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Short communication

Pooling sexes when assessing ground reaction forces during walking: Statistical Parametric Mapping versus traditional approach

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ABSTRACT

Ground reaction force (GRF) data from men and women are commonly pooled for analyses. However, it may not be justifiable to pool sexes on the basis of discrete parameters extracted from continuous GRF gait waveforms because this can miss continuous effects. Forty healthy participants (20 men and 20 women) walked at a cadence of 100 steps per minute across two force plates, recording GRFs. Two statistical methods were used to test the null hypothesis of no mean GRF differences between sexes: (i) Statistical Parametric Mapping—using the entire three-component GRF waveform; and (ii) traditional approach—using the first and second vertical GRF peaks. Statistical Parametric Mapping results suggested large sex differences, which post-hoc analyses suggested were due predominantly to higher anterior–posterior and vertical GRFs in early stance in women compared to men. Statistically significant differences were observed for the first GRF peak and similar values for the second GRF peak. These contrasting results emphasise that different parts of the waveform have different signal strengths and thus that one may use the traditional approach to choose arbitrary metrics and make arbitrary conclusions. We suggest that researchers and clinicians consider both the entire gait waveforms and sex-specificity when analysing GRF data.

1. Introduction

Three-dimensional (3D) ground reaction forces (GRFs) during walking have been used to assess differences in gait patterns for people with various disorders and to assess effectiveness of interventions (Fransz et al., 2013), to determine risk for injury (Fransz et al., 2013), to develop shoe components (Castro et al., 2014; Liedtke et al., 2007), and as input for biomechanical models (Winter, 2009). Typically, GRF analyses have relied on parameters extracted from discrete points of gait waveforms (for example the first vertical GRF peak during load acceptance), calculating time integrals (for example GRF impulses) of the curves, or loading rates (for example the slope from the initial contact to the first vertical GRF peak). Consequently, this traditional approach of discrete parameter extraction is limited to specific events or summary metrics. Thus other parts of the gait waveform that may be meaningful, are not assessed. Moreover, extraction of discrete parameters often leads to testing of multiple variables, with increased risk of Type 1 error. Although corrections for multiple comparisons have been used (e.g. Bonferroni's correction), this approach generally inflates Type II error because multiple variables extracted from a single waveform tend to be correlated (Friston et al., 2007; Pataky et al., 2013). Recently, the use of the Statistical Parametric Mapping (SPM) method and random field theory (RFT) were proposed for gait analyses, and it appears to be a good alternative to overcome the aforementioned limitations (Pataky et al., 2013; Pataky, 2010).

Effects of sex on anatomical factors, such as skeleton alignment and flexibility (Krivickas, 1997), in gait kinematics (Hurd et al., 2004; Kerrigan et al., 1998), and electromyography (Chumanov et al., 2008) have been suggested. Such differences may affect the adaptation of the human body to external forces, including GRFs, and be an important factor to explain sex-specific prevalence of musculoskeletal disorders (Cross et al., 2014; Vardaxis and Goulermas, 2006). While discrete values from the vertical GRF waveform have shown differences between sexes at the first and second vertical GRF peaks (Chiu and Wang, 2007). GRF data from men and

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women are more commonly pooled for analyses when control groups and patients with gait disorders are compared (Schmalz et al., 2014; Liddle et al., 2000; Nolan and Lees, 2000), or to verify the effect of interventions on walking (Castro et al., 2013; Doets et al., 2007; Hansen et al., 2006). However, it may not be justifiable to pool sexes on the basis of discrete parameters extracted from continuous GRF waveform because this can miss continuous effects. We aimed to use two statistical methods to explore whether pooling sexes while assessing GRFs during walking is justifiable. For that, we used two techniques to test the null hypothesis of equal mean three-component GRF waveforms between sexes: (i) we used SPM to analyse the entire three-component waveform with a single two-sample Hotelling's T^2 test; and (ii) we used a traditional approach to analyse the first and second vertical GRF peaks with two separate two-sample t tests. These two peaks were selected because they yielded opposite conclusions (see Results), and this highlights the fact that the discrete approach permits arbitrary metric analysis. Before analysing the data we expected that sex pooling may not be always appropriate for GRF data when based on discrete parameters because those parameters may be limited in temporal scope.

