Linear and Nonlinear Dynamic Methods towards Investigating Proprioception Impairment in Non-specific Low Back Pain Patients

Seyed Mohammadreza Shokouhyan[a], Mehrdad Davoudi[a], Maryam Hoviat Talab[a], Mohsen Abedi[b], Soha Bervis[c], Mohamad Parnianpour[a], Simon Brumagne[d], Kinda Khalaf[e] *

[a] Department of Mechanical Engineering, Sharif University of Technology, Tehran, Iran

[b] Physiotherapy Research Center, School of Rehabilitation, Shahid Beheshti University of Medical Science, Tehran, Iran

[c] Physical Therapy Department, School of Rehabilitation sciences, Shiraz University of Medical Science, Shiraz, Iran

[d] Department of Rehabilitation Sciences, KU Leuven, Leuven, Belgium

[e] Department of Biomedical Engineering, Khalifa University of Science and Technology, and Healthcare Engineering Innovation Center, Abu Dhabi, UAE

Abstract

Central nervous system (CNS) uses vision, vestibular, and somatosensory information to maintain body stability. Research has shown that there is more lumbar proprioception error among low back pain (LBP) individuals as compared to healthy people. In this study, two groups of 20 healthy people and 20 non-specific low back pain participants (LBP) took part in this investigation. This investigation focused on somatosensory sensors and in order to alter proprioception, a vibrator (frequency of 70Hz, amplitude of 0.5 mm) was placed on the soleus muscle area of each leg and two vibrators were placed bilaterally across the lower back muscles. Individuals, whose vision was occluded, were placed on two surfaces (foam and rigid) on force plate, and trunk angles were recorded simultaneously. Tests were performed in 8 separate trials; the independent variables were vibration (4 levels) and surface (2 levels) for within subjects and 2 groups (healthy and LBP) for between subjects ($4\times2\times2$). MANOVA and multi-factor ANOVA tests were done. Linear parameters for center of pressure (COP) (deviation of amplitude, deviation of velocity, phase plane portrait (PPP), and overall mean velocity) and nonlinear parameters for COP and trunk angle ((recurrence quantification analysis) RQA and Lyapunov exponents) were chosen as dependent variables. Results indicated that NSLBP individuals relied more on ankle proprioception for postural stability. Similarly, RQA parameters for the COP on both sides and for the trunk sagittal angle indicated more repeated patterns of movement among the LBP cohort. Analysis of short and long Lyapunov exponents showed that people with LBP caused no use of all joints in their bodies (non-flexible), are less stable than healthy subjects.

Keywords: Posture control, low back pain, COP, proprioception, Recurrence Quantification Analysis, Vibrator

1. Introduction

60 to 80 percent of the world's population have experienced at least one incidence of low back pain (LBP) in their lifetime (Waddell, 1987; Burton et al., 1995; Méndez and Gómez-Conesa, 2001; Truchon, 2001), with 15% reporting pain in the acute range (Liebenson, 1996). Overall, the documented monthly prevalence of LBP is estimated around 23.2% (Hoy et al., 2012). Although

* Corresponding author at: Department of Biomedical Engineering, Khalifa University of Science and Technology, and Healthcare Engineering Innovation Center, Abu Dhabi, UAE. cell phone number: , fax number: , kinda.khalaf@ku.ac.ae

