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Abstract

Sensory information the foot receives appears to be related to kinematic variability. Since footwear material densities affect sensory information, footwear may be an important factor that dictates variability. This study hypothesized that modifications in footwear would result in changes in kinematic variability during the running stance period. Subjects ran on a treadmill for three conditions: hard shoe, soft shoe and barefoot. The spanning sets of the mean ensemble curves of the knee and ankle changes for each condition were used to define variability. Variability was significantly larger in the barefoot condition in comparison with the two footwear conditions for both joints. These results suggest that variability can be affected by peripheral sensory information. The spanning set methodology can be utilized to examine changes in variability.

1. Introduction

It has been suggested that sensory information is a control mechanism for maintaining balance, and adjusting limb trajectories during locomotion [1,2]. Furthermore, a lack of peripheral sensory information in neuropathic and elderly subjects has been related to changes in variability found in locomotive patterns [3,4]. Based on these investigations, it can be suggested that the sensory information the foot receives may be an important factor that determines the amount of variability in locomotor patterns. Since changes in footwear material densities affect the amount of sensory information the foot receives, [5-7] footwear may be an important factor that determines the amount of kinematic variability. No investigations have considered the relationship between footwear and variability. Since previous investigations have theoretically suggested that changes in variability may be related to running injuries [8], scientific information about the effect of footwear on variability may be useful for understanding the etiology of running injuries.

The variability about a mean ensemble curve (expressed usually as the standard deviation curves) can be defined as a set of kinematic joint movements that produce a functional locomotor pattern. For example, a mean ensemble curve of the angular displacement for the knee joint describes the typical joint pattern during stance period. The standard deviation about the mean ensemble curve represents the possible variations in the movement of the knee joint during the stance period for repetitive footfalls. The larger the distance between the standard deviation curves of the mean ensemble, the greater the variability in the movement pattern.

In a similar fashion, vectors that compose a spanning set describe the possible linear combinations (or solutions) to an equation [9]. Linear combinations (and scalar multiples) of the respective vectors of the spanning set fill in an area that can be graphically described as a plane in R^n. Thus, the vectors that compose the spanning set can be visualized the edges of the plane that contains the possible solutions of the system. The larger the distance between the vectors that define the spanning set, the greater the span of the plane [9].

We suggest that the standard deviation about the mean ensemble curve can be represented as the spanning set that characterizes the amount of variability present during the stance period. Increased variability within the locomotor pattern will be indicated by a larger span between the vectors of the spanning set. The goal of this investigation was twofold: (1) provide scientific information about the relationship of variability and footwear, (2) present how the spanning set can be used to quantify variability. In this investigation, we hypothesized that modifications in footwear would result in changes in variability during the running stance period. We speculated that an increase in variability may be related to sensory information the foot receives during the stance period.

2. Materials and methods

Eight healthy male (N=8) runners who were running 44.5±29.5 km week^{-1} for the past 4 months volunteered as subjects (mean age: 27.1±4.9 years; mean body mass: 71.9±9.1 kg; mean height: 1.76±0.07 m). All subjects exhibited a heel-toe footstrike pattern while running at a self-selected comfortable pace on a treadmill. Each subject had prior treadmill running experience. Prior to testing, each subject read and signed an informed consent that was approved by the University Institutional Review Board.

Subjects ran barefoot and with two different types of footwear on a treadmill, while sagittal kinematic data of the right lower extremity were collected using a high speed (180 Hz) camera (JC Labs, Mountain View, CA). A single camera was used in this investigation because sagittal view measures of running correspond well in two- and three-dimensions [10,11]. Prior to videotaping, reflective markers were positioned on the subject's right lower extremity. All positional markers were placed on the subjects by the same examiner. Sagittal plane marker placement was as follows: (a) greater trochanter, (b) axis of the knee joint as defined by the alignment of the lateral condyles of the femur, (c) lateral malleolus, (d) outsole of the shoe approximately at the bottom of the calcaneus, (e) outsole of the shoe approximately at the fifth metatarsal head. When the shoes were removed for the barefoot condition, the sagittal plane markers were relocated directly on the skin and at the same anatomical locations.