2. Methods

2.1. Participants

A convenience sample of 20 healthy male (with mean age of 21.8 ± 3.7, weight 73.1 ± 6.6 kg, height 177.8 ± 6.4 cm, body mass index—BMI 23.5 ± 1.9 kg/m^2) and 20 healthy female (with mean age of 21.4 ± 3.3, weight 59.1 ± 6.6 kg, height 164.0 ± 5.5 cm, and BMI 22.2 ± 2.9 kg/m^2) participants was recruited. Subjects with any kind of pain, neurological or musculoskeletal disorder were excluded. The two groups showed similar ages (t=0.365, p=0.717) and BMIs (t=1.596, p=0.120). The study was approved by the local ethical committee, and all participants gave their written consent prior to data collection.

2.2. Procedures

The GRFs were recorded by two force plates (FP4060-07-1000 and FP4060-10-2000, Bertec Corporation, Columbus, OH, USA) of the same size (width of 400 mm, and length of 600 mm) and operating at 1000 Hz, embedded mid-way in a 12-metres walkway. Participants wore neutral shoes (ballet sneakers) and walked across the walkway and force plates at a cadence of 100 steps per minute, controlled by a metronome software (Metronome Beat, AndyStone). We used this gait cadence because it was most commonly adopted when the participants freely walked in pilot studies. The participants familiarised themselves with the environment, the neutral shoes and the gait cadence by walking on the walkway. One of the researchers subjectively assessed the participants' gait pattern to observe whether they were walking at the required gait cadence with their natural gait pattern. Then three trials were obtained per participant. Each trial consisted of a minimum of eight steps with three steps prior to hitting the first force plate and, at least, three steps following the second force plate. Thus the fourth and fifth steps were on the first and second force plates, respectively. This protocol generally ensures a steady state of walking (Macfarlane and Looney, 2008). Gait symmetry was assumed (Goble et al., 2003) and data from both lower limbs from the three trials were used for analyses.

2.3. Statistics

2.3.1. Statistical Parametric Mapping

We used a two-sample waveform-level Hotelling's T^2 test as described elsewhere (Pataky et al., 2013). Briefly, we first scaled GRF data to the participants' body weight and temporally normalised by stance phase duration using linear interpolation which is more conservative for detecting group differences than is nonlinear temporal normalisation (Sadeghi et al., 2003). Then the mean GRF vector difference between males and females was computed at each point in time. Afterwards this vector difference waveform was normalised by the instantaneous covariance to yield a scalar T^2 test statistic waveform. We used RFT to compute the critical threshold (T2*) above which only α=5% of T2 would reach if produced by completely random 3D Gaussian vector waveforms with identical smoothness as the observed residual waveforms. From a classical hypothesis testing perspective a T2 waveform which exceeds T2* leads to null hypothesis rejection at α. Next, we computed probability (p) values for all threshold-surviving clusters using RFT expectations regarding suprathreshold cluster breadth (Friston et al., 1994). Last, we conducted post-hoc tests on individual GRF components (Pataky, 2012) to explore the relative contributions of each component to the vector (T2*) results.

2.3.2. Traditional approach

To illustrate that extraction of discrete parameters can lead to arbitrary conclusions we separately analyzed the first and second vertical GRF peaks, which we found a posteriori to yield opposite conclusions (see Section 3). We used two-sample t tests to compare sexes with α set at 0.05. Just like SPM, the traditional approach uses α to determine a critical test statistic threshold (t^*) and if the observed t value exceeds t^* then the null hypothesis is rejected. The only difference is that SPM uses a model of smooth 1D waveform randomness, and the traditional approach uses a model of 0D scalar randomness (Pataky et al., 2015).

