LEG STIFFNESS DURING JOGGING ON SMALL CURVED PATH

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The aim of this study was to describe the mechanics of curved running using spring-mass model. We hypothesized that 1) the leg spring stiffness in curved running is greater than in straight running, and 2) outside leg stiffness is greater than inside during curved running. Ten male participated in this study. All participants performed 3 types of running. Data were collected by 2 forceplates and a motion capture system. Mechanical parameters of spring-mass model (leg force, leg compression, and leg stiffness) were calculated. The leg forces were smaller for curved running than straight running. The leg compression of curve-outside trial was smallest among trials. The leg stiffness of curve-outside was largest among trials. Therefore, runners would use their outside leg stiffer during curved running.

KEY WORDS: non-linear locomotion, spring-mass model, curved running

INTRODUCTION: Non-linear locomotion is a fundamental movement for human in daily life and sport activities. When compared with a straight running, a curved running shows differences in temporal muscular activities of lower extremity (Smith et al., 1997), kinematics and kinetics (Alt et al., 2015; Chang & Kram, 2007; Churchill et al., 2015; Hamill et al., 1987; Kawamoto et al., 2002; Smith et al., 1997; Smith et al., 2006; Stoner & Ben-Sira, 1978). Moreover, it was reported that the maximal vertical and resultant ground reaction force (GRF) is smaller during curved running than during straight running (Chang & Kram, 2007; Smith et al., 2006), and that the outside leg generated larger maximal vertical and resultant GRF than the inside leg during curved running (Chang & Kram, 2007; Smith et al., 2006). However, the study of the mechanics of curved running is still not sufficient. Hamill et al. (1987) proposed using an inverted pendulum model with forces acting through the runner's feet to explain the mechanics of curved running. In the biomechanical study, such system can be expressed as the spring-mass model (McMahon and Cheng, 1990), and this model has been used to describe the mechanics of running consisted of a mass and a single linear massless leg spring (Arampatzis et al., 1999; McMahon and Cheng, 1990; Morin et al., 2007). The main mechanical parameter of this model is the leg spring stiffness. Morin et al. (2007) have reported that foot contact time could be a major determinant of spring-mass characteristic of human running; shorter contact time induced higher leg stiffness. The contact time is one of typical variables for curved running, because it indicates the differences between two paths (straight and curve) and between two legs (outside and inside). It was shorter in curved running when compared with linear running, and that of outside was shorter than that of inside in curved running (Alt et al., 2015; Chang and Kram, 2007; Churchill et al., 2015; Smith et al., 2006). Therefore, it is expected the leg stiffness values of outside leg in curved running would be larger than that in straight running and that of inside in curved running. However, little is known about the characteristic of spring-mass during curved running. Then, this study aims to describe the mechanics of curved running using spring-mass model. We hypothesized that 1) the leg spring stiffness in curved running is greater than in straight running, and 2) outside leg stiffness is greater than inside during curved running.

METHODS: Ten males (age: 22.4±2.0 years, height: 1.78±0.06 m, body mass: 71.6±11.1 kg) volunteered for the study. All participants had no lower extremity injuries. Informed consent was obtained from all, and the protocol was approved by the institutional research ethics committee. Straight and curved paths (radius: 5 m) were set up in a laboratory. This radius was chosen from the previous study (Smith et al., 1997). Two forceplates (Type 9281, Kistler