46   LBP is very common among people between the ages of 35-55(Sarker et al., 2017), it impacts
47   individuals of all ages. Indeed, reports indicate that low back pain represents a prevalent limiting
48   physical factor for adults under 45 years of age, and is considered as the most common cause of job-
49   related disability and a key contributor to missed work days. Health economists estimate that the
50   caring cost for 15% of people with low back pain is equivalent to taking care of 85% of the remaining
51   population (Hashemi et al., 1997; Hashemi et al., 1998; Filiz et al., 2005). The cost of treating
52   patients with low back pain has major economic implications. In the U.S. alone, the direct and indirect
53   costs associated with LBP range from $84 billion to $624 billion annually (Dagenais et al., 2008).
54   In 2006, American insurance claims associated with low back pain were estimated at $100-200
55   billion, 66% of which was due to loss of revenue and reduced productivity (Katz, 2006; Rubin,
56   2007; Dagenais et al., 2008). Importantly, prevalence of LBP has increased by more than 50%
57   since 1990, and is projected to continue to increase specially in low and middle income countries
58   (LMICs) where resources are limited and the lifestyle is rapidly becoming more sedentary (Clark and
59   Horton, 2018).
60
61   Although postural control for LBP patients is an active area of research, many questions remain
62   unanswered, particularly in terms of changes in sensory input and proprioception. In terms of the
63   physiological processes associated with postural control, it is assumed that once the human neuronal
64   control system senses a deviation associated with the trunk reference location, it sends commands for
65   producing corrective ankle torque to counteract such deviations. This process, however, is highly
66   dependent on the integrity of the three sensory systems: the vision, vestibular, and somatosensory
67   systems. It is likely that the disruption of any one of these systems would negatively impact the final
68   output of the postural system.
69   The proprioception sensory system or central processing of proprioception information may be
70   impaired in individuals with chronic low back pain (della Volpe et al., 2006). It should be noted,
71   however, that the compromised delivery of proprioceptive information does not necessarily disturb
72   the postural function of a person with LBP as he/she may still have sufficient motor control to
73   overcome the deficit. Nonetheless, a disturbed sense of proprioception in people with LBP often
74   impacts their ability to control postural response, particularly when the complexity of postural
75   conditions increases (e.g. walking on unstable or uneven surfaces, standing on one leg, rapid
76   movements of the upper limb (bending), whole body vibration (X), etc.), As such, postural
77   fluctuations and consequent postural control adaptation strategies are likely to significantly increase in
78   LBP patients (della Volpe et al., 2006).
79   Brumagne et al. (Brumagne et al., 2008) indicated that individuals without LBP are more reliant on
80   ankle proprioception while standing on an unstable surface as compared to standing on a stable
81   surface. In contrast, nonspecific low back pain (NSLBP) patients exhibit similar levels of reliance on
82   ankle proprioception regardless of stability conditions. Thus, the ability to discriminately employ
83   ankle proprioception strategy is decreased in NSLBP individuals. Similarly, Claeys et al. (Claeys et
84   al., 2011) reported decreased variables in postural control strategies among LBP patients during
85   standing and sitting conditions. They found that young people without LBP are able to choose an
86   optimal strategy for postural control based on postural conditions, while conversely, young adults
87   with NSLBP shows reduced variability in self-selected proprioception control strategies. Claeys et al.
88   (Claeys et al., 2012) also evaluated the variability in proprioception during sitting and rising
89   movements, demonstrating that people with low back pain used less lumbar proprioception to control
90   posture in comparison to their healthy counterparts. Claeys et al (Claeys et al., 2015) further examined
91   the potential impact of strategy change for LBP risk, with findings indicating that a higher reliance on
92   ankle-steered proprioception elevated the risk for mild NSLBP. In contrast, fluctuations in postural
93   angle, psychological variables, and physical activity levels did not increase the risk for LBP among
94   the study's cohort. This study expands previous research by describing a methodology using various
95   advanced linear and nonlinear dynamic analysis tools (RQA and Lyapunov exponents) to quantify and
96   compare proprioception control parameters (body sway and stability) between non-specific low back
97   pain patients and healthy controls towards effective personalized LBP interventional therapy and
98   treatment.
99

