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Short Communication

Vector field statistics for objective center-of-pressure trajectory analysis during gait, with evidence of scalar sensitivity to small coordinate system rotations

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ABSTRACT

Center of pressure (COP) trajectories summarize the complex mechanical interaction between the foot and a contacted surface. Each trajectory itself is also complex, comprising hundreds of instantaneous vectors over the duration of stance phase. To simplify statistical analysis often a small number of scalars are extracted from each COP trajectory. The purpose of this paper was to demonstrate how a more objective approach to COP analysis can avoid particular sensitivities of scalar extraction analysis. A previously published dataset describing the effects of walking speed on plantar pressure (PP) distributions was re-analyzed. After spatially and temporally normalizing the data, speed effects were assessed using a vector-field paired Hotelling's T^2 test. Results showed that, as walking speed increased, the COP moved increasingly posterior at heel contact, and increasingly laterally and anteriorly between ~60 and 85% stance, in agreement with previous independent studies. Nevertheless, two extracted scalars disagreed with these results. Furthermore, sensitivity analysis found that a relatively small coordinate system rotation of 5.5° reversed the mediolateral null hypothesis rejection decision. Considering that the foot may adopt arbitrary postures in the horizontal plane, these sensitivity results suggest that non-negligible uncertainty may exist in mediolateral COP effects. As compared with COP scalar extraction, two key advantages of the vector-field approach are: (i) coordinate system independence, (ii) continuous statistical data reflecting the temporal extents of COP trajectory changes.

1. Introduction

Center of pressure (COP) trajectories detail the dynamic interaction between the foot and ground, and have been widely used to characterize gait mechanics in both health [1] and disease [2]. They are typically analysed first qualitatively [1] and then statistically, through the extraction of a number of scalar parameters like planar orientation and maximum displacement [2–5].

One problem with COP trajectory parameterization is that a large number of scalars – on the order of 50 – exist for describing even single COP trajectories [3,5], and many additional scalars exist for describing multiple COP trajectories [2,4]. Since different studies tend to report different parameters, multi-study comparisons and meta-analyses are difficult. A potentially more serious problem is that *ad hoc* scalar extraction can bias statistical analysis via unjustified focus on particular coordinates and/or temporal windows [6].

The purpose of this study was to demonstrate how vector field statistics can be used to more objectively analyse COP trajectories. The method stems from statistical parametric mapping (SPM) [7,8], an applied statistical technique used to detect signals in spatiotemporal continua.

We use previously collected plantar pressure data [9] to test the null hypothesis that walking speed does not affect the COP trajectory, both to clarify trends in those data and to corroborate vector field COP results with independently reported walking speed effects [5,10]. Since coordinate system definitions can affect COP interpretations [10], we also conduct a coordinate system sensitivity analysis.

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2. Methods

2.1. Dataset

Ten male subjects (mean 28.8, SD 8.3 years) provided informed consent and performed 20 trials of each of slow, normal and fast walking [9]. Plantar pressures (PP) and walking speed were recorded using a Footscan 3D system (RSscan, Belgium) and a ProReflex system (Qualisys, Sweden), respectively.

PP data were spatially normalized using optimal scaling transformations [9] to align the average PP distribution's principal axes with the measurement device's coordinate system. COP trajectories were linearly interpolated to 101 values (0–100% stance). The data were fitted to two different statistical models: (i) a paired t test and (ii) linear regression. Analyses of these two models were found to produce qualitatively identical interpretations, so for simplicity only the former is presented below.

2.2. Scalar extraction analysis

Although our only formal hypothesis test was a single vector field test (Section 2.3), we also separately analyzed COP scalars to emphasize the pitfalls of trajectory simplification. Specifically, we extracted the two scalars that appeared to be most affected by walking speed (Fig. 1b and c): (i) r_x at time = 70% stance, and (ii) r_y at time = 55%. A Šidák threshold of $p = 0.0253$ corrected for the two tests.

