New insights into the plantar pressure correlates of walking speed using pedobarographic statistical parametric mapping (pSPM)

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Abstract

This study investigates the relation between walking speed and the distribution of peak plantar pressure and compares a traditional ten-region subsampling (10RS) technique with a new technique: pedobarographic statistical parametric mapping (pSPM). Adapted from cerebral fMRI methodology, pSPM is a digital image processing technique that registers foot pressure images such that homologous structures optimally overlap, thereby enabling statistical tests to be conducted at the pixel level. Following previous experimental protocols, we collected pedobarographic records from 10 subjects walking at three different speeds: slow, normal, and fast. Walking speed was recorded and correlated with the peak pressures extracted from the 10 regions, and subsequently with the peak pixel data extracted after pSPM preprocessing. Both methods revealed significant positive correlation between peak plantar pressure and walking speed over the rearfoot and distal forefoot after Bonferroni correction for multiple comparisons. The 10RS analysis found positive correlation in the midfoot and medial proximal forefoot, but the pixel data exhibited significant negative correlation throughout these regions ($p < 5 \times 10^{-5}$). Comparing the statistical maps from the two approaches shows that subsampling may conflate pressure differences evident in pixel-level data, obscuring or even reversing statistical trends. The negative correlation observed in the midfoot implies reduced longitudinal arch collapse with higher walking speeds. We infer that this results from pre- or early-stance phase muscle activity and speculate that preferred walking speed reflects, in part, a balance between the energy required to tighten the longitudinal arch and the apparent propulsive benefits of the stiffened arch.

Keywords: Plantar pressure; Gait biomechanics; Stance phase; Biomedical image processing; Plantar aponeurosis; Longitudinal arch; Midfoot; Locomotor efficiency

1. Introduction

The human foot is a complex structure that constitutes the primary mechanical interface between our bodies and the environment. As walking speed increases, the foot must transmit increasing propulsive impulsion to the ground, the mechanics of which are not fully understood (Zatsiorsky et al., 1994; Alexander, 2004; Erdemir et al., 2004; Erdemir and Piazza, 2004). Previous studies have demonstrated that peak pressures are positively correlated with walking speed across the plantar surface of the foot (Rosenbaum et al., 1994; Zhu et al., 1995; Drerup et al., 2001; Burnfield et al., 2004; Segal et al., 2004; Taylor et al., 2004; Warren et al., 2004; Yang et al., 2005). The only exception is that, in some of these studies, a peak pressure decrease was observed in the lateral midfoot as a function of walking speed, but this trend either failed to reach significance (Drerup et al., 2001; Taylor et al., 2004) or was not explicitly discussed (Rosenbaum et al., 1994; Segal et al., 2004).

We believe that a decrease in midfoot peak pressure is non-trivial because it implies decreased longitudinal arch collapse modulated by pre-stance or early stance muscular...
activity. If the arch is not loaded in this manner, the higher vertical ground reaction forces associated with faster walking speeds (Keller et al., 1996) would cause the arch to collapse to a greater extent. Decreased longitudinal arch collapse would thus imply that there is some propulsive benefit, direct or indirect, to active arch collapse prevention. To our knowledge this issue has not been explicitly addressed in the biomechanics literature.

All previous studies of the plantar pressure correlates of walking speed have employed traditional subsampling methodology. ‘Subsampling’ refers to spatial data reduction; the foot is discretized into on the order of 10 regions (Rosenbaum and Becker, 1997), and one metric is extracted per region (usually the maximal pressure). While effectively reducing the large data set to a manageable size, the main problem with subsampling is that it ignores most of the data. An adult foot can contact over 500 sensors when using currently available commercial hardware, so subsampling can entail an approximately 50-fold decrease in spatial information. Disposing of so much data could be problematic if there is substantial intra-region variation.

Here we employ the established cerebral fMRI methodology: ‘Statistical parametric mapping’ (SPM) (Friston et al., 1995) to analyze pedobarographic images collected for a range of walking speeds. The technique first registers plantar pressure images such that homologous structures optimally overlap, and then conducts pixel-level statistical tests using a mass univariate approach. The result is a continuous statistical map that can be viewed in the context of the original foot pressure images.

The purposes of the current study were: (1) to use SPM to clarify the midfoot pressure correlates of walking speed, and (2) to corroborate the results with those obtained using a traditional ten-region subsampling (10RS) technique.