2. Materials and methods

2.1. Subjects specifications

40 males participated in this study. The subjects were equally divided into two groups: an NSLBP group and a healthy control group. The number of individuals in each group was estimated using the literature (COP displacement) (Claeys et al., 2011), as well as a G-Power statistical software (Gpower, 2019). The inclusion criteria for the NSLBP patients included being free of vestibular disorders, radiculopathy, neurological, or respiratory disease, in addition to any surgical procedures involving the spine, neck, chest, or lumbar. After all 40 participants completed the required informed consent form approved by the University Internal Ethics Board (approved by IRB of Shahid Beheshti University of Medical Sciences, Tehran, IR, No: IR.SBMU.RETECH.REC.1396.1392), demographic data was recorded including age, height, weight, and BMI index (Table 1). Prior to experimental testing, each individual completed two questionnaires designed to assess LBP by ODI (Oswestry Disability Index) (Fairbank and Pynsent, 2000), and to rate back pain on a numerical scale by NPRS (quantization of pain), respectively (Joos et al., 1991). Individuals were then assigned to the "healthy" group if they reported ODI>6 or NPRS>0. However, all men in the healthy cohort reported zero for both NPRS and ODI questionnaires in this study. If any participant reported any pain at the time of the test, it was postponed to a later date.

Table 1 :Demographic Data of Healthy and Low Back Patients Participants

Variables	Healthy	NSLBP	p-value
N (Gender)	20 (Male)	20 (Male)	
Age	25.5($\pm$0.7)	24.5($\pm$0.9)	NS
Height (cm)	174($\pm$6.5)	172($\pm$7.5)	NS
Weight (kg)	64($\pm$8.6)	62($\pm$7.5)	NS
BMI (kg/m^2)	20.3($\pm$2.3)	21.7($\pm$2.4)	NS

2.2. Muscle proprioception

There are several ways to alter proprioception input, the most common of which is to externally vibrate the muscles (Goodwin et al., 1972; Roll and Vedel, 1982). In order to alter proprioception of the soleus and lumbar muscles, we developed an in-house vibrator apparatus equipped with four brushless DC motors to produce muscle vibration (**Figure 1**). The device was placed at the longissimus and multifidus muscles spanning the lumbar vertebrae L3 to L5, as well as in the triceps surae located at the calf of the lower legs. Previous research suggests that optimal proprioception alteration occurs at a frequency of 70 Hz (Goodwin et al., 1972; Roll and Vedel, 1982; Cordo and Gurfinkel, 2004), while another reports a frequency of 60 Hz and an amplitude of 0.5 mm as ideal for altering one's sense of proprioception (Claeys et al., 2011). The vibration frequency of our device was set to 70 Hz, with amplitude of about 0.5 mm to produce optimal altered proprioceptive data. When the vibrators were applied to the soleus muscles, dorsiflexion was externally induced. In response, the central nervous system (CNS) used the proprioceptive data to move the body rearward to maintain balance. Conversely, when the vibrations were applied to the lumbar area, an extension was externally induced, causing the CNS to execute a forward movement.
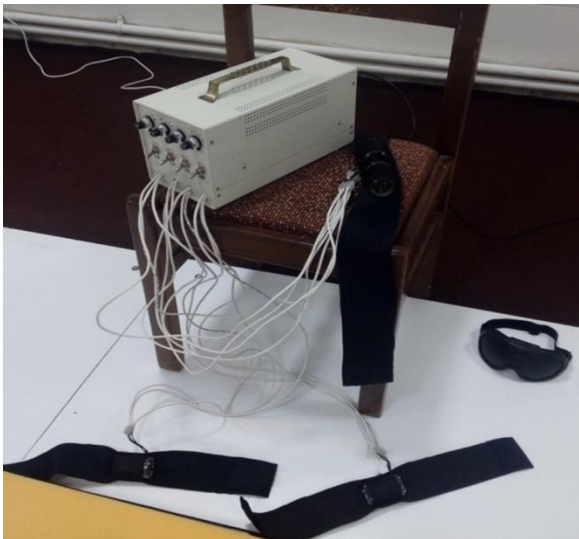
Figure 1: in-house vibrator apparatus for producing of muscle vibration

