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Short communication

Reproducibility of a new signal processing technique to assess joint sway during standing

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ABSTRACT

Postural control strategies can be investigated by kinematic analysis of joint movements. However, current research is focussing mainly on the analysis of centre of pressure excursion and lacks consensus on how to assess joint movement during postural control tasks. This study introduces a new signal processing technique to comprehensively quantify joint sway during standing and evaluates its reproducibility. Fifteen patients with non-specific low back pain and ten asymptomatic participants performed three repetitions of a 60-second standing task on foam surface. This procedure was repeated on a second day. Lumbar spine movement was recorded using an inertial measurement system. The signal was temporally divided into six sections. Two outcome variables (mean absolute sway and sways per second) were calculated for each section. The reproducibility of single and averaged measurements was quantified with linear mixed-effects models and the generalizability theory. A single measurement of ten seconds duration revealed reliability coefficients of .75 for mean absolute sway and .76 for sways per second. Averaging a measurement of 40 seconds duration on two different days revealed reliability coefficients higher than .90 for both outcome variables. The outcome variables' reliability compares favourably to previously published results using different signal processing techniques or centre of pressure excursion. The introduced signal processing technique with two outcome variables to quantify joint sway during standing proved to be a highly reliable method. Since different populations, tasks or measurement tools could influence reproducibility, further investigation in other settings is still necessary. Nevertheless, the presented method has been shown to be highly promising.

1. Introduction

Postural control is defined as the ability to keep or regain a specific posture, such as standing (Pollock et al., 2000). Commonly, this ability is quantified by centre of pressure excursion (Mazaheri et al., 2013). Postural control strategies are described as a feedback mechanism derived by the interaction of sensory input and adapted motor output (Hodges, 2004). Centre of pressure excursion represents whole body movement and does not differentiate between joints. Kinematic measures of joint sway would give more insight into postural control strategies. Joint sway was previously assessed by the standard deviation of angular displacement (Mientjes and Frank, 1999). Standard deviation is one measure of sway but quantifies only its amplitude. This study introduces a new signal processing technique with two outcome variables to comprehensively quantify joint sway, including amplitude and frequency. The technique and its clinical application are demonstrated at the lumbar spine with both, patients suffering from low back pain and asymptomatic participants. Since filtering is a major issue in movement analysis, this study presents a new approach to finding an optimal filter, evaluating the reproducibility of the outcome variables, and recommending a reliable measurement protocol.

2. Methods

2.1. Participants

Fifteen adult patients with non-specific low back pain for longer than four weeks and ten asymptomatic, adult participants were recruited for this study. A detailed description of the recruitment procedures, as well as inclusion and exclusion criteria, is provided elsewhere (Schelldorfer et al., 2015). The study was

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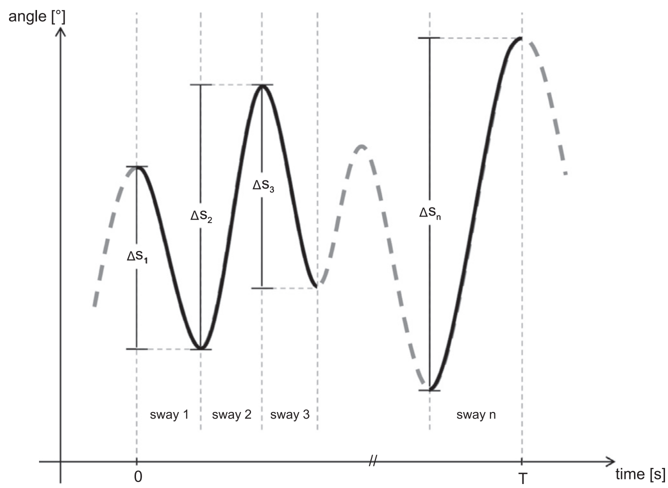

Fig. 1. Illustration of the outcome variables. ΔS_i=the angular displacement of the *i*th sway, defined by two consecutive local extrema. n=the total number of sways. T=total duration of the corresponding section.

approved by the local ethics committee. All participants signed informed consent prior to the study.

2.2. Procedure

Lumbar spine movement was measured at 200 Hz by an inertial measurement unit (IMU) system (ValedoMotion, Hocoma AG, Volketswil, Switzerland). IMUs were placed on the sacrum and the first lumbar vertebra (Ernst et al., 2013). The IMU system provides concurrently valid estimates of spinal kinematics (Bauer et al., 2015). Participants were blindfolded and instructed to stand with arms crossed and feet together as stable as possible for 60 seconds on a foam surface (Airex® Balance-Pad, height 6 cm). The task was repeated three times with self-selected resting periods between repetitions. The procedure was repeated within five days (mean interval and standard deviation: 2.6 ± 1.1 days).

2.3. Data processing

Based on the differential signal between the IMUs, the lumbar spine angles for frontal plane movements were calculated (Bauer et al., 2015). The signals were filtered by fourth-order zero-phase Butterworth filters with forty different cut-off frequencies (f_c), ranging from 1 to 40 Hz. Thereafter, the signals were divided into six sections, each of ten seconds duration. This subdivision enables recommendations about the duration of the standing task for future studies. Finally, two outcome variables were calculated for each section (Fig. 1):

$$\text{mean absolute sway (MAS)} = \frac{\sum_{i=1}^{n} |\Delta S_i|}{n}$$

$$\text{sways per second (SPS)} = \frac{n}{T}$$

with ΔS_i being the angular displacement of the ith sway, defined by two consecutive local extrema, n being the total number of sways, and T being the total duration of the corresponding section.

