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

2   **standing**

3   Fabian Marcel Rast[1], Judith Verena Graser[1,2], André Meichtry[1], Markus Josef Ernst[1], and

4   Christoph Michael Bauer[1]

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6   [1]School of Health Professions, Institute of Physiotherapy, Zurich University of Applied

7   Sciences, Winterthur, Zurich, Switzerland; [2]Rehabilitation Center for Children and

8   Adolescents, University Children's Hospital Zurich, Affoltern am Albis, Zurich, Switzerland.

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12   **Correspondence Address:** Fabian Rast, Technikumstrasse 71, P.O. Box, CH-8401

13   Winterthur, Switzerland | Phone: +41 (0) 58 934 63 30 | Fax: +41 (0) 58 935 63 30 |

14   fabian.rast@zhaw.ch

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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

65   Lumbar spine movement was measured at 200 Hz by an inertial measurement unit

66   (IMU) system (ValedoMotion, Hocoma AG, Volketswil, Switzerland). IMUs were placed on

67   the sacrum and the first lumbar vertebra (Ernst et al., 2013). The IMU system provides

68   concurrently valid estimates of spinal kinematics (Bauer et al., 2015). Participants were

69   blindfolded and instructed to stand with arms crossed and feet together as stable as possible

70   for 60 seconds on a foam surface (Airex® Balance-Pad, height 6 cm). The task was repeated

71   three times with self-selected resting periods between repetitions. The procedure was repeated

72   within five days (mean interval and standard deviation: 2.6±1.1 days).

73   **Data processing**

74   Based on the differential signal between the IMUs, the lumbar spine angles for frontal

75   plane movements were calculated (Bauer et al., 2015). The signals were filtered by

76   fourth-order zero-phase Butterworth filters with forty different cut-off frequencies (f_c),

77   ranging from 1 to 40 Hz. Thereafter, the signals were divided into six sections, each of ten

78   seconds duration. This subdivision enables recommendations about the duration of the

79   standing task for future studies. Finally, two outcome variables were calculated for each

80   section (Figure 1):

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

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

81   with ΔS_i being the angular displacement of the ith sway, defined by two consecutive local

82   extrema, n being the total number of sways, and T being the total duration of the

83   corresponding section.

84   **Statistical analysis**

85   A mixed-effects model containing three fixed effects (group: low back pain and

86   asymptomatic, age and gender) and four fully crossed random effects (participant x day x

87   repetition x section) was fitted for each outcome variable and f_c:

$$\log Y_{gepdrs}(f_c) = \mu + \beta_{group,g} + \beta_{age} * a_p + \beta_{gender,e} + P_p + D_d + R_r + S_s + PD_{pd} + PR_{pr}$$

$$+ PS_{ps} + DR_{dr} + DS_{ds} + RS_{rs} + \varepsilon_{gepdrs}$$

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

88   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

89   the eth gender effect, P as the random effect of participant p, D as the random effect of day d,

90   R as the random effect of repetition r, S as the random effect of section s and ε_{gepdrs} as

91   unexplained error. Based on residual analysis, the logs of the outcomes were modelled.

92   Choosing the optimal f_c for the Butterworth filter is a compromise between the amount

93   of signal distortion and the amount of noise allowed to pass through it (Winter, 2005). It was

94   hypothesized that a high f_c would increase the residual sum of squares, whereas a low f_c

95   would decrease the total sum of squares. Under both scenarios, the conditional R-squared, R^2

96   will decrease:

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

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

98   and $\bar{y}$ being the mean of observed values. The optimal f_c was therefore established by

99   maximizing the mean of the R^2 of both outcome variables:

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

100   Further analyses were conducted with outcome variables of the optimally filtered signals.

101   Reproducibility was quantified according to the generalizability theory (Brennan, 2001) with

102   the universe score being the expected value of a person over the facets of generalization D, R,

103   and S. The index of dependability (reliability coefficient) of a single measurement was

104   computed as the ratio of universe score variance to observed score variance:

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

105   The reliability coefficient of an average measurement was given by

$$\varphi_{average}(n_D, n_R, n_S)$$

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

106   with n_D being the number of days, n_R the number of repetitions and n_S the duration of the

107   measurement (e.g. $n_S = 3$: 3*10s = 30s), and used to establish measurement protocols which

108   achieve very high reliability ($\phi_{average} \geq .90$) (Carter and Lubinsky, 2015).

Results

110   The relationship between R^2 and f_c was a reversed U-shaped curve with a maximum of

111   .88 at 26 Hz. The corresponding R^2 of MAS and SPS were .88 and .87, respectively.

112   The grand mean of MAS and SPS were 0.5 °/sway and 30.8 sways/s. The variance

113   components of all random effects and their interactions are listed in Table 1. Averaging both

114   outcome variables, the sum of all variances including "day" was 0.63, including "repetition"

115   was 0.22, and including "section" was 0.12. All values are expressed relative to the residual

116   variance.

117   The reliability coefficients of averaged measurements are illustrated in Table 2.

118   Overall, to obtain highly reliable results, it is required to take measurements once for 40

119   seconds on two different days and to calculate the average of each section and day. Using this

120   design, the standard errors of measurements are 0.03 °/sway for MAS and 0.02 sways/s for

121   SPS.

122   Fixed effects are expressed as relative changes: $(e^{fixed\ effect} - 1)*100$ %. Low back pain

123   patients had 7 % higher MAS values and 3 % lower SPS values compared to asymptomatic

124   participants. Female participants had 12 % higher MAS values and 4 % lower SPS values

125   than male participants. The age effect for one year was plus 0.1 % for MAS values and minus

126   0.1 % for SPS values. None of the effects were statistically significant.