2.3. Procedure

A force plate (Bertec USA) was used to record the body's center-of-pressure (COP) fluctuations and to obtain the trunk angles through inverse dynamics. A Vicon optical motion capture system with markers synced to the force plate was used in conjunction. The markers were positioned at the C7, T12, lower sternum (xiphoid process), clavicle (*Incisura jugularis*), right scapula, right and left sides of the PSIS (posterior superior iliac spine) and ASIS (anterior superior iliac spine) based on literature. The coordinate system was defined such that the axis perpendicular to the individual's coronal plane was defined as the X-axis (anterior-psoterior (AP)), the axis perpendicular to the sagittal plane was set as the Y-axis (medial-lateral (ML)), and the Z-axis (proximal distal (PD)) was perpendicular to the transverse plane. The selected sampling frequency on both devices was 100 Hz. The motor straps were attached to the end of triceps surae muscle (muscle spindle) on each foot, and on the multifidus muscles bilaterally. Each participant, with occluded vision (using am eye mask), performed 8 separate trials as follows: 1) standing on a motionless rigid surface (without any vibrator-induced movement); 2) standing on a rigid surface with the activation of the triceps vibrators; 3) standing on a rigid surface with the activation of the multifidus vibrators; 4) standing on a rigid surface with the activation of both the triceps and multifidus vibrators; 5) standing on a motionless foam surface; 6) standing on a foam surface with the activation of the triceps vibrators; 7) standing on a foam surface with the activation of the multifidus vibrators; and 8) standing on a foam surface with the activation of both the triceps and multifidus vibrators. For each trial, COP data was recorded in both the anterior posterior (AP) and medial lateral (ML) positions; trunk angles were also recorded in the three anatomical planes. Each trial lasted 30 seconds: (1) 10 seconds with the individual standing on the force place in the absence of any vibration (the balance phase); and (2) 20 seconds when the motors were turned on at a frequency of 70 Hz (the vibration phase). The experimental set-up in this study is shown in **Figure 2** (written informed consent was obtained from the individuals for the publication of any potentially identifiable images or data included in this article).

Figure 2: Experimental set-up

164

2.4. Filtering and time series separation

In order to filter COP and trunk angle data, the exact cutoff frequency was determined acoustically via spectral analysis. The amount of signal energy was determined in terms of the frequency. 99% of signal strength for all COP and trunk sagittal angles was at a frequency of less than 5 Hz; thus, the cutoff frequency of 5 Hz was used for data filtering **(Figure 3c)**. The data was then filtered by selecting a second-order Butterworth non-linear filter, according to literature (Ghomashchi et al., 2011).

2.5. Linear analysis of COP time series

In order to analyze center-of-pressure data, the standard deviation of displacement, standard deviation of velocity, the mean total velocity, and the phase plane portrait for both anterior-posterior (AP) and medial-lateral (ML) directions were obtained according to **Eq. 5-Eq. 12   Table A (Appendix)**, in which $\bar{x}$ is the average of balance time series, x_i corresponds to each point of vibration time series, and N indicates the length of the time series.

Although COP sway toward balance condition can be explained by linear analysis, it is usually not sufficiently powerful for a detailed kinematic interpretation of physiological signal results. Thus, other nonlinear tools were required, which are explained in the following sections.

181

2.6. Nonlinear analysis of COP time series and trunk angle

2.6.1. Phase space reconstruction

The phase space for a dynamic system refers to a space in which all possible states are shown. Each possible state for the system represents a point in this space. Although there are several methods for analyzing the nonlinear time series of a phase space for a dynamic system, the Time delay method is most commonly used. The most challenging step of this method is to identify (τ) Time Delay and (m) Embedding Dimension. For a time series of scalar variables according to **Eq. 1**

$$x(t_i), \qquad i = 1, .., N \qquad\qquad\qquad \text{Eq. 1}$$

189
190   We can construct a vector in the phase space according to **Eq. 2** at any time:

$$X(t_i) = [x(t_i), x(t_i + \tau), x(t_i + 2\tau), \dots, x(t_i + (m-1)\tau)]$$ Eq. 2