3. Results

3.1. Statistical Parametric Mapping

Random 3D waveforms would produce a T2 waveform as high as the observed T2 waveform (Fig.1) with a probability less than α=5%. We therefore reject the null hypothesis of equal mean three-component waveforms between sexes. In particular, sex differences as manifested in the observed T2 waveform were greater than the critical threshold both at the beginning of the stance (between 0% and 5%) and between 70% and 80% of the stance phase (referred to as pre-swing phase). Post-hoc analyses suggested statistically significant between-sex differences for the anterior–posterior and vertical GRF components for early stance, while no statistically significant differences were found for the GRF components for pre-swing (Fig. 2). The discrepancy between vector analysis and post-hoc analyses for pre-swing may have occurred because the covariance between GRF components is not considered when analysing individual components (Pataky et al., 2013). Women had higher anterior–posterior and vertical GRFs during early stance (Fig. 3) and tended to have higher vertical GRF during pre-swing compared to men (Fig. 3c). No significant differences were found for the medial–lateral GRF (Fig. 2a).

3.2. Traditional approach

The results reached significance for the first peak (t=2.765, p=0.007) with males exhibiting larger mean vertical GRF than females. Nevertheless, SPM results failed to reach significance in the region of the first peak (Fig.2c). This emphasises the fact that the traditional approach uses a threshold for significance which is too low to control Type I error at the whole-waveform level. Traditional results for the second vertical GRF peak failed to reach statistical significance (t=0.746, p=0.458). The effects at the first-

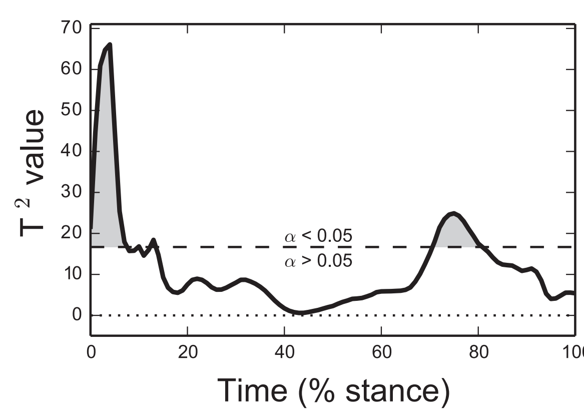

Fig. 1. Main hypothesis test results (two-sample waveform-level Hotelling's T^2 test). The wider horizontal dotted line indicates the critical random field theory threshold.

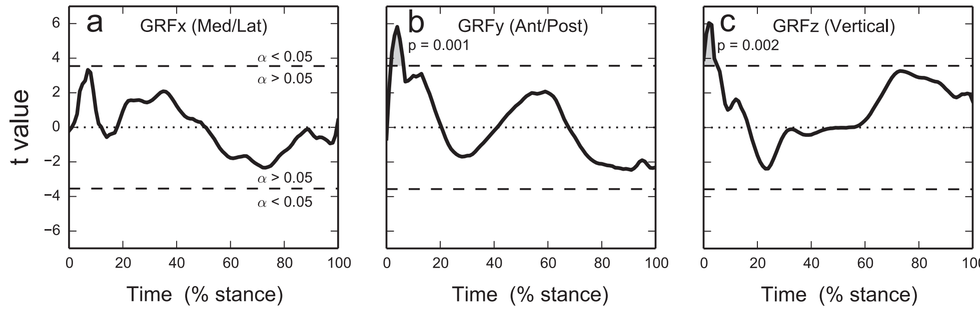

Fig. 2. Post-hoc tests on individual ground reaction force (GRF) components: (a) Medial–lateral GRF, (b) Anterior–posterior GRF, and (c) Vertical GRF.