Discussion

127

128   The chosen approach to establish the optimal f_c showed a distinct maximum at 26 Hz.

129 If the approach was applied to MAS and SPS separately, the results would have been 20 Hz

130 and 26 Hz, respectively. However, a single f_c was preferred to maintain comparability of the

131 results.

132   The sum of variance components including "day" as the random factor was more than

133 twice as high as those including "repetition" or "section". Therefore, the daily state of

134 participants and/ or the placement of IMUs might have a high impact on the outcome

135 variables. The reliability of MAS and SPS was .89 when averaging three repetitions and a

136 duration of 60 seconds, which compares favourably to previously established scores using the

137 same measurement protocol, but different outcome variables (Schelldorfer et al., 2015).

138 Averaging over two days, three repetitions and a duration of 30 seconds, as in a previous

139 study investigating centre of pressure measures, the reliability of MAS and SPS was .93,

140 which is again favourable compared to previous results that ranged from .51 to .74 (Salavati et

141 al., 2009). The sample size of the current study was smaller compared to the first study and

142 similar compared to the second study. Still, it remains questionable how an increased sample

143 size would have affected the current results.

144   None of the fixed effects were statistically significant and their interpretation remains

145 questionable. The reason for including fixed effects in the model was to correct for previously

146 established factors which affect between-participants variance (σ_P^2) (Schelldorfer et al.,

147 2015). Still, R^2 of the final model was .88, meaning that 12 % of the total variance was caused

148 by unknown factors.

149   The new signal processing technique with two outcome variables to quantify joint

150 sway during standing is a highly reliable method when the postural control task lasts for 40

151 seconds and is performed on two different days. The chosen outcome variables assess the

152 amplitude and frequency of lumbar spine sway on average. They do not represent the

153 complexity of postural control during standing completely. Lumbar spine movement was

154 chosen as an example to introduce the new technique, as a previous study demonstrated

155 significantly altered lumbar spine sway in patients suffering from low back pain compared to

156 asymptomatic controls (Schelldorfer et al., 2015). However, since different body joints,

157 populations, tasks, or measurement tools could influence reproducibility, further

158 investigations in other settings are still necessary. Nevertheless, the presented method has

159 been shown to be highly promising.

160 **Conflict of interest statement**

161 None of the authors are aware of any financial or personal relationships with other

162 people or organizations that could improperly influence this work.

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168 **References**

169 Bauer, C.M., Rast, F.M., Ernst, M.J., Kool, J., Oetiker, S., Rissanen, S.M., Suni, J.H.,
170   Kankaanpää, M., 2015. Concurrent validity and reliability of a novel wireless inertial
171   measurement system to assess trunk movement. J. Electromyogr. Kinesiol. 25, 782–
172   790.
173 Brennan, R.L., 2001. Generalizability Theory, Statistics for Social and Behavioral Sciences.
174   Springer, Berlin.
175 Carter, R., Lubinsky, J., 2015. Rehabilitation Research: Principles and Applications, 4th
176   edition. ed. Elsevier Health Sciences.
177 Ernst, M.J., Rast, F.M., Bauer, C.M., Marcar, V.L., Kool, J., 2013. Determination of thoracic
178   and lumbar spinal processes by their percentage position between C7 and the PSIS
179   level. BMC Res. Notes 6, 58.
180 Hodges, P.W., 2004. Motor control of the trunk, in: Grieve's Modern Manual Therapy.
181   Elsevier Churchill Livingstone, Edinburgh, pp. 119–39.
182 Mazaheri, M., Coenen, P., Parnianpour, M., Kiers, H., van Dieën, J.H., 2013. Low back pain
183   and postural sway during quiet standing with and without sensory manipulation: a
184   systematic review. Gait Posture 37, 12–22.
185 Mientjes, M.I., Frank, J.S., 1999. Balance in chronic low back pain patients compared to
186   healthy people under various conditions in upright standing. Clin. Biomech. Bristol
187   Avon 14, 710–716.

188 Pollock, A.S., Durward, B.R., Rowe, P.J., Paul, J.P., 2000. What is balance? Clin. Rehabil.
189   14, 402–406.
190 Salavati, M., Hadian, M.R., Mazaheri, M., Negahban, H., Ebrahimi, I., Talebian, S., Jafari,
191   A.H., Sanjari, M.A., Sohani, S.M., Parnianpour, M., 2009. Test-retest reliability
192   [corrected] of center of pressure measures of postural stability during quiet standing in
193   a group with musculoskeletal disorders consisting of low back pain, anterior cruciate
194   ligament injury and functional ankle instability. Gait Posture 29, 460–464.
195 Schelldorfer, S., Ernst, M.J., Rast, F.M., Bauer, C.M., Meichtry, A., Kool, J., 2015. Low back
196   pain and postural control, effects of task difficulty on centre of pressure and spinal
197   kinematics. Gait Posture 41, 112–118.
198 Winter, D.A., 2005. Biomechanics and Motor Control of Human Movement, 3rd ed. Wiley,
199   Waterloo.
200

201 **Table 1**

202 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

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

204

205 **Table 2**

206 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_S / n_R	1	2	3	4	5	6	n_S / n_R	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_S / n_R	1	2	3	4	5	6	n_S / n_R	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**

207 n_D, number of days; n_R, number of repetitions; n_S, number of sections; bold numbers indicate

208 a value higher than .90.

209 **Figure Captions**

210 **Figure 1** Illustration of the outcome variables. ΔS_i = the angular displacement of the ith

211 sway, defined by two consecutive local extrema. n = the total number of sways. T = total

212 duration of the corresponding section.