191
192   Average Mutual Information (AMI) and False Nearest Neighbors (FNN) represent two standard
193   methods for determining the time-delay parameter and the embedding dimension parameter,
194   respectively (Horak, 2003). MATLAB software was used to reconstruct the phase space. For each
195   individual, the phase space was reconstructed separately for each of the three signals: APCOP,
196   MLCOP, and trunk angle. In most cases, the space embedding dimension for both the COP and trunk
197   angle was 3. The time delay was assumed to be the first minimal relative for each person.
198   Subsequently, the obtained phase space was verified using Chaos Data Analyzer software (Sprott,
199   1998), which confirmed the validity of the embedding dimension value. Time delay and embedding
200   dimension values for COP and trunk data were assessed for each person individually and are
201   summarized in **Table 2**.
202
203   **Table 2: Embedding Dimension and Time delay values used as Input parameters for phase space
204   reconstruction of COP and Trunk angle**

	COP		Trunk angle
	AP	ML	
Embedding Dimension	**3 or 4**	**3 or 4**	**4 or 5**
Time delay (sec)	**0.35 - 0.6**	**0.35 - 0.6**	**0.1 - 0.2**

205
206
207   ### 2.6.2. RQA method
208   Another prominent method for nonlinear time series analysis is Recurrence Quantification Analysis
209   (RQA). Using this approach, the dynamic properties of a system's path in a phase space can be
210   represented in a two dimensional space. Riley et al. (Riley et al., 1999) expressed numerical criteria
211   based on diagonal lines in n recurrence plot (RP), which can be used to analyze the amount of
212   recurrence or complexity of the dynamics of an observed time series. In this study, RQA quantitative
213   measurements were calculated using the RQA software (Webber Jr, 2009), developed by Webber et
214   al. (Webber Jr and Zbilut, 2005). The Euclidean norm was used for calculating these criteria and the
215   neighborhood radius was identified (Riley et al., 1999), which was considered 2.5% of the mean
216   distance.
217   ### 2.6.3. Short and Long Terms of Lyapunov
218   Next, the phase space for both the COP and trunk angle time series were reconstructed. $X_{\bar{j}}$ can be
219   determined by exploring through all points such that its distance from the reference $X_{\bar{j}}$ is minimized,
220   according to **Eq. 3**:

$$d_i(0) = \min_{X_{\bar{j}}} \left\| X_j - X_{\bar{j}} \right\|$$ Eq. 3

221   Where $\|\dots\|$ is a Euclidean norm.
222   A Lyapunov function was used for both the COP (both directions) and trunk angle using **Eq. 4**:

$$y(i) = \frac{1}{\Delta t} \langle \ln(d_j(i)) \rangle = [\lambda] i + c$$ Eq. 4

223   Where $\langle \dots \rangle$ expresses the mean of the neighboring data points for all values of j. This function was
224   divided by the sampling time intervals (Rosenstein et al., 1993). The short term time (λ_S) scale was
225   obtained by the initial slope of the curve for the first few sampling intervals. Similarly, the long-term
226   Lyapunov (λ_L) exponent was obtained by the slope of the function after the rising interval. Positive

227 values for the two exponents represent the divergence of the two neighboring paths of phase space
228 (unstable), while negative values represent the convergence of the two neighboring paths— their
229 combination expresses the relative stability of the system. Large and positive exponents are indicators
230 of the system's dynamic instability; conversely, the larger and negative the exponents, the greater the
231 stability of the system. For this investigation, the slope of the Lyapunov function in the range of 1 to
232 30 samples determined the short-term Lyapunov, while the slope of the Lyapunov function in the
233 range of 250-500 samples determined the long-term Lyapunov exponent for both the COP and trunk-
234 angle time series.

235 **2.7. Statistical Analysis**

236 The results from the linear and nonlinear methods to obtain COP and trunk data were compared using
237 SPSS (SPSSsoftware, 2019), where analysis of variance (ANOVA) and multiple analysis of variance
238 (MANOVA) were employed to check for significant differences. In this study, the independent
239 variables consisted of the group category (healthy or NSLBP), the vibration covered muscular area
240 (triceps, multifidus, none and both), and the foot placement condition (rigid or foam) $2 \times 4 \times 2$. The
241 results were considered significant at a level of $P < 0.05$. Subsequently, all dependent variables were
242 subjected to multi-factor ANOVA, followed by Bonferroni adjustment/correction of the independent
243 variables(Field, 2013).