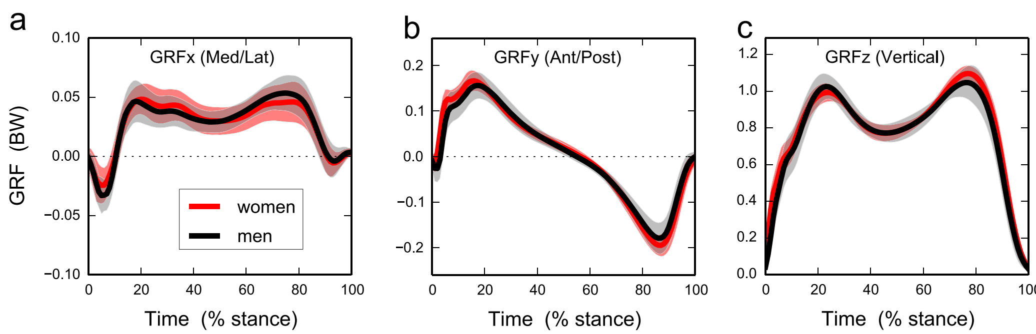

Fig. 3. Mean and standard deviation clouds of ground reaction forces (GRF) during walking of men and women: (a) Medial–lateral GRF, (b) Anterior–posterior GRF, and (c) Vertical GRF.

and second-vertical GRF peak were not only unequal in magnitude but also in direction (Fig.3c), and this was reflected in the t value trajectory at approximately time=20% and 80%, respectively (Fig.2c). Effect magnitude and direction similarly changed over time in the two other GRF components (Fig.2a and b). This poses a problem for the traditional approach, because the same dataset could yield opposite conclusions.

4. Discussion

For this dataset, SPM results suggest that sex pooling is not appropriate when assessing the 3D GRF gait waveforms. We also observed that sex pooling may appear to be appropriate or inappropriate depending on which discrete parameter one selects. Moreover, we observed that discrete parameters may reach significance even when there is no waveform-level evidence of significance. The discrepancy is caused by the randomness model from which p values and critical thresholds are computed. SPM uses a 1D model of randomness and the traditional approach uses a 0D model, and it has recently been shown that a 0D model of randomness is inappropriate for making probabilistic conclusions regarding 1D data (Pataky et al., 2015). Equivalently, if one's hypothesis explicitly or implicitly pertains to the entire three-component 1D GRF waveform, then we would argue that one is obliged to analyze the entire three-component waveform using SPM or another method which employs a multi-component 1D model of randomness.

In terms of sex pooling, the SPM result is unambiguous: since significant waveform-level differences were observed between sexes, it would appear inappropriate to pool sexes for this dataset. The traditional approach contrastingly produced ambiguous conclusions: sex pooling appears appropriate if based on second-peak results, but appears inappropriate if based on first-peak results. SPM avoids this problem because just one test is conducted and therefore just one conclusion is made.

A previous study assessing discrete parameters extracted from the vertical GRF gait waveform found higher first and second vertical GRF peaks for women than men (Chiu and Wang, 2007). Results from the present study with both statistical techniques (SPM and traditional approach) disagree with those findings. Differences between populations, protocol of gait assessment and data analysis may thus contribute towards different conclusions. The authors (Chiu and Wang, 2007) pooled data from three groups walking at different gait cadences (from 101 to 138 steps per min) and with different levels of exertion, as well as it is unclear whether the discrete parameters were explicitly identified before the experiment as the empirical variables of interest. In our study both males and females walked at the same gait cadence, with similar low levels of effort, and the entire gait waveform was assessed.

5. Conclusion

The results of this study suggest advantages of using SPM for justifying group pooling because it conducts just a single waveform-level test and therefore yields a single unambiguous conclusion regarding data pooling. The traditional approach yields comparatively ambiguous results because one may choose arbitrary metrics which yield multiple and potentially conflicting results. For the specific GRF dataset investigated in this paper, our results suggest that, if there were truly no sex differences, random waveforms would produce the observed mean three-component waveform differences with a probability less than 5%. Therefore sex pooling appears to be inappropriate for this dataset. We suggest that researchers and clinicians consider both the entire gait waveform and sex-specificity when analysing GRF data.

Conflict of interest statement

The authors declare no competing interests.

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