2. Methods

2.1. Design

Ten males (age: 28.8 ± 8.3 years, height: 177.1 ± 8.3 cm, mass: 76.1 ± 11.7 kg) volunteered to participate in this experiment. Following previous studies (Rosenbaum et al., 1994; Burnfield et al., 2004; Taylor et al., 2004; Yang et al., 2005), subjects were asked to walk either ‘slow’, ‘normal’, or ‘fast’ over a 10 m gait runway. Right foot pressure data were collected at 500 Hz using a 0.5 m Footscan 3D system (RSscan, Olen, Belgium). A Kistler force plate (model 8281B, Winterthur, Switzerland) was used to continuously calibrate the pressure data. Subjects took four steps before contacting the pressure plate. Walking speed was measured as the average velocity of a single reflective marker that was strapped to the participant’s abdomen; motion was recorded at 50 Hz using a six camera ProReflex system (Qualysys, Gothenburg, Sweden). Twenty repetitions of each speed were performed in random order, yielding a total of 600 pedobarographic records. To avoid gait adjustments due to pressure plate targeting, subjects used tape to mark starting positions and were given 15 min to practise the three walking speeds. They were instructed to look forward and to disregard foot placement; if their foot landed outside the sensing zone of the equipment, the trial was discarded and immediately repeated. This type of failure occurred, on average, 2.8 times over the 60 trials. Prior to participation subjects gave informed consent according to the policies of the Research Ethics Committee of the University of Liverpool.

2.2. Pedobarographic statistical parametric mapping

Pedobarographic SPM (pSPM) analyses were conducted on peak pressure images and consisted of three main steps: (1) Image generation, (2) Registration, and (3) Statistical tests. All analyses were implemented in MATLAB 7.4 (The MathWorks, USA).

The images produced by the RSscan software had pixel coordinates spaced 5.08 and 7.62 mm in the horizontal and vertical directions, respectively (manufacturer specified). To produce an image on a square grid and thus accurately depict foot geometry, pixel coordinates were mapped to new locations using a vertical stretching transformation:

\[ y = \begin{pmatrix} 1 & 0 \\ 0 & 7.62/5.08 \end{pmatrix} x \]  

(1)

The transformed image was then obtained by resampling over the new coordinates using bilinear interpolation (Goshtasby, 2005). Images were then registered (Mainitz and Viergever, 1998) and spatially smoothed using a recently described algorithm that minimized the mean squared error between the images (Pataky and Goulermas, in press) such that homologous structures optimally overlapped. The first normal walking peak pressure image was used as the registration template for each subject. All within-subjects (WS) images were registered to this template using an optimal rigid-body transformation and were then registered again to the resulting mean image. Between-subjects (BS) registration was performed once per subject using the mean images and an optimal affine transformation.

Following Friston et al. (1995), statistical analyses were conducted using linear mass-univariate parametric regression models. The WS model was:

\[ I_y = (\beta_1)_{i} + (\beta_2)_{i} t_i + (\beta_3)_{i} + e_{ij} \]  

(2)

where \( I_y \) is the pressure observation at the \( j \)th pixel in the \( i \)th trial, \( e_{ij} \) is the walking SPEED, and \( t_i \) models an experimental TIME drift nuisance factor across the experimental session; we chose to include a linearly varying \( t_i \) factor in the statistical model after observing a small baseline drift in the force plate (≈20 N/h). The \( \beta \) are unknown regression parameters. The residuals (\( e_{ij} \)) are assumed to be normally distributed. In a subsidiary analysis we tested this assumption using pixel-level Kolmogorov–Smirnov tests (Conover, 1971); such analysis is not strictly necessary (see Discussion), but is included to emphasize registration quality and the nature of the data.

The BS model was

\[ I_y = (\beta_1)_{i} + (\beta_2)_{i} t_i + (\beta_3)_{i} s_i + (\beta_4)_{i} + e_{ij} \]  

(3)

where \( s_i \) is a nuisance factor that blocks SUBJECTS to account for gross differences (e.g. body weight). Here \( k \) and \( l \) index the 10 experimental sessions (one per subject) and the nine SUBJECT degrees of freedom, respectively. We note that the TIME and SUBJECT nuisance effects are not of empirical interest. Including these terms both isolates SPEED effects and protects against type II error.

Pixel test statistics having the Student’s \( r \) distribution were computed according to Friston et al. (1995). To demonstrate the statistical robustness of the current data set, statistical inferences were made with both an uncorrected \( p \) threshold of 0.05 and a Bonferroni threshold of \( 5 \times 10^{-5} \) to correct for multiple comparisons.