2.3. Vector field analysis

Each (101×2) COP trajectory was regarded as a single vector field $\mathbf{r}(q) = \{r_x(q)\, r_y(q)\}$, where q represents time. Within-subject mean $\mathbf{r}(q)$ trajectories were estimated for each subject and for both slow and fast walking, yielding the jth subject's fast–slow difference trajectory:

$$\Delta\mathbf{r}(q)_j = (\mathbf{r}(q)_{\text{Fast}})_j - (\mathbf{r}(q)_{\text{Slow}})_j \tag{1}$$

The paired Hotellings T^2 test statistic trajectory was computed as:

$$T^2(q) = n(\Delta\bar{\mathbf{r}}(q)^{\mathrm{T}})\mathbf{W}(q)^{-1}(\Delta\bar{\mathbf{r}}(q)) \tag{2}$$

where n is the number of subjects, $\Delta\bar{\mathbf{r}}(q)$ is the cross-subject mean, and $\mathbf{W}(q)$ is the 2×2 variance/covariance matrix of Δr_x and Δr_y at time q (Supplementary Material, Appendix A). Although Eq. 2 neglects within-subject variability, this does not affect population-level analyses when the data are normally distributed [7].

Statistical inference was conducted by calculating the T^2 threshold above which only $\alpha = 5\%$ of T^2 trajectories would be expected to traverse, if the null hypothesis were true, and if the underlying COP data were generated by a random (Gaussian) process with the observed 1D smoothness [6,8]. Following thresholding, exact p values were computed for each supra-threshold cluster based on their temporal extent [7,8]. Last, *post hoc t* tests were conducted on $r_x(q)$ and $r_y(q)$ using the identical procedure, with a Šidák threshold of $p = 0.0253$. Additional details regarding this inference procedure are provided in Supplementary Material.

2.4. Coordinate system sensitivity

COP trajectories were rotated in the xy plane in increments of 0.5° between $-15°$ (external rotation) and $+15°$ (internal rotation). Sensitivity to these rotations was evaluated using the *post hoc* null hypothesis rejection decision for the rotated r_x trajectories.

3. Results

Walking speed produced no qualitative COP change in the xy plane (Fig. 1a), but fast walking appeared to medialize the COP over 60–80% stance (Fig. 1b) and anteriorize the COP over 50–70% stance (Fig. 1c). Scalar extraction analysis yielded $p < 0.001$ and $p = 0.003$, respectively (Fig. 1d,e).

Vector field results (Fig. 2a) agreed with the medialization trend over 65–80% stance ($p < 0.001$) via a *post hoc* test on $r_x(q)$ (Fig. 2b). *Post hoc* analysis also agreed with the anteriorization trend over 65–90% stance ($p < 0.001$) (Fig. 2c), but this effect failed to reach significance at the instant of scalar analysis (time = 55%). Last, vector field analysis revealed an effect not detected in scalar analyses: a more posterior COP at heel contact in fast vs. slow walking (0–1% stance; $p = 0.00723$) (Fig. 2c).

Coordinate system sensitivity analysis found that the medialization effect (Fig. 2b) reduced in magnitude with external foot rotation (Fig. 3a). Effect significance disappeared for external rotations greater than 5° (Fig. 3b).