2.4. Statistical analysis

A mixed-effects model containing three fixed effects (group: low back pain and asymptomatic, age and gender) and four fully crossed random effects (participant × day × repetition × section) was fitted for each outcome variable and f_c:

$$\log Y_{gepdrs}(f_c) = \mu + \beta_{group,g} + \beta_{age} * a_p + \beta_{gender,e} + P_p + D_d + R_r + S_s + PD_{pd} + PR_{pr} + PS_{ps} + DR_{dr} + DS_{ds} + RS_{rs} + \varepsilon_{gepdrs}$$

$$g = 1,2; p = 1,2,\ldots,25; e = 1,2; d = 1,2; r = 1,2,3; s = 1,2,\ldots,6$$

with β_{group} as the gth group effect, β_{age} as the age effect, a_p as the age of participant p, β_{gender} as the e^{th} gender effect, P as the random effect of participant p, D as the random effect of day d, R as the random effect of repetition r, S as the random effect of section s and ε_{gepdrs} as unexplained error. Based on residual analysis, the logs of the outcomes were modelled.

Choosing the optimal f_c for the Butterworth filter is a compromise between the amount of signal distortion and the amount of noise allowed to pass through it (Winter, 2005). It was hypothesized that a high f_c would increase the residual sum of squares, whereas a low f_c would decrease the total sum of squares. Under both scenarios, the conditional R-squared, R^2 will decrease:

$$R^2 = 1 - \frac{\mathrm{residual\backslash sum\backslash of\backslash squares}}{\mathrm{total\backslash sum\backslash of\backslash squares}} = 1 - \frac{\sum_i (y_i - \hat{y}_i)^2}{\sum_i (y_i - \overline{y})^2},$$

with y_i being the observed value, $\hat{y}_i$ being the predicted value using random and fixed effects, and $\overline{y}$ being the mean of observed values. The optimal f_c was therefore established by maximizing the mean of the R^2 of both outcome variables:

$$f_{c,opt} = \arg\max_{f_c} \left(\frac{R^2{}_{\mathrm{MAS}}(f_c) + R^2{}_{\mathrm{SPS}}(f_c)}{2} \right)$$

Further analyses were conducted with outcome variables of the optimally filtered signals. Reproducibility was quantified according to the generalizability theory (Brennan, 2001) with the universe score being the expected value of a person over the facets of generalization D, R, and S. The index of dependability (reliability coefficient) of a single measurement was computed as the ratio of universe score variance to observed score variance:

$$\varphi_{\text{single measurement}} = \frac{\sigma_P^2}{\sigma_P^2 + \sigma_{PD}^2 + \sigma_{PR}^2 + \sigma_{PS}^2 + \sigma_D^2 + \sigma_{DR}^2 + \sigma_{DS}^2 + \sigma_R^2 + \sigma_{RS}^2 + \sigma_S^2 + \sigma_\varepsilon^2}$$

The reliability coefficient of an average measurement was given by

$$\varphi_{\text{average}}(n_D, n_R, n_S) = \frac{\sigma_P^2}{\sigma_P^2 + \frac{\sigma_{PD}^2}{n_D} + \frac{\sigma_{PR}^2}{n_R} + \frac{\sigma_{PS}^2}{n_S} + \frac{\sigma_D^2}{n_D} + \frac{\sigma_{DR}^2}{n_D * n_R} + \frac{\sigma_{DS}^2}{n_D * n_S} + \frac{\sigma_R^2}{n_R} + \frac{\sigma_{RS}^2}{n_R * n_S} + \frac{\sigma_S^2}{n_S} + \frac{\sigma_\varepsilon^2}{n_D * n_R * n_S}}$$

with n_D being the number of days, n_R the number of repetitions and n_S the duration of the measurement (e.g. n_S=3: 3*10 s = 30 s), and used to establish measurement protocols which achieve very high reliability ($\phi_{\text{average}} \geq .90$) (Carter and Lubinsky, 2015).

3. Results

The relationship between R^2 and f_c was a reversed U-shaped curve with a maximum of .88 at 26 Hz. The corresponding R^2 of MAS and SPS were .88 and .87, respectively.

The grand mean of MAS and SPS were 0.5°/sway and 30.8 sways/s. The variance components of all random effects and their interactions are listed in Table 1. Averaging both outcome variables, the sum of all variances including "day" was 0.63, including "repetition" was 0.22, and including "section" was 0.12. All values are expressed relative to the residual variance.

The reliability coefficients of averaged measurements are illustrated in Table 2. Overall, to obtain highly reliable results, it is required to take measurements once for 40 seconds on two different days and to calculate the average of each section and day.

Table 1
Variance components of the random effects, expressed relatively to the variance of residuals.

	mean absolute sway (MAS)	sways per second (SPS)
σ_P^2	6.19	6.09
σ_{PD}^2	0.63	0.61
σ_{PR}^2	0.23	0.15
σ_{PS}^2	0.05	0.04
σ_D^2	0.00	0.00
σ_{DR}^2	0.01	0.02
σ_{DS}^2	0.00	0.00
σ_R^2	0.01	0.02
σ_{RS}^2	0.00	0.00
σ_S^2	0.09	0.06
$\sigma_D^2+\sigma_{PD}^2+\sigma_{DR}^2+\sigma_{DS}^2$	0.64	0.63
$\sigma_R^2+\sigma_{PR}^2+\sigma_{DR}^2+\sigma_{RS}^2$	0.25	0.18
$\sigma_S^2+\sigma_{PS}^2+\sigma_{DS}^2+\sigma_{RS}^2$	0.14	0.10
σ_ε^2	1.00	1.00

σ^2, relative variance; P, participant; D, day; R, repetition; S, section.