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Spanning set defines variability in locomotive patterns

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Abstract

The purpose of the investigation was to use the spanning set methodology to quantify variability in locomotive patterns and to compare this method with traditional measures of variability. Subjects ran on a treadmill while sagittal plane kinematic data were collected with a high-speed (180Hz) camera. Changes in variability were evaluated as the subject ran barefoot and in shoes. Mean ensemble curves for the knee angle during the stance period were created for each condition. From these curves, traditional measures of variability were calculated using the coefficients of variation (CVs), and the mean deviation (MD). Spanning set vectors were defined from the coefficients of polynomials that were fitted to the respective standard deviation curves. The magnitude of the spanning set was determined by calculating the norm of the difference between the two vectors. The normalized difference between the two conditions was 6.6%, 6.9% and 98%, for the MD, CV and spanning sets, respectively. The results indicated that the spanning set was capable of statistically ($p< 0.05$) determining differences in variability between the two conditions. CV and MD measures were unable to detect statistical differences ($p>0.05$) between the two conditions. The spanning set provides an alternative, and sensitive measure for evaluating differences in variability from the mean ensemble curve.

Introduction

Evaluation of locomotive patterns suggests that intra-subject variability exists from one gait cycle to the next. Recently, these variations have received attention because they may be an indicator of human health (CAVANAGH el al., 1993; DINGWELL et al., 1999; HAMILL et al., 1999). Measurements of the standard deviation of the mean ensemble curve have been used to define the amount of variability in the locomotive patterns (CAVANAGH et al., 1993: DJNGWELL *et al.*, 1999: GABEL and NAYAK, 1984; HAMILL *et al.*, 1999: WINTER, 1983). The variability about a mean ensemble curve (expressed usually as the standard deviation curves) can be defined a set of joint movements that produce a functional locomotive pattern. For example, a mean ensemble curve of the angular displacement for the knee joint describes the typical joint pattern during the 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 curve, the greater the variabilityy in the movement pattern (Fig. I).

Similarly to the standard deviations about the mean ensemble curve, vectors that compose a spanning set describe the possible Linear combinations (or solutions) to an equation (LAY, 1999). 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*". *R*" represents the dimension of the

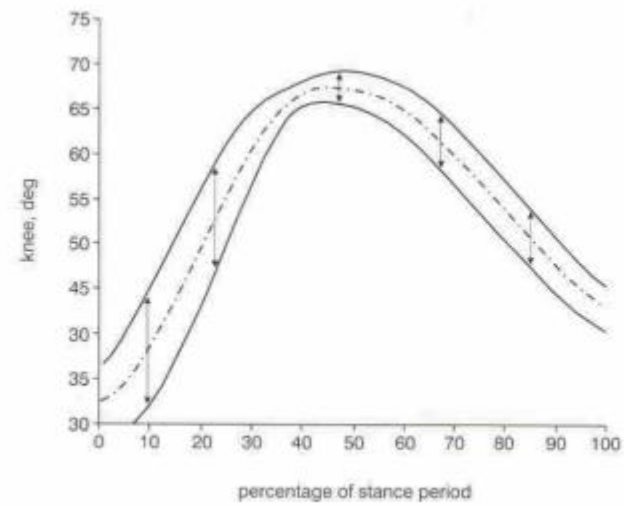

Fig. 1 *Mean ensemble curve for knee joint during stance phase: (-·-) mean joint pattern; (—) standard deviation about mean ensemble curve. Larger arrows between standard deviation curves indicate greater variability in movement pattern*

given set of variables (i.e. R^2 =two dimensions). The vectors that compose the spanning set can be visualized as the edges of the plane that contain 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 (LAY, 1999).

We suggest that the standard deviation about the mean ensemble curve can be represented as the spanning set that defines the variations in the movement pattern during locomotion. Greater variability within the locomotive pattern will be indicated by a larger span between the vectors of the spanning set. The purpose of this investigation was to present a new technique for the evaluation of variability in locomotive patterns, based on the spanning set methodology, and to compare this method with traditional mathematical measures of variability.

Materials and methods

Eight healthy male (*N*=8) runners who had been 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.

The subjects were allowed to warm up for a minimum of 8 min prior to data collection. This duration of warm-up has been considered sufficient for individuals to achieve a proficient treadmill movement pattern (JENG *et al.*, 1997). During the warm-up session, each subject established a self-selected pace 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}. Kinematic data of the right sagittal lower extremity were collected using a high-speed (180 Hz) camera* interfaced to a high-speed video recorder. A single camera was used in this investigation, because sagittal view measures of running correspond well in two- and three-dimension (AREBLAD *et al.*, 1990; SOUTAS-LIITLE *et al.*, 1987). Differences in variability were evaluated as subjects ran barefoot and in shoes.