3. Results

245 As shown in **Table 3**, the results from the ODI and NPRS questionnaires demonstrate significant
246 differences between the healthy participants and the LBP group.
247
248
249   **Table 3: Oswestry Disabity Inventory Questionnaire and Pain Scale results from participants**

Questioners	Healthy (SD)	Patient (SD)	Significant difference
ODI-2 (0-100)			
	0	12.3(3.6)	Yes
NPRS (0-10)			
	0	2.5(1.2)	Yes

250
251 The recorded data associated with the force-plate testing was divided into two 10-second segments
252 (balance part) and one 20-second segment (vibration part). **Figure 2 a** and **2b** show the results for the
253 second trial in both directions (AP and ML), while the cutoff frequency (5 Hz) for the sample data is
254 shown in **Figure 3c** with the person standing on the stationary rigid surface with active triceps
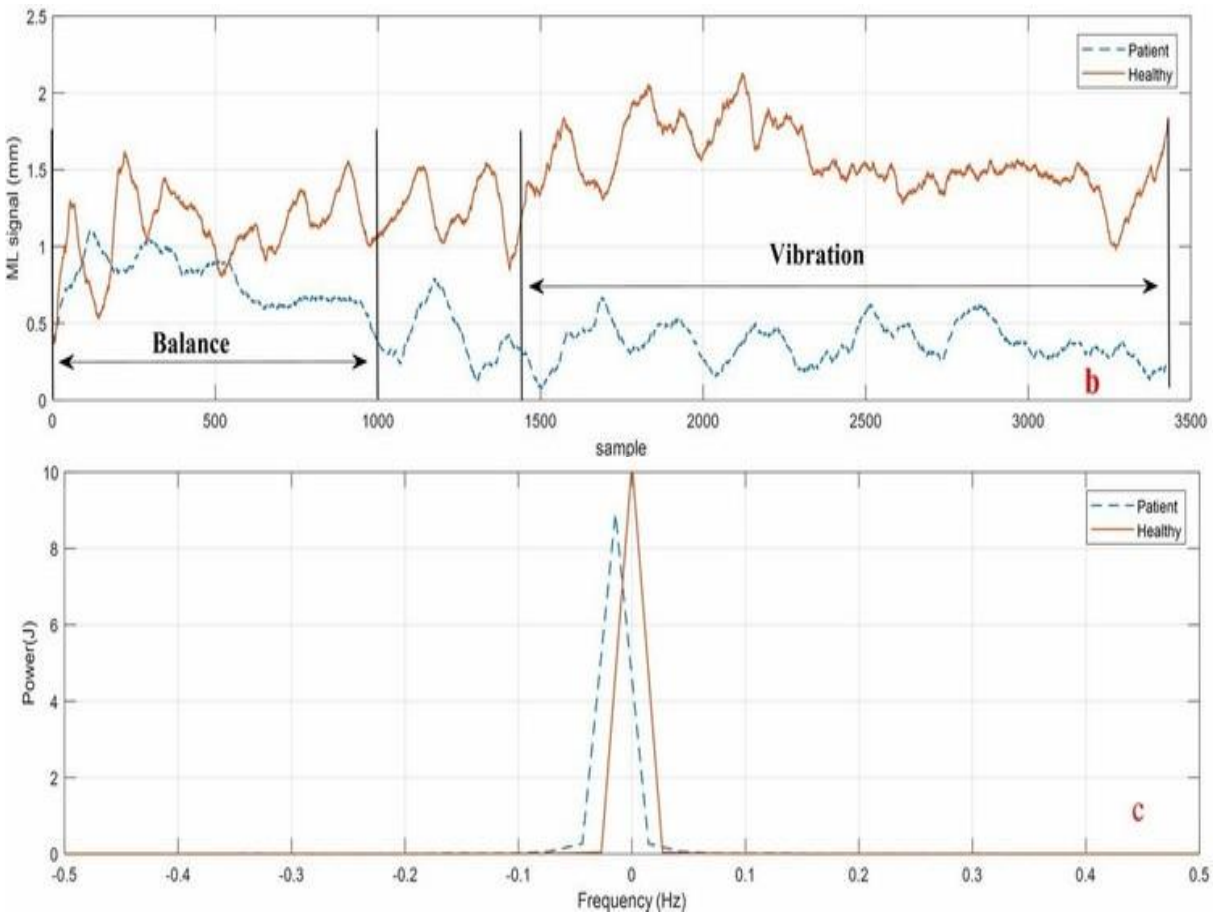255 vibrators.
256
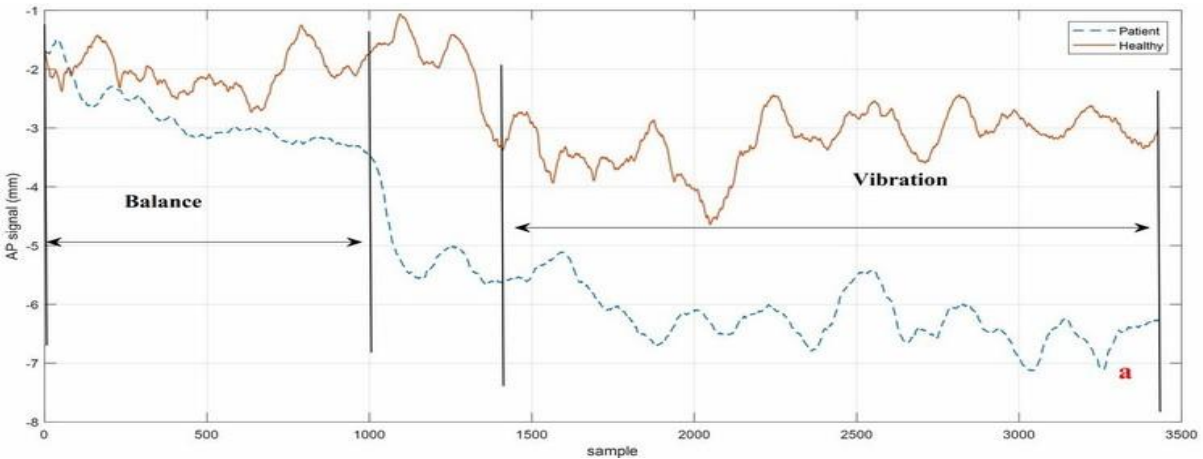
Figure 3: Divided signal and signal power of COP for a healthy subject and a LBP subject during Trial #2. a) AP direction; b) ML direction; c) signal power