Inc., Winterthur, Switzerland) were placed at middle of paths (1000 Hz). All participants were asked to perform three types of running at the same velocity— 1) straight (St): running along straight path with right foot touchdown on the forceplate, 2) curve-outside (CuO): running along curved path with outside (right) foot touchdown on the forceplate and 3) curve-inside (CuI): running along curved path with inside (left) foot touchdown on the forceplate —with sufficient inter-trial intervals to prevent fatigue. The velocities were checked by a photocell system. In curve trials, the running direction was the counter-clockwise. The trial order was randomized among participants. The data were obtained with average velocity 2.71±0.28 m/s for all trials. Forty-one retro-reflective markers (diameter: 14 mm) were placed on body landmarks selected from a previous study (Ishimura and Sakurai, 2013). 3D positional data of the markers were recorded using a motion capture system (250 Hz) with 10 infrared cameras (Vicon-MX13, Vicon Motion Systems, Oxford, Oxford, UK), which operating in synchrony with forceplate system. Obtained positional data were smoothed using a singular spectrum analysis technique with a window length L of $n \times 10^{-1}$, where n represents the number of positional data in the time series and the first two principal components for data reconstruction (Alonso et al., 2005). A right-handed global coordinate system (O-XYZ), which overlaid on the forceplate and X, Y, and Z axes respectively indicated the medio–lateral, anterior-posterior, and vertical component, was rotated to match the anterior-posterior (Y) axis and direction of horizontal velocity vector of center of mass (CM) at each frame. Then, the rotated new X'- and Y'- axes can indicate the radial and tangential components relative to the CM path, respectively. A 3D spring-mass model was utilized to describe the mechanics of curved running (Figure 1). The orientation of leg spring was expressed with the leg spring length L (distance between subject's CM and the point of force application; in m), the polar angle α (angle between vertical axis and leg spring; in degree), and the azimuth angle β (angle between radial axis of positive and leg spring in horizontal plane; in degree). In addition, the heading angle (θ; in degree) was calculated, defined as the angle between the direction of horizontal velocity vector of CM and Y-axis of global coordinate system overlaid on the forceplate. $\Delta\theta$ indicated the change of running direction during stance.

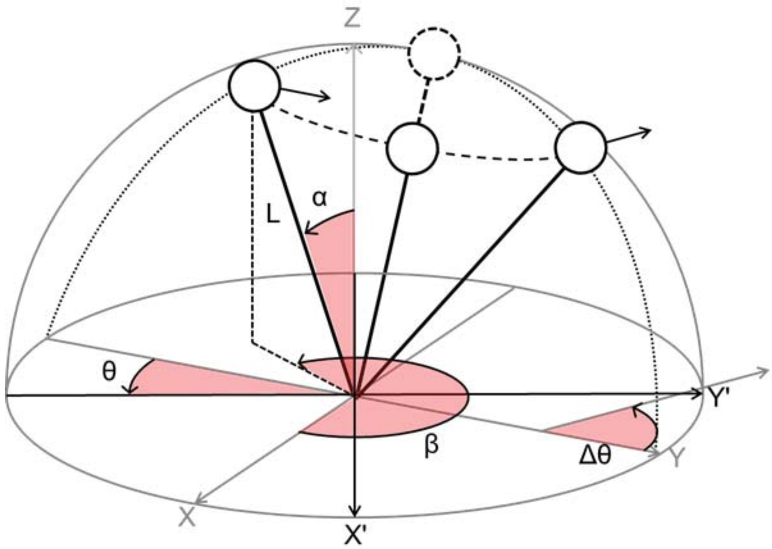

Figure 1: Orientation of leg spring for curved running.

The leg force (F_{leg}; in kN) is the resultant ground reaction force (GRF) acting in the direction of leg spring during stance (Coleman et al., 2012). The leg stiffness (in kNm-1) was calculated as the ratio of the maximal leg force to maximal leg spring compression (ΔL): $k_{leg} = F_{leg}(max) \cdot \Delta L^{-1}$.

A one-way repeated measures ANOVA was used to determine whether there were differences in the spring-mass parameters and the kinematic variables among the trial types. If an assumption of sphericity was not hold by a Mauchly's test for sphericity, the degree of freedom was adjusted using a Greenhouse-Geisser correction. When warranted, a

Bonferroni post hoc multiple comparisons were conducted to determine which trial types differed. In addition, the 95 % confidence intervals (CI) were calculated. All statistical tests were conducted on SPSS 23.0 (IBM, Chicago, IL).