Prior to the videotaping, reflective marker ·were positioned on the subject's right lower extremity. Marker placement were 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

Joint markers were digitized using the Peak Motus System for ten consecutive footfalls. The kinematic positional coordinates of the markers obtained were scaled and smoothed using a Butterworth low-pass filter, with a selective cutoff algorithm based on JACKSO (1979). It was theorized that the Jackson optimum filter routine selected the best cutoff value that was a compromise between maintaining the true biological properties of the kinematic signal and removal of noise (i.e. Measurement error) in the data. The cutoff frequency values used were 13-16 H z.

From the plane co-ordinates obtained, the sagittal shank and thigh angular displacements were calculated relative to the right horizontal axis. The calculation of the knee joint angle was based on the absolute approach ($0_{Knee} = 0_{Thigh} - 0_{Shank}$). The knee joint angular displacements were normalized to l00 points for the stance period, using a cubic spline routine to enable a mean ensemble curve to be derived for the ten consecutive footfalls of each subject condition combination.

Continuous measures of variability during t11e stance period were calculated using the coefficient of variation CV (Winter, 1983) and mean deviation MD (Hamill et al., 1999).

$$CV = \frac{1/N \sum_{i=1}^{N} S_i}{1/N \sum_{i=1}^{N} |x_i|} \times 100 \quad (1)$$

$$MD = \frac{\sum_{i=1}^{N} |S_i|}{N} \quad (2)$$

where S is the standard deviation of the mean ensemble curve, x is the ith point of the mean ensemblele curve, and N is the number of points in the mean ensemble curve. Lower CV and MD values indicated less variability in the locomotive pattern.

To create the spanning set, 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 accounted for 99.8% of the variance above and below the mean standard deviation curves of the mean ensemble curve. For this investigation, a change in the coefficient of determination indicated that polynomials beyond the seventh order did not significantly account for any additional variance ($p > 0.05$). Using a regression equation that does not account for a significant amount of the variance in the standard deviation curves (i.e. a lower-order polynomial) may not adequately capture the curve configuration of the standard deviations of the mean ensemble curve. Thus care should be taken when selecting the order of the polynomial that explains the variance in the standard deviation curve configurations.

Co-ordinate mapping was used to introduce a familiar co-ordinate system that could be utilized to describe the properties of the polynomials in R^n (LAY. 1999). We utilized the coefficients from the respective standard deviation polynomials to map to a vector space that could be used to define vectors in the spanning set. Spanning sets were created from the mean ensemble curves for the knee of each subject condition combination. 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 (see (3)). In (3), *u* represents the vector formed by the coefficients from the first polynomial (i.e. standard deviation above the mean), and *v* represents the vector formed by the coefficients from the second polynomial (i.e. standard deviation below the mean). The larger the norm of the difference between the two vectors in the spanning set, the greater the span between the two standard deviation curves about the mean ensemble. Therefore a larger span indicates more variability in the joint pattern. Conversely, a lower spanning set magnitude indicates less variability.

$$y = \|u - v\| \tag{3}$$

The independent variables in this investigation were the barefoot and shod conditions. The dependent variables were the three measures of variability (i .e. CV, MD and spanning set). Differences between the mathematical measures of variability were determined by calculating the normalized absolute difference and dependent *t*-test (0.05 α level) between the respective conditions (barefoot and shod running). The normalized absolute difference was calculated by dividing the absolute difference between the condition means by the mean of the footwear condition. The normalized absolute difference was expressed as a percentile.

Table 1 Continuous measures of variability from mean ensemble curve of knee joint during stance period

Variable	Shod	Barefoot	Difference	Normalised difference
CV, %	4.38 (0.7)	4.67 (1.3)	0.29	6.6%
MD, deg	2.30 (0.3)	2.46 (0.6)	0.16	6.9%
Magnitude of spanning set, (deg)	4.57 (1.7)*	9.05 (4.9)	4.48	98.0%

*Significant differences at 0.05 α level between conditions

Results

The results of this investigation suggested that all the mathematical measures indicated an increased variability during the barefoot condition. However, the spanning set was the only mathematical measure capable e of determining statistical l difference ($p < 0.05$) between the two conditions (Table I). The statistical differences noted by the spanning set also coincided with graphical observations that the barefoot condition had more variability. For example, we plotted a sample subject in Fig. 2. It is graphically evident that the barefoot condition has