2.3. Ten-region subsampling (10RS)

Commercial software (Footscan 7, RSscan) was used to automatically define 10 anatomical regions (Fig. 1A) for the template image of each subject. Regional peak pressures were then extracted from the WS registered images (Fig. 1B and C) and statistical tests were conducted using the models above (Eqs. (2) and (3)). We corrected for multiple
comparisons using a Bonferroni threshold of $p < 0.0051$ (across the 10 regions). Differences between 10RS and pSPM results were assessed qualitatively.

3. Results

3.1. Walking speed

The average normal walking speed was $1.44 \pm 0.14$ m s$^{-1}$. Slow and fast speeds differed from normal by approximately $0.45 \pm 0.15$ (1.09 ± 0.15 and 1.95 ± 0.15, respectively). ANOVA found significant effects of SPEED, SUBJECT, and SPEED × SUBJECT ($p < 0.001$) indicating that we adequately controlled walking speed. The SUBJECT and SPEED × SUBJECT effects were not considered problematic because our statistical model incorporated recorded velocity directly in the linear regressions and also blocked SUBJECT effects.

3.2. Peak pressure

Mean images exhibited a general increase in peak pressure with SPEED (Fig. 2A), a trend that was also observable at the pixel level (Fig. 2B). Pixel data tended to be normally distributed within conditions (Fig. 2C). Within-subjects (WS) 10RS and pSPM analyses confirmed statistical significance of the general positive correlation between peak pressure and SPEED (Fig. 3), but pSPM also found areas of negative correlation in the midfoot and/or proximal forefoot in all subjects.
The 10RS analysis (Fig. 3A) obscured these results. Most notably, 10RS midfoot data exhibited positive correlation in most subjects. Between-subjects (BS) correlations were highly significant (Fig. 4). The 10RS midfoot data exhibited strong positive correlation (Fig. 4A), representing a clear departure from the pixel data, which were negatively correlated broadly over the midfoot and proximal forefoot (Fig. 4B and C). Apparent discrepancies between these data and the WS data can be explained by the smaller WS data sets and also narrow midfoot contact regions; the midfoot and forefoot trends emerge with the larger BS data set.

Both the BS and WS results were insensitive to \( p \) thresholding; statistical clusters sizes reduced slightly with the harsh Bonferroni correction (Figs. 3B and C, 4B and C), but the data were qualitatively identical irrespective of threshold.

### 3.3. Statistical assumptions

The statistical models (Eqs. (2) and (3)) assume that the residuals \( e_{ij} \) are normally distributed. Kolmogorov–Smirnov tests revealed that only the foot periphery was associated with non-normality in the WS registered images (Fig. 5), attesting to both successful registration and statistical assumption validity. Kolmogorov–Smirnov results were similar for BS registered images (Fig. 6) except for the posterior midfoot region, which exhibited non-normal residuals. We observed, however, that removing high arched subjects one-by-one from the data set caused the midfoot residuals to become increasingly normally distributed (data not presented in interest of space). Thus the non-normal midfoot residuals in the BS images are attributable to arch height differences across subjects and are responsible for the lower \( t \) values in the posterior midfoot (Fig. 4B).

We also note that the proximal forefoot, an area associated with highly negative peak pressure correlation, exhibited normally distributed residuals (Fig. 6). We infer that the midfoot data reflect a spatially continuous extension of the proximal midfoot trends, the significance of which is weakened by slight non-normality due to anatomical rather than functional variability.
4. Discussion

The current pSPM results reproduced previous findings of general positive correlation between plantar pressure and walking speed (Rosenbaum et al., 1994; Drerup et al., 2001; Burnfield et al., 2004; Segal et al., 2004; Taylor et al., 2004; Yang et al., 2005). The current 10RS (Fig. 4A) data were nearly identical to those of Rosenbaum et al. (1994, p. 194) and were very similar to the data of three other studies (Drerup et al., 2001; Segal et al., 2004; Taylor et al., 2004), indicating that our subjects and data set are consistent with published studies. The two main new findings were that: (1) midfoot and proximal forefoot peak pressures decrease as walking speed increases, and (2) subsampling can produce erroneous results. These findings are addressed separately.