Joint markers were digitized using the Peak Performance Technologies' Motus System (Peak Performance Technologies, Inc., Englewood, CO). The obtained kinematic positional coordinates of the sagittal markers were scaled and smoothed using a Butterworth Low- pass Filter with a selective cut-off algorithm [12]. The cut-off frequency values used were 13-16 Hz. It was theorized that the Jackson optimal filter routine selected the best possible cut-off value that compromised be- tween maintaining the true biological properties of the kinematic signal and removal of noise (i.e. measurement error) in the data.

Shoe hardness was determined from rearfoot impact characteristics. Two running shoe models from two major manufacturers had similar characteristics for all shoe features except for midsole hardness. The two shoes were evaluated using an Impact Testing System (Exeter Research Inc., Brentwood, NH). The testing procedure involved 25 pre-impacts with a mass of 8.5 kg dropped from a height of 0.05 m followed by 20 impact trials. ASTM recommendations were followed for the testing procedure except the number of trials was increased (from 10 to 20) to improve data reliability and validity. Based on the impact testing results regarding peak acceleration, the two running shoes were then classified as hard (15.1±0.3 Gs) and soft (10.5±1.0 Gs).

The subjects were allowed to warm-up for a minimum of 8 min. This duration of warm-up has been considered sufficient for individuals to achieve a proficient treadmill movement pattern [13]. During the warm-up session, each subject established a self-selected comfortable running pace. Subjects were instructed to select a pace that would be similar to a pace that they would use when performing continuous aerobic running. This self- selected pace was used for all conditions. The average pace was 3.24±0.85 m s^{-1}. Following warm-up, the subjects ran for three different conditions: soft shoe, hard shoe, and barefoot. The order of presentation of the conditions was randomly selected. All subjects eased into their self-selected running pace prior to data collection. Collection of data did not occur until the subject stated that they felt comfortable and could maintain the pace for a long duration. Once the subject felt comfortable running on the treadmill, ten consecutive footfalls (trials) were collected. Between each condition the subjects were allowed a minimum of 5 min of rest.

From the plane coordinates obtained, the sagittal foot, shank, and thigh angular displacements were calculated relative to the right horizontal axis. Calculation of the ankle and knee joint angles was based on an absolute approach ($\Theta_{Knee} = \Theta_{Thigh} - \Theta_{Shank}$; $\Theta_{Ankle} = \Theta_{Shank} - \Theta_{Foot}$). The knee and ankle joint angular displacements were normalized to 100 points for the stance period using a cubic spline routine to create a mean ensemble curve to be derived from the representative footfalls from each subject-condition.

A least squared method was utilized to fit seventh order polynomials to the respective standard deviation curves. A seventh order polynomial was selected for this study because this order provided the least difference between the actual data and the polynomial function values. The coefficients from the respective standard deviation polynomials were used to map to a vector space that defined vectors in the spanning set [9]. Spanning sets were created from the mean ensemble curves for the knee and ankle of each subject-condition. The magnitude of each spanning set (that described variability) was determined by calculating the norm of the difference between the two vectors of the respective spanning sets (Eq. (1)).

$$\mathbf{y} = \|\mathbf{a} - \mathbf{b}\| \quad (1)$$

where **a** represents the vector formed from the polynomials of the above the mean standard deviation curve, **b** represents the vector composed of the polynomials from the below the mean standard deviation curve, and **y** is the magnitude of the spanning set.

One-way repeated measures ANOVAs (shoe condition with subject as the repeated factor) were performed on the subject's spanning set magnitudes for each joint (ankle and knee). In tests that resulted in significant *F*- ratios (P <0.05), a post hoc Tukey multiple comparison test was performed to identify the location of significant differences. The statistical power of each test was calculated using the methods described by Zar [14]. All statistical comparisons were conducted at a 0.05 alpha level.