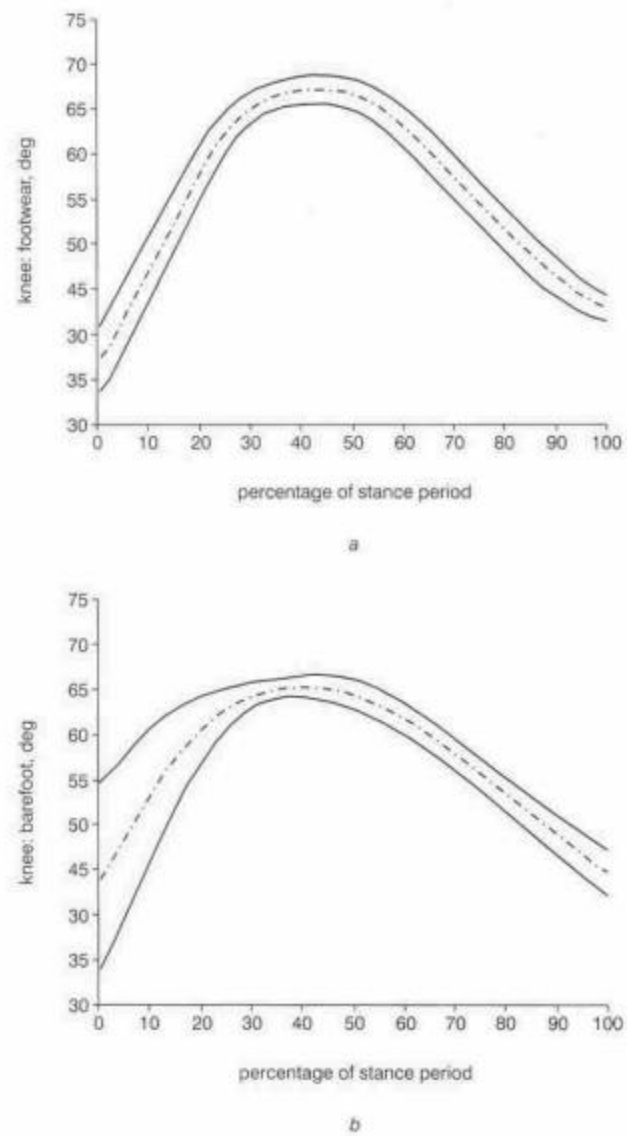

Fig. 2 *Sample mean ensemble curves and standard deviations of respective conditions during stance period: (a) shod: CV = 4.18%; MD = 2.35°; spanning set = 7.26°; (b) barefoot: CV = 4.96%; MD = 2.85°; spanning set = 20.00°;. (—) Standard deviation curves (–·–·–) mean ensemble curves*

more variability . However, the MD and CV measures only suggest a slight increase in variability between the two conditions.

Discussion

The purpose of this investigation was to present the panning set as a new method for evaluating variability in locomotive patterns and to compare this method with traditional measures of variability. Compared with the CV and MD measures of variability, the spanning set method appears to be a more sensitive technique for the quantification of variability based on the mean ensemble curve. Although the CV and MD did suggest increased variability during the barefoot condition, these increases were not significant. Previous investigations that have used the CV and MD have not been able to detect significant differences in variability but have noted trend s (DINGWELL *et al.*, 1999; GABEL and NAYAK, 1984; HAMILL *et al.*, 1999). It is possible that changes in variability may have gone undetected in past investigations, owing to the lack of sensitivity of these measures.

Traditionally, the CV has been used as a measure of variability because it controls the magnitude of variability by dividing by the mean (see (1)). This technique allows for a data set with a larger mean and a larger standard deviation to be compared with the variability of a data set with a smaller mean and associated smaller standard deviation. Conversely, an argument can be made against the value of normalizing the standard deviation by the mean. Inspection of the CV formula suggests that there may be some instances where problems can arise when this mathematical measure is used to quantify variability in locomotive patterns. As the CV formula contains the mean value of the joint pattern in the denominator, a larger denominator will influence the magnitude of the CV. Therefore different mean joint pattern magnitudes may affect the reliability of using the CV mea sure to quantify variability. Based on this notion, utilizing the CV to determine the amount of variability in movement pattern from the mean ensemble curve may not be the best mathematical measure. If subjects have different ranges of motion during the gait pattern, the CV may not be able to quantify the true variability in the movement pattern.

The MD offers an alternative measure of variability about the mean ensemble curve that is not influenced by differences in the mean joint pattern between subjects and conditions. However, the MD revealed the smaller values of variability in both conditions. Thus significant differences in variability between mean ensemble curves were not observed using the MD. With the interest in relating variability of the mean ensemble curve to the health and stability of the joint, better mathematical measures of variability are necessary.

This investigation indicated that the spanning set offered an alternative method for calculating variability from the mean ensemble curve. Compared with traditional measures of variability from the mean ensemble curve (i.e. CV and MD), it appears that the spanning set may provide a more sensitive measure of variability. Future investigations that attempt to link variability in the joint pattern from the mean ensemble curve to movement strategies may want to consider using the spanning set.

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