4.1. Stance-phase foot biomechanics

The negative correlation between peak pressure and walking speed observed over the midfoot and proximal forefoot indicates reduced longitudinal arch collapse. In the absence of muscle activity, the main arch support is provided passively by the plantar aponeurosis (PA) via the windlass mechanism (Hicks, 1954). If arch height was supported only passively then one would expect the opposite of what we observed: that the longitudinal arch would collapse to a greater extent under the larger ground reaction forces associated with faster walking (Keller et al., 1996). We must therefore infer that pre- or early stance phase muscle activity was responsible for preventing arch collapse. This contention is supported by previous findings of general increases in ankle EMG with walking speed (Hof et al., 2002; Warren et al., 2004; Neptune and Sasaki, 2005). Many muscles can perform this function, including especially: the toe dorsiflexors (Hicks, 1954; Carlson et al., 2000) and the ankle plantar flexors (Carlson et al., 2000; Erdemir et al., 2004).

But why is it beneficial to actively prevent arch collapse? One possibility is that arch stiffness itself has propulsive benefits via elastic energy return, although such energy return is expected mainly during jogging and running (Ker et al., 1987). Another is that PA loading may improve propulsive force transmission (Erdemir and Piazza, 2004), a possibility highlighted by data showing compromised propulsion following plantar fasciotomy (Daly et al., 1992). A third possibility is that increased arch stiffness is necessary to achieve semi-rigid leverage for propulsion (Bojsen-Moller, 1979). Reduced arch collapse may also be secondary to some other mechanism whose function varies systematically with walking speed.

If we assume that PA tension is directly beneficial to propulsion, then the current data are somewhat resolved. Muscular loading of the PA via toe dorsiflexion (Hicks, 1954; Carlson et al., 2000) and/or Achilles tendon tension (Erdemir et al., 2004) would imply that arch collapse prevention is secondary to the propulsive benefits associated with increased PA tension. Published in vivo PA data are scarce but show that longitudinal arch collapse effectively loads the PA prior to push off (Gefen, 2003). Pre-loading the PA would prevent arch collapse but would also lead to increased PA tension in late stance phase following the inevitable albeit reduced passive arch collapse. This could increase the rearward pull on the forefoot during late stance phase and thus assist propulsion.

If this assumption is valid, then the current data suggest that the speed-dependent changes in PA behaviour may be an important factor for determining preferred walking speed. That is, it is conceivable that the body balances the muscular work required to pre-load the PA in early stance phase with the propulsive work done by the PA in late stance phase. Such ideas warrant modelling efforts to
elucidate the PA’s propulsive role. Presently, we may conclude only that the data suggest that reduced longitudinal arch collapse is either directly beneficial to or symptomatic of walking at faster speeds.

4.2. Pedobarographic methodology

The main methodological finding was that subsampling can produce erroneous results. The current 10RS method found positive correlation in the midfoot and medial forefoot, findings that are consistent with six previous studies (Rosenbaum et al., 1994; Drerup et al., 2001; Burnfield et al., 2004; Segal et al., 2004; Taylor et al., 2004; Yang et al., 2005), but that are inconsistent with the pixel-level data. Subsampling distorted the forefoot effects and reversed the midfoot effects, showing a negative correlation only in the lateral forefoot (Fig. 4A), identical to the data of Rosenbaum et al. (1994).

Since the current subsampled data were consistent with previous studies we attribute the negative midfoot correlation finding to pSPM’s ability to detect such differences rather than to data peculiarities. The contradiction between the two methods can be explained by the midfoot region definition. Its posterior edge encroaches on the anterior heel, a region associated with high pressure.
(Fig. 2A) and positive correlation with walking speed (Fig. 4B and C). Since subsampling extracts only a single maximum value, the 10RS midfoot data are driven by this high anterior heel pressure.

The subsampling results (Fig. 4A) would lead one to infer that load shifts medially as speed increases; this is indeed what has been inferred previously (Rosenbaum et al., 1994). However, the pixel-level data (Fig. 4B and C) elucidate that the decreased peak pressure actually occurs across the entire midfoot and proximal forefoot, both medially and laterally. This observation is critical because it implies that employing subsampling methods may produce results that lead to incorrect interpretations of foot biomechanics.

The functional brain imaging community has largely abandoned subsampling (termed “Region of Interest” analysis in the literature) in favour of SPM analyses for precisely these reasons. Defining physical boundaries on arbitrary regions constitutes a biased ad hoc solution that disregards the spatial structure inherent in the data. We thus recommend that pedobarographical analyses should include all regional pixel data rather than just single regional values.

