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.

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.

Methods

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

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).

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 (Figure 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 i^{th} sway, defined by two consecutive local extrema, n being the total number of sways, and T being the total duration of the corresponding section.

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 x day x repetition x 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 g^{th} 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:

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

with y_i being the observed value, $\hat{y}_i$ being the predicted value using random and fixed effects, and $\bar{y}$ 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:

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

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*10s = 30s), and used to establish measurement protocols which achieve very high reliability ($\phi_{\text{average}} \geq .90$) (Carter and Lubinsky, 2015).

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. Using this design, the standard errors of measurements are 0.03 °/sway for MAS and 0.02 sways/s for SPS.

Fixed effects are expressed as relative changes: ($e^{\text{fixed effect}}$ – 1)*100 %. Low back pain patients had 7 % higher MAS values and 3 % lower SPS values compared to asymptomatic participants. Female participants had 12 % higher MAS values and 4 % lower SPS values than male participants. The age effect for one year was plus 0.1 % for MAS values and minus 0.1 % for SPS values. None of the effects were statistically significant.

Discussion

The chosen approach to establish the optimal f_c showed a distinct maximum at 26 Hz. If the approach was applied to MAS and SPS separately, the results would have been 20 Hz and 26 Hz, respectively. However, a single f_c was preferred to maintain comparability of the results.

The sum of variance components including “day” as the random factor was more than twice as high as those including “repetition” or “section”. Therefore, the daily state of participants and/ or the placement of IMUs might have a high impact on the outcome variables. The reliability of MAS and SPS was .89 when averaging three repetitions and a duration of 60 seconds, which compares favourably to previously established scores using the same measurement protocol, but different outcome variables (Schelldorfer et al., 2015). Averaging over two days, three repetitions and a duration of 30 seconds, as in a previous study investigating centre of pressure measures, the reliability of MAS and SPS was .93, which is again favourable compared to previous results that ranged from .51 to .74 (Salavati et al., 2009). The sample size of the current study was smaller compared to the first study and similar compared to the second study. Still, it remains questionable how an increased sample size would have affected the current results.

None of the fixed effects were statistically significant and their interpretation remains questionable. The reason for including fixed effects in the model was to correct for previously established factors which affect between-participants variance (σ_P^2) (Schelldorfer et al., 2015). Still, R^2 of the final model was .88, meaning that 12 % of the total variance was caused by unknown factors.

The new signal processing technique with two outcome variables to quantify joint sway during standing is a highly reliable method when the postural control task lasts for 40 seconds and is performed on two different days. The chosen outcome variables assess the amplitude and frequency of lumbar spine sway on average. They do not represent the complexity of postural control during standing completely. Lumbar spine movement was chosen as an example to introduce the new technique, as a previous study demonstrated significantly altered lumbar spine sway in patients suffering from low back pain compared to asymptomatic controls (Schelldorfer et al., 2015). However, since different body joints, populations, tasks, or measurement tools could influence reproducibility, further investigations in other settings are still necessary. Nevertheless, the presented method has been shown to be highly promising.

Conflict of interest statement

None of the authors are aware of any financial or personal relationships with other people or organizations that could improperly influence this work.

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Table 1

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

	mean absolute sway (MAS)	sways per second (SPS)
σ^2_{P}	6.19	6.09
σ^2_{PD}	0.63	0.61
σ^2_{PR}	0.23	0.15
σ^2_{PS}	0.05	0.04
σ^2_{D}	0.00	0.00
σ^2_{DR}	0.01	0.02
σ^2_{DS}	0.00	0.00
σ^2_{R}	0.01	0.02
σ^2_{RS}	0.00	0.00
σ^2_{S}	0.09	0.06
$\sigma^2_{D} + \sigma^2_{PD} + \sigma^2_{DR} + \sigma^2_{DS}$	0.64	0.63
$\sigma^2_{R} + \sigma^2_{PR} + \sigma^2_{DR} + \sigma^2_{RS}$	0.25	0.18
$\sigma^2_{S} + \sigma^2_{PS} + \sigma^2_{DS} + \sigma^2_{RS}$	0.14	0.10
σ^2_{ε}	1.00	1.00

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

Table 2

Reliability coefficient $\phi_{average}$, when using the average of repeated measures.

$n_D = 1$	mean absolute sway (MAS)						$n_D = 1$	sways per second (SPS)					
n_R \ n_S	1	2	3	4	5	6	n_R \ n_S	1	2	3	4	5	6
1	.75	.81	.83	.84	.85	.85	1	.76	.82	.84	.85	.86	.86
2	.82	.85	.86	.87	.87	.88	2	.82	.86	.87	.88	.88	.88
3	.84	.87	.88	.88	.88	.89	3	.85	.87	.88	.89	.89	.89
$n_D = 2$	mean absolute sway (MAS)						$n_D = 2$	sways per second (SPS)					
n_R \ n_S	1	2	3	4	5	6	n_R \ n_S	1	2	3	4	5	6
1	.84	.88	.89	**.90**	**.90**	**.90**	1	.85	.89	**.90**	**.91**	**.91**	**.91**
2	.88	**.91**	**.92**	**.92**	**.92**	**.92**	2	.89	**.91**	**.92**	**.93**	**.93**	**.93**
3	**.90**	**.92**	**.93**	**.93**	**.93**	**.93**	3	**.91**	**.92**	**.93**	**.93**	**.94**	**.94**

n_D, number of days; n_R, number of repetitions; n_S, number of sections; bold numbers indicate a value higher than .90.

Figure Captions

Figure 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.