3. Results

The magnitude of the spanning set indicated that significant differences in variability existed for both the knee ($F(2, 14)=8.63$, $P<0.05$) and ankle joints ($F(2, 14)=19.24$, $P<0.05$). The statistical power of this investigation was calculated to be 0.88 for the test knee and 0.98 for the angle test. Significant differences for both joints were found between the barefoot and the hard shoe conditions, and the barefoot and the soft shoe conditions. No statistical differences ($P>0.05$) were found in the variability between the two shoe conditions (Table 1).

Graphically, it can be observed that the two shoe conditions had similar amounts of variability at the ankle during the stance period (Fig. 1A and B). Compared to the two shoe conditions, the barefoot condition had more overall variability at the ankle joint (Fig. 1C). Similar findings were evident at the knee joint for the respective conditions.

Table 1
Means and standard deviations for the respective spanning sets

Joint/condition	Soft shoe (°)	Hard shoe (°)	Barefoot (°)
Ankle	$2.5\pm0.9^{\text{Barefoot}}$	$2.9\pm1.0^{\text{Barefoot}}$	7.2 ± 3.5
Knee	$5.0\pm2.0^{\text{Barefoot}}$	$4.6\pm1.7^{\text{Barefoot}}$	9.1 ± 4.9

The spanning set represented the variability in the neuromuscular system. Larger spanning set magnitudes indicated an increase in variability. Significant differences ($P<0.05$) are indicated by superscripts.