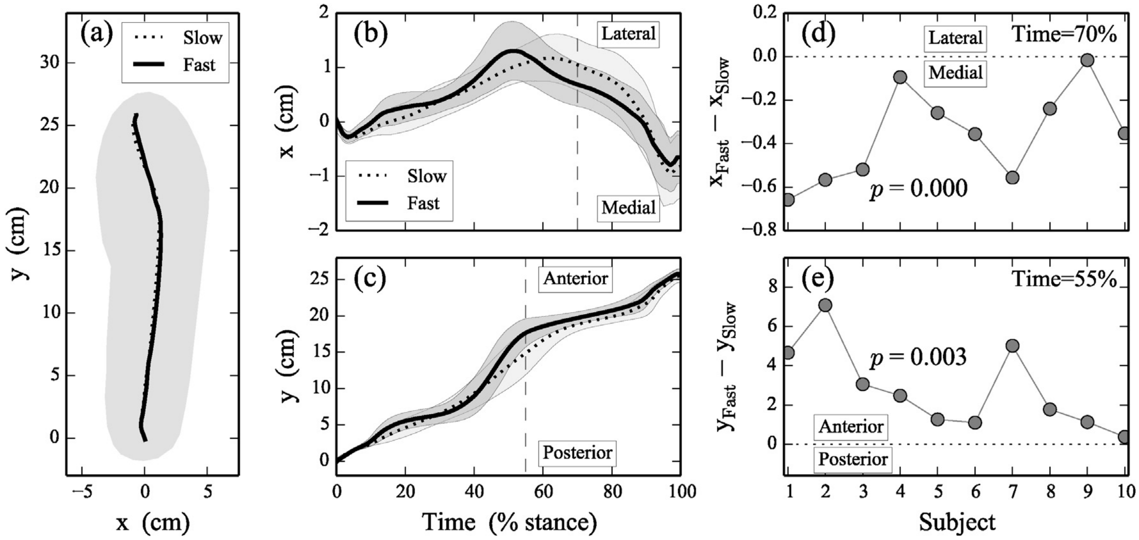

Fig. 1. Mean COP trajectories in the (a) x–y, (b) x-time, and (c) y-time planes. In panels (b) and (c) error clouds depict one standard deviation, and vertical lines depict the instants of scalar extraction paired t tests (d and e), which were conducted for illustrative purposes (see text). (d) Medio-lateral (r_x) position differences at time = 70% stance. (e) Antero-posterior (r_y) position differences at time = 55% stance.

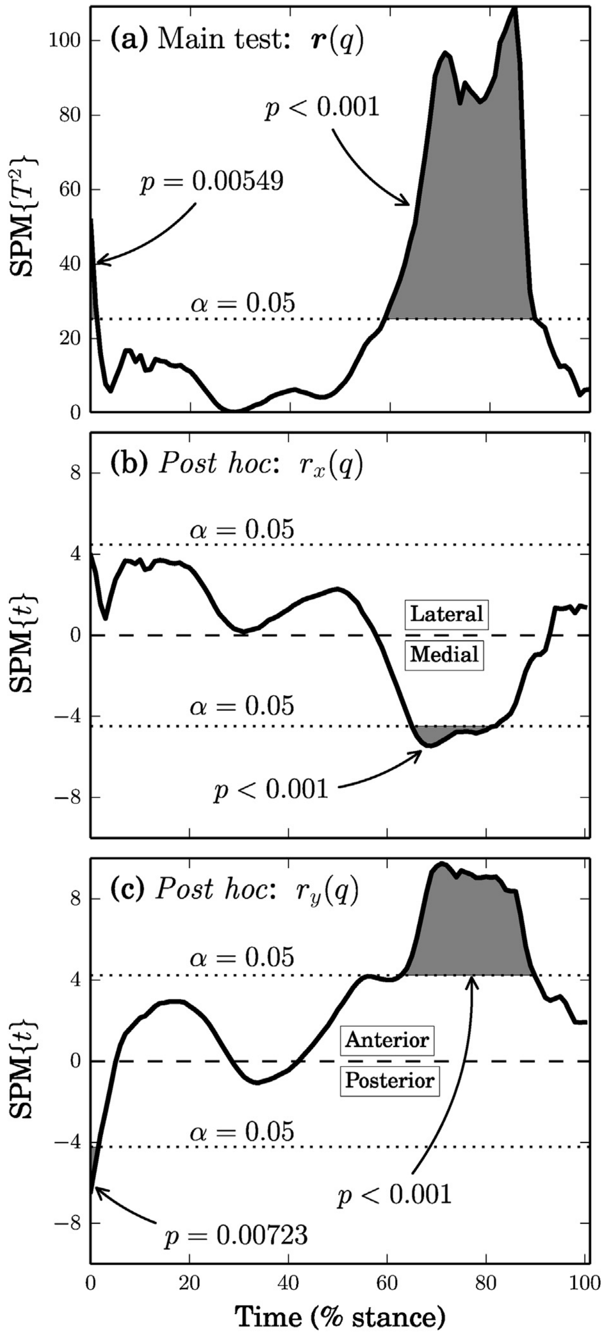

Fig. 2. Vector field statistical test (the paper's only formal hypothesis test). (a) Hotelling's paired T^2 test on **r**(q), depicting where in time slow and fast differed; critical T^2 = 25.30. (b and c) *Post hoc* scalar field tests on $r_x(q)$ and $r_y(q)$, respectively, depicting where in time fast had a more positive position than slow; critical t = 4.47 and 4.24, respectively.