RESULTS: Mechanical parameters of spring-mass model were shown in Figure 2. The maximal leg forces of curved trails were significantly smaller than that of straight (mean ± SD: St 2.03 ± 0.31kN, CuO 1.96 ± 0.26kN, CuI 1.90 ± 0.28kN). The maximal leg compressions were significantly smaller for curve-outside than that of straight and curve-inside (St 0.079 ± 0.010m, CuO 0.065 ± 0.012m, CuI 0.073 ± 0.013m). The leg stiffness of straight and curve-inside were identical, however, that of curve-outside was greater than those (St 26.21 ± 6.65kN/m, CuO 31.49 ± 8.65kN/m, CuI 26.89 ± 7.19kN/m).

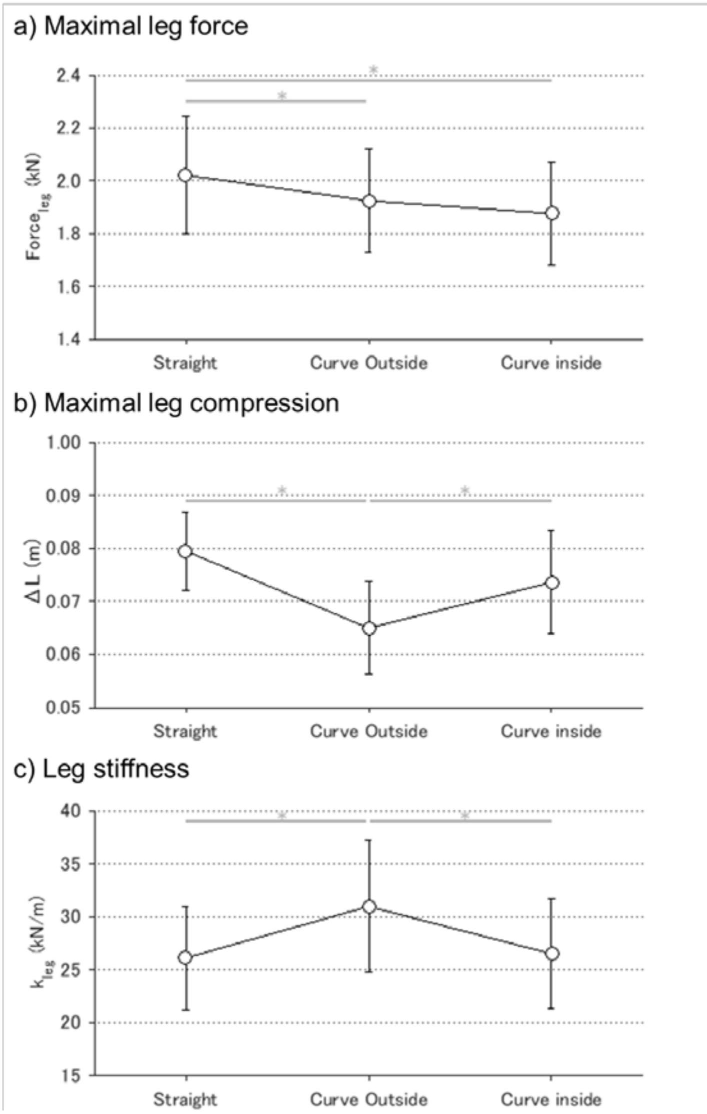

Figure 2: Mean and 95% confidence intervals of spring-mass parameters. * indicates a statistical significant difference at p<0.05.

DISCUSSION: The values of leg stiffness and its parameters in this study were similar to a previous study (Arampatzis et al., 1999). Our participants generated smaller leg forces during curved running than during straight running. This is supported by previous studies (Chang and Kram, 2007; Smith et al., 2006). The compressions of leg were smaller for outside in curved running than inside and straight. This less compression induced mainly the greater leg stiffness.

Our results have revealed that runners cannot exert larger force during curved jogging, and then they use their leg stiffer in curved jogging than in straight jogging. This indicates that runners should acquire the ability to exert larger force within a short contact time. Therefore, the jump training like plyometric training would be better to develop curved running performance. In this study, the running velocity was low (2.71±0.28 m/s), thus, higher running velocities should be investigated in a future study.

CONCLUSION: This study this study aims to describe the mechanics of curved running using spring-mass model. Our two hypotheses, 1) the leg spring stiffness in curved running is greater than in straight running, and 2) outside leg stiffness is greater than inside during curved running, were accepted by results of current study.

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