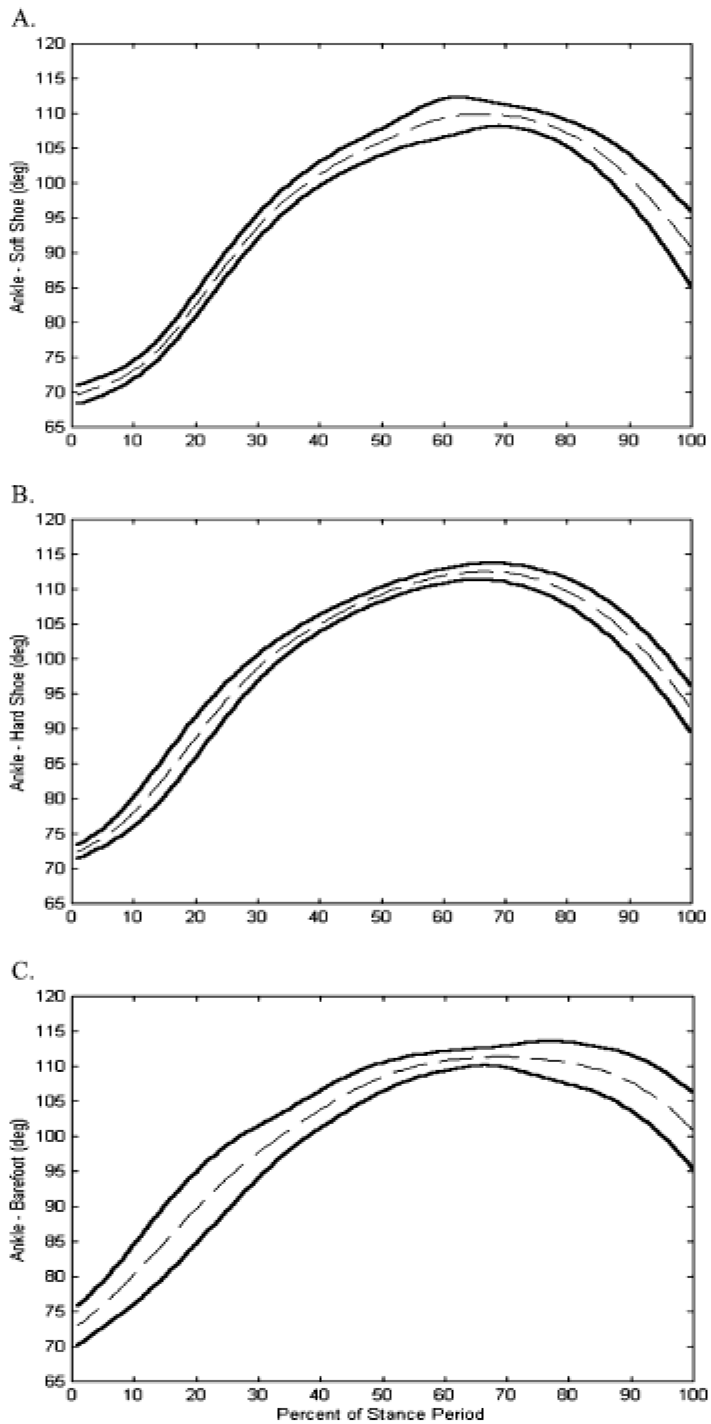

Fig. 1. Ankle joint mean ensemble curves and standard deviations of the respective conditions during the stance period for an exemplar subject: (A) soft shoe, (B) hard shoe, (C) barefoot. The standard deviation curves are represented with bold lines, and the mean ensemble curves are presented with a dashed line.

4. Discussion

The results of our investigation support our hypothesis that footwear influences lower extremity variability. Our results appear to agree with previous investigations that have found a correlation between variability and sensory information the foot receives [3,4]. De Clercq et al. [15] have indicated that the mechanoreceptors of the foot are responsible for neuromuscular strategies to prevent overloading of the heel to avoid injury. Therefore, variations in the lower extremity joints may be related to the ability of the mechanoreceptors of the heel pad and forefoot to sense the amount of impact forces experienced during the stance period.

From a theoretical perspective, joint variability may be necessary to prevent running injuries [8]. The increased variability in the joint pattern during the barefoot condition may be a mechanism for over- coming repetitive impact forces. By varying the joint pattern, joint forces are spread across various tissues to prevent over-use injuries. Based on the results of this investigation, footwear may affect joint variability. Further prospective investigations are necessary to determine the relationship between injuries and variability. Such additional information may be useful for the prevention of running injuries via footwear modifications.

Lake and Lafortune [6] determined that individuals were not able to perceive differences in impact between small incremental changes in material densities. Our investigation may have experienced similar results where changes in shoe hardness may have not been sufficient for subjects to exhibit a change in variability between footwear conditions. Additionally, it is possible that the subjects' daily footwear may have matched the footwear densities used in this investigation. Perhaps if the subjects used footwear that had a similar stiffness factor, the neuromuscular system may not have sensed a need for change. Future investigations on the relationship between variability and footwear should take into consideration the type of daily footwear used by the subjects.

If sensory information was the primary factor involved in variability, changes in variability most likely would have been evident throughout the stance phase. Inspection of the mean ensemble curve for the ankle (Fig. 1) indicated that this was not the case. Variability measured in this investigation may also be due to mechanical changes that occur while running barefoot. It is possible that the intrinsic muscles of the foot and ankle may play a different role in barefoot running. Mechanical changes in the role of the muscles while barefoot may promote subtle changes in the positioning of the lower extremity at foot strike and toe-off. Such modifications may be the reason that the barefoot mean ensemble curves had more variability in the early and late portions of the stance period (Fig. 1C).

In conclusion, the purpose of this investigation was to provide insight on the relationship of variability and footwear. We used the spanning set methodology to describe changes in variability as footwear and shoe hardness were modified. This methodology provided unique insights on joint variability based on the mean ensemble curve. Our hypothesis that modifications in footwear would result in changes in variability during the running stance period was supported by the results of this study. Variability seen in the joint patterns while running barefoot appears to be affected by a combination of peripheral sensory information and mechanical changes. Future investigations may want to utilize the spanning set to further address the effect of footwear on kinematic variability.

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