Journal of Biomechanics 46 (2013) 2769–2777

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Kinetics of cross-slope running

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ARTICLE INFO

Article history:
Accepted 5 September 2013

Keywords:
Running mechanics
Tilted surface
Surface conditions

ABSTRACT

The purpose of the present study was to identify kinetic responses to running on mediolaterally elevated (cross-sloped) running surfaces. Ground reaction forces (GRFs), GRF lever arms and joint moment characteristics of 19 male runners were analyzed when running at 3.5 m/s on a custom-made, tiltable runway. Tilt angles of 3° and 6° for medial and lateral elevation were analyzed using a 10 camera Vicon Nexus system and a force platform. The point of force application of the GRF showed a systematic shift in the order of 1–1.5 cm to either the lateral or medial aspect of the foot for lateral or medial inclinations, respectively. Consequently, the strongest significant effects of tilt orientation and level on joint kinetics and ground reaction force lever arms were identified at the ankle, knee and hip joint in the frontal plane of movement. External eversion moments at the ankle were significantly increased by 35% for 6° of lateral elevation and decreased by 16% for 6° of medial elevation. Altering the cross-slope of the running surface changed the pattern of ankle joint moments in the transversal plane. Effect sizes were on average larger for laterally elevated conditions, indicating a higher sensitivity of kinetic parameters to this kind of surface tilt. These alterations in joint kinetics should be considered in the choice of the running environment, especially for specific risk groups, like runners in rehabilitation processes.

1. Introduction

Distance running is one of the most popular recreational sports in the world and is performed in a variety of environmental settings. Running surfaces are widely different with respect to their material properties and surface characteristics. In a natural environment, the running surface is seldom perfectly level. Running surfaces can be tilted in the sagittal plane of movement (uphill or downhill) or in the frontal plane of movement (cross-sloped; laterally elevated or medially elevated). The medio-lateral elevation of the ground is referenced to the respective stance leg. Therefore, a cross-sloped, laterally elevated surface is elevated on the right hand side for the right leg and on the left hand side for the left leg. While the mechanics of up and downhill running have been investigated quite frequently (e.g. Paradisis and Cooke, 2001, Minetti et al., 2002, Gottschall and Kram, 2005, Telhan et al., 2010), only few studies on mechanical effects of cross-sloped surfaces exist.

One of the first studies on uneven running surfaces analyzed the effects of sprinting on banked turns (Greene, 1987). Running and walking on cross-sloped surfaces require asymmetrical changes in the medio-lateral shear forces (Dixon and Pearsall, 2010, Damavandi et al., 2012) and induce substantial intra-foot, ankle and knee joint kinematic adjustments (Gehlsen et al., 1989; O'Connor and Hamill, 2002; Damavandi et al., 2010; Dixon et al., 2011; Kwon et al., 2012). In walking, changes in functional leg length, a reduction in step width and several changes in sagittal plane and frontal plane joint kinematics and kinetics have been observed (Dixon and Pearsall, 2010). Still, information on changes in cross-slope running at typical distance running speeds are limited as regards to ground reaction force (GRF) and intra-foot kinematics until now.

The use of laterally or medially wedged insoles can be considered analogous to a situation where a small cross-slope is introduced by means of a shoe. For walking, it has been shown that wearing laterally wedged insoles shifts the point of force application (PFA) to a more lateral position underneath the foot, thereby affecting moment arms of lower extremity joints (Kerrigan et al., 2002, Kakihana et al., 2005). A similar shift might be expected for laterally or medially tilted running surfaces. A shift of the PFA may affect the lever arms of the GRF with respect to lower extremity joints. Consequently, changes in PFA and ground reaction forces suggest that joint moments might also be altered when running on a cross-sloped surface.

The majority (78.6%) of all traumatic injuries in elite orienteering were found to occur while running on uneven running surfaces (Johansson, 1986). Bovens and coworkers (Bovens et al., 1989) explained their finding that lower leg and Achilles tendon overuse injury occurrence was significantly higher in the left

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http://dx.doi.org/10.1016/j.jbiomech.2013.09.006

leg by the fact that runners in their study frequently ran on cambered roads, which introduces a cross-slope to their running surface.

Joint moments give an estimate of the net sum of moments created by muscle tendon unit, ligament as well as bone to bone contact forces. Correspondingly, altered joint moments indicate altered loading conditions of these structures without being able to exactly allocate these differences to individual structures. Greater insight into joint loading regulation in running on permanently or non-permanently tilted surfaces could improve the understanding of traumatic and overuse injury development in running. Further, recommendations for runners with regards to the choice of the appropriate running environment could be made based on actual scientific results.

Therefore, the purpose of the current study was to investigate the effects of cross-slope on differences in three dimensional lower extremity joint moment and power patterns, GRF characteristics and PFA changes in running.

Based on previous literature on GRF moment arm alterations using insoles with a lateral inclination in walking (Kakihana et al., 2005; Kerrigan et al., 2009), it was hypothesized that cross-sloped running surfaces would lead to a systematic PFA shift in the medio-lateral direction in running. It was expected that laterally elevated running surfaces would shift the PFA to a more lateral direction and vice versa for medially elevated surfaces. It was further hypothesized that external ankle eversion moments would increase and knee and hip external adduction moments would decrease as a consequence of increased (ankle) or decreased (knee, hip) lever arms in the laterally elevated conditions. Again, the opposite effect was expected for medially elevated surfaces. GRFs were hypothesized to be altered in the medio-lateral direction in order to compensate for perturbations in center of mass movement imposed by inclined surfaces in this direction.