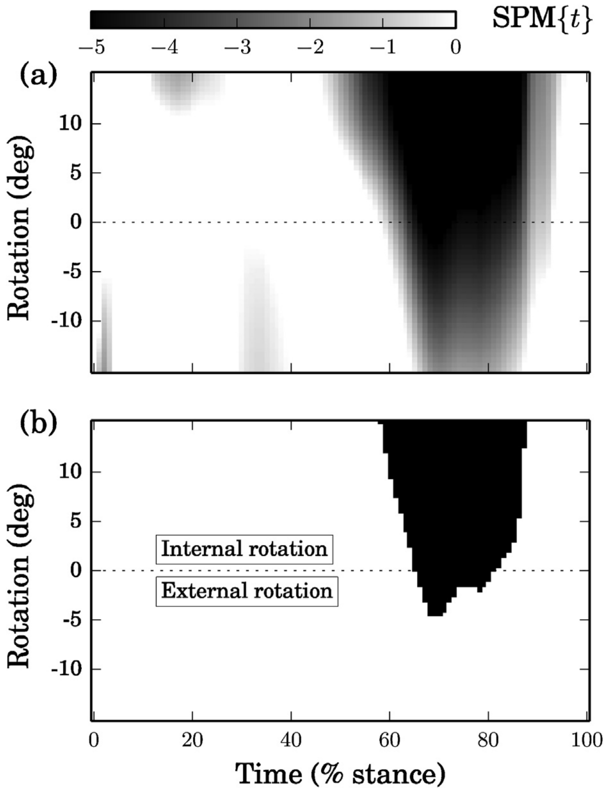

Fig. 3. Coordinate system sensitivity analysis. (a) The t statistic value for r_x analysis (Fig. 2b), as a function of both time and the coordinate system rotation angle. (b) Inference image depicting significance (black); a rotation of −5.5° (i.e. external rotation) caused r_x effects to fall below the threshold for significance.

4. Discussion

The current r_y results (Fig. 2c) agree with independent findings of increasingly posterior heel contact [10] and increasingly rapid transfer on to the forefoot [5] with walking speed. Nevertheless the scalar results (Fig. 1e) disagreed regarding the existence of anteriorization at time = 55%, and this disagreement persisted in supplementary analyses using a different statistical model (Appendix D). The reason is that scalar extraction analysis fails to account for both vector covariance (Appendix A) and multiple tests across the time series (Appendix B). By observing the mean r_y curve (Fig. 1c) *before* choosing our scalar, we effectively conducted 101 tests, but then chose to report only one, without considering vector covariance.

The current scalar and vector analyses agreed regarding speed-related medialization (Figs. 1d, and 2b), but this effect disappeared for a small coordinate system rotation on the order of 5° (Fig. 3), in agreement with previous reports of coordinate-system dependence in COP results [10]. This sensitivity finding is practically relevant because: (i) laboratory equipment may be oriented manually, (ii) motion generally does not parallel the laboratory coordinate system [1], and (iii) foot posture is variable between trials. All factors conspire to imply that near-threshold COP results should be interpreted cautiously, and preferably with accompanying sensitivity analyses.

Vector field analyses via SPM account for both vector covariance (Appendix A) and multiple comparisons across the trajectory (Appendix B) and are therefore more objective than scalar extraction analysis. A second advantage of SPM is analysis efficiency. Whereas scalar parameterizations of COP trajectories can lead to tabulated results for on-the-order-of 50 different parameters [3], SPM efficiently focusses on just a single parameter, the vector field **r**(q). This focus on **r**(q) is consistent with most studies' null hypotheses, which implicitly pertain to a single entity: the COP trajectory as a whole. To justify scalar extraction one would have to devise explicit *a priori* hypotheses regarding each extracted scalar.

In summary, this study has shown that temporally normalized COP trajectories can be analyzed in their original form using SPM, and that *ad hoc* scalar simplification is generally biased because it fails to account for both vector covariance and multiple comparisons across time. This study also confirms previous reports of COP coordinate system sensitivity, implying that vector statistics are better suited to generalized COP analyses.

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Conflict of interest

None declared.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.gaitpost.2014.01.023.

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