventionally has a uniform sole thickness of ∼1 cm that provides a small cushioning effect and shock absorption that are absent during barefoot. Although the sole is much thinner in MS than TS—which is about 2.5−3 cm at the heel and 1.5−2 cm at the forefoot—running in MS is not the same as barefoot and direct inferences of results from barefoot to MS are not fully substantiated. There is a paucity of papers reporting stiffness during running in MS, which would assist in furthering our understanding of training, performance, and injury in this sport.

In reality, a sufficient level of stiffness is required to optimize the utilization of the stretch-shortening cycle[20] and minimize the risk of musculoskeletal injury.[21] More specifically, low leg stiffness has been associated to an increased risk of soft tissue injuries, whereas high leg stiffness to an increased risk of bone-related injuries.[22] Although the appropriate amount of stiffness for runners has not yet been coined and is likely to vary on the basis of running discipline and individual characteristics,[23] quantifying stiffness under various running conditions in healthy individuals might assist in determining normative stiffness levels, understanding how the human body responds to changes in environmental conditions, and identifying maladaptive responses to training or pathological function. Such an understanding of human biomechanics is of interest to runners, coaches, and clinicians when preparing training, competition, injury prevention, and/or rehabilitation programs.

In this last context of uphill and downhill running, changes in slopes are frequent when running outdoors and clearly influence running biomechanics and physiology, including running velocity,[24] stride parameters,[25] the *Cr*,[6] and the stretch-shortening cycle.[27] For instance, increases in slope gradients have been associated to decreases in flight time (t_f) and elastic energy storage with increases in *f* and *Cr*.[6,26] Although there are limits to the assessment of stiffness during slope running (e.g., the assumption of symmetric oscillations of the spring-mass model is not entirely respected), it seems important to investigate if and how stiffness changes with slope, and whether MS modulates these changes in stiffness. Such knowledge might be useful to runners in preventing injuries or promoting specific training adaptations, with individuals selecting situations that are associated with high and/or low stiffness values depending on which present the greatest benefits.

Whereas vertical stiffness (k_{vert}) is suggested to represent the overall body stiffness and defines the relationship between the ground reaction force and the vertical displacement of the center of mass, k_{leg} further represents the stiffness of the lower extremity complex (e.g., foot, ankle, knee, and hip joints) and describes the ratio between the ground reaction force and the deformation in leg length.[27] During locomotion, k_{vert} is always greater than k_{leg} because leg length changes exceed those of the center of mass.[27] Although k_{vert} and k_{leg} are derived from similar mechanical concepts, they are not synonymous and they adapt to changes in running conditions differently,[8,28] which justifies examining both k_{vert} and k_{leg}.

Thus, the main objective of this study was to characterize and compare the k_{vert} and k_{leg} measured during running in MS to TS, using kinematic data only, with the hypothesis that stiffness would be greater in MS than TS in the level condition. A secondary objective was to investigate the effect of slope on these two stiffness measures, with the hypothesis that k_{vert} and k_{leg} would decrease during downhill and increase during uphill running, with stiffness always greater in MS than TS irrespective of slope.

2. Materials and methods

2.1. Subjects

Fourteen healthy male runners (mean ± SD: age 23.4 ± 4.4 years, height 177.5 ± 5.2 cm, body mass 69.5 ± 5.3 kg, maximal aerobic velocity (MAV) 18.0 ± 1.4 km/h) participated in this study voluntarily. All subjects were recreationally trained runners running at least 45 km/week for the 6 months prior to this study. Most of the subjects were habituated to trail running, with 11 subjects reporting being trail exclusive runners (∼100% trail) and the remaining three being mixed runners (∼70% trail and ∼30% road). No subject had previous experience in barefoot or MS running. All subjects were, and had been for the previous 12 months, free from injuries and able to run sub-maximally at 10 km/h on downhill, level, and uphill terrain. Each subject provided verbal and written informed consent before