2. Methods

2.1. Participants

The study included 19 male participants (age: 25.6 ± 2.8 years; height: 1.80 ± 0.08 m; mass: 76.2 ± 7.4 kg). All participants were free of pain for at least 12 months prior to their participation in the study and all signed informed written consent. The participants ran on a regular basis with at least two exercise sessions per week (weekly mileage > 15 km). No restrictions were made with respect to the foot strike patterns of the subjects. Post hoc analysis of the results revealed that all runners showed a dorsiflexed foot orientation of the foot at touchdown in the level condition (3.1°–26.7°), indicating that all runners were rearfoot or midfoot strikers.

2.2. Experimental setup and protocol

A custom-made, tiltable runway was constructed for this study. The runway consisted of wooden base units and surface units that were covered with a 10 mm thick tartan layer. In the level condition, the runway had a height of 0.3 m (see Fig. 1). The runway was split into two parts, with a $0.9 \times 0.6\ m^2$ force plate (2500 Hz, Kistler AG, Winterthur, Switzerland) installed in between. The force platform was mounted on a granite base. On top of the platform, stiff wooden wedges were screwed in order to make the surface even with the rest of the runway. The bottom surface of the wedges and the top surface of the force plate were matched precisely with each other in order to avoid any rocking of the wedges on the force plate. Different wooden wedges were used for the different cross-slope conditions. The wedges were covered with the same tartan layer as the rest of the runway. The force platform itself and all parts on top of it had no contact to the rest of the runway in order to allow for a precise measurement of GRFs and PFAs. The runway could be set to inclination levels of 3° and 6°. Medial and lateral elevations were realized by running in opposite directions. Anterio-posterior and medio-lateral GRF components were corrected to compensate for the difference in running direction.

Five different conditions were analyzed at a running speed of 3.5 m/s in randomized order. The running speed (3.5 m/s) was within the range described by the subjects as average training speed but also comparable to the range of running speeds used in the literature for similar experiments. The level running surface (level) was compared to medially and laterally elevated running surfaces with tilt angles of 3° and 6° (med3/med6 and lat3 and lat6 conditions, respectively). Running speed was controlled by two light barriers, placed 0.5 m in front and behind the outer edges of the force platform. All participants wore the same kind of neutral racing flat running shoes (Brooks T6 Racer, Brooks Sports Inc., Bothell, WA, USA) in order to avoid any shoe effect on the observed results. In each condition, five valid trials per subject were analyzed. Trials were considered valid when the running speed was within a range of 3.5 m/s ± 5% and contacted the force platform without any changes in running technique with their right foot.

Running kinematics were captured by means of a ten camera Vicon Nexus system (250 Hz, Vicon Motion Systems, Oxford, UK). Retro-reflective markers were attached to the pelvis and the right lower extremity at the following positions: left and right anterior and posterior superior iliac spines; right greater trochanter; right medial and lateral femoral condyles; tibial bone at approximately the midpoint between knee and ankle joint; lateral and medial malleoli; lateral, medial, and posterior aspect of the heel; first and fifth metatarsal heads and on top of the tip of the first toe. Heel markers were glued directly onto the skin through holes in the heel cap (diameter: approximately 30 mm) (Stacoff et al., 1992). Holes were broken in to the heel cap using a hole puncher.

2.3. Data analysis

All variables were analyzed for the stance phase of the right leg. The stance phase was defined as all data points when the vertical GRF component exceeded a threshold value of 10 N. GRF components were analyzed in the laboratory coordinate system, with the vertical axis pointing vertically up (perpendicular to the level surface condition), the antero-posterior axis pointing into the running direction and the medio-lateral axis pointing to the left. Initially, the PFA was calculated for the top of the force plate surface. Subsequently, the PFA was transformed to the cross-sloped running surface by calculating the intersection point of the GRF vector and the respective tilted surface and represented in the foot's anatomical coordinate system orientation at the instant when the foot is

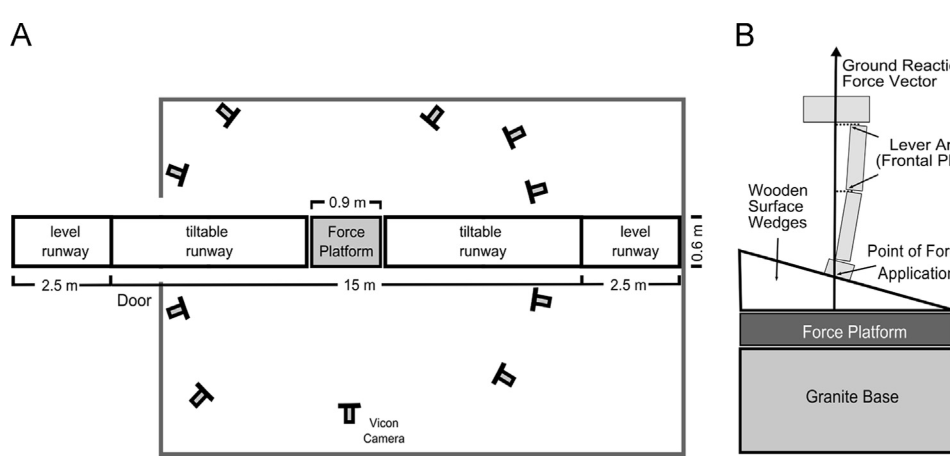

Fig. 1. Experimental setup of the study. (A) Top view on the custom made runway. The length of the runway exceeded the length of the laboratory and therefore subjects were running from the outside to the inside of the lab. (B) Details of the force platform construction and schematic description of lever arms in the frontal plane. Different wooden surface wedges were used to adapt the force platform surface to the respective cross-slope condition.