We must note that regional hypotheses may still be tested in the context of pixel-level statistical mapping. One approach is to examine the profile of the statistical map in the vicinity of a specified region, without defining hard spatial limits (Friston, 1997). The only adjustment to the methodology is at the level of statistical inference. Implementing such regional tests is facilitated by pSPM preprocessing methodology because anatomical segmentation needs to be performed only once on a template image. Image registration then ensures efficient homologous data extraction.

One statistical challenge peculiar to pedobarographic SPM is the inclusion of subjects with varying longitudinal arch heights in a common statistical model. This is a challenge because high arched subjects (e.g. Subjects 2 and 6, Fig. 3) will exhibit many null midfoot values. The continuous statistical fields observed in the current data set allowed us to retain a parametric approach and to assume that the lower midfoot significance was a result of null observation model with an arbitrary number of levels. In such cases a non-parametric approach may be more suitable.

An additional statistical challenge is power analysis or, equivalently, protection against Type II error. Power analysis is not currently relevant because we found significant effects across the entire foot surface (the null effects observed in the normality analyses are subsidiary results that we consider demonstrative of the nature of the data rather than constituting a scientific result). We caution that power analyses (Friston et al., 1996) would be necessary in cases where pSPM results procure conclusions of no significant effects of experimental treatments.

A third important statistical issue is SPM-based inference and the multiple comparisons problem. In this paper we used a simple Bonferroni correction to control for family-wise Type I error over the search area, an approach which ignores the spatial structure of the pSPMs. Grounding statistical inferences in random field theory (Friston et al., 1995) furnishes a much more sensitive analysis because it accounts for spatial smoothness in the underlying data. One does not need to control for pixel-level Type I error but rather only for Type I error in local maxima or ‘blobs’ in the smooth pSPMs. The critical thresholds can be derived from distributional approximations as a function of the residual term smoothness. We intend to demonstrate this in future applications when the sensitivity of detecting group differences becomes more of an issue.

The final statistical issue requiring discussion is residual normality. We have presented a spatial analysis of normality (Figs. 5 and 6) for completeness, to show that the raw (registered) data conform to the statistical assumptions. This is not necessary in general because typical SPM analyses smooth data prior to inference which, by the central limit theorem, ensures that the residuals are normally distributed. Interestingly, if the data are smoothed with a very large kernel corresponding to the size of the 10RS regions, the results would converge roughly to the current 10RS data. This emphasizes a weakness of the subsampling approach; greater spatial smoothing yields small spatial precision of the inferences that ensue.

We finally note that one individual in the current data set (Subject 9, Fig. 3) had excessive pronation. Despite the apparent pathology, this subject’s foot was successfully registered to the BS template (Fig. 6). This highlights the generalized nature of pSPM’s algorithms and indicates that it may be possible to compare healthy and pathological populations directly using pSPM. Such comparisons would require random effects modelling (Holmes and Friston, 1998), where each subject effect is treated as a random variable. The current paper employed fixed effects BS analysis; subject effects were treated as fixed free parameters. To implement random effects analysis, one would create WS contrast images and then submit these pSPMs to a second level between-subject analysis where a one-sample t-test can test the null hypothesis that the particular effect was zero. For example, the effect of walking speed could be summarized with the map of regression coefficients $\beta_1$ (Eq. (3)) for each subject and these speed-dependent summaries could be used to compare normal and patient groups. This is an established procedure in human brain mapping and can be generalised to any hierarchical observation model with an arbitrary number of levels.

5. Summary

Using a cerebral fMRI protocol adapted for pedobarographic image analysis, we found that midfoot and proximal forefoot peak plantar pressures are negatively...
correlated with walking speed. This is a novel result which suggests that early stance phase muscular activity prevents arch collapse to achieve a propulsive benefit, possibly via PA tension. We also found that traditional subsampling methods obscure and may even reverse statistical trends, demonstrating that subsampling may lead to incorrect inferences regarding foot function. Pedobarographic studies should consider pixel-level data where possible.

Conflict of interest statement

Software that performs the analyses described herein is associated with a UK Patent application (reference # GB0725094.7, filed 21 December 2007). The authors confirm the scientific integrity of all data presented in this manuscript and report no other conflict of interest.

Acknowledgements

Financial support was provided by the Leverhulme Trust (Grant F/0025/x) and NERC (Grants GR3/11202 and GR3/12004).

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