The trunk kinematics (angular velocity and the angular acceleration) were obtained using sequential numerical derivatives of the trunk angular position. Since the noise effects increase may impact RQA analysis, the derivate was filtered once again. On the other hand, subsequent RQA analyses of angular velocity and angular acceleration data showed unexpected results (positive trend (+1.2)), which we attribute to the noise effect. Therefore, while no analysis was conducted on the angular velocity and acceleration of the trunk, the effect of noise on angular velocity remains uncertain and cannot be factored out from the data analysis. The angular position, velocity and acceleration for the trial #2 are depicted in **Figure 4** for both healthy and the LBP participants.
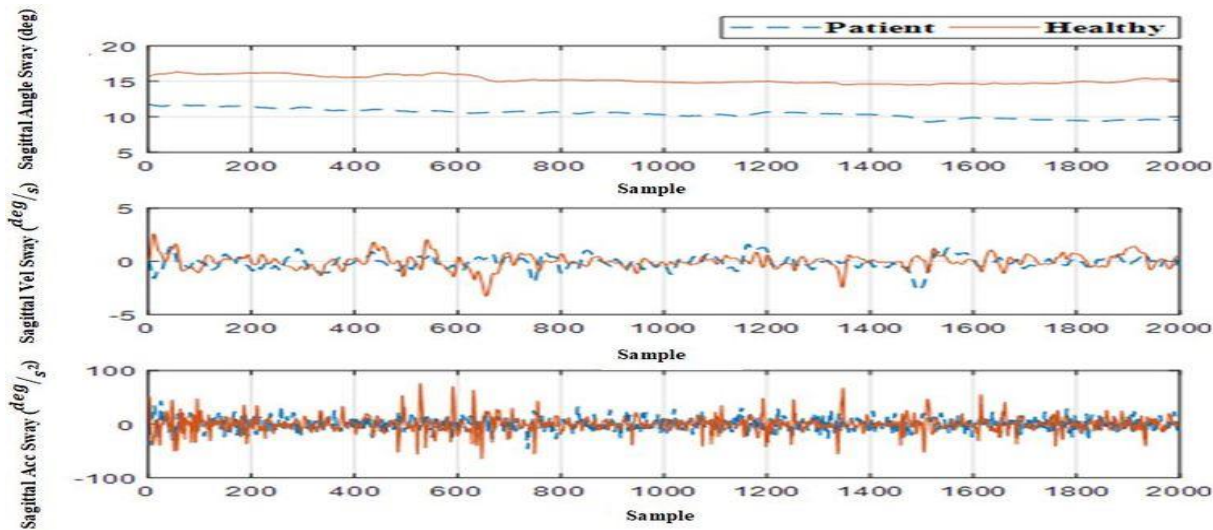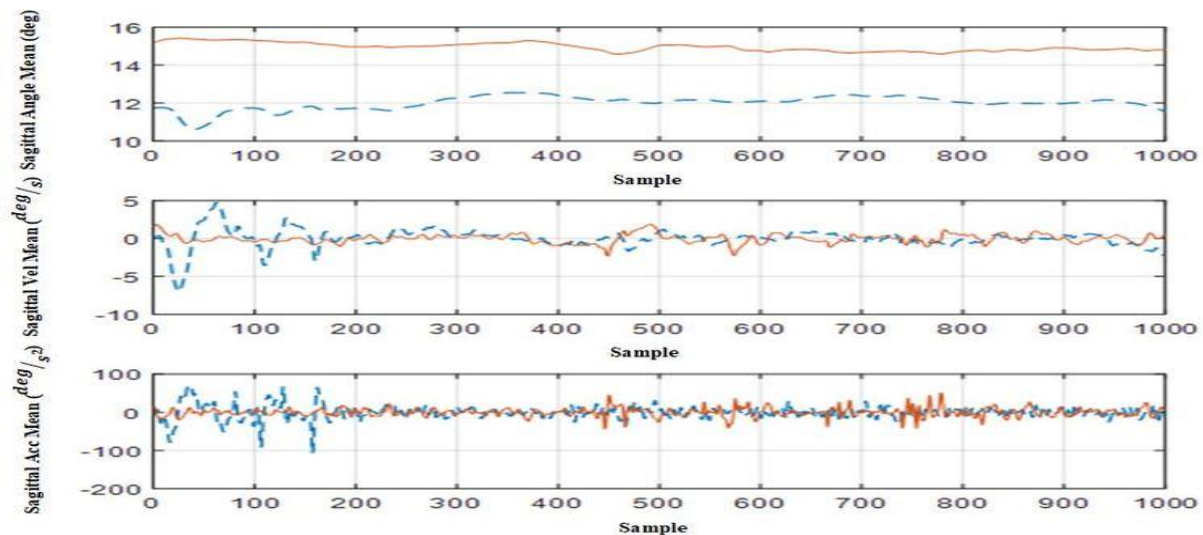
Figure 4: Angle, angular velocity, and angular acceleration of trunk in sagittal view for a healthy participant and a LBP participant in Trial #2(ankle vibration on rigid surface).

All linear parameters are listed in **Table A2** and **Table A3** of the **Appendix**. Note that the values for the linear parameter data were higher in the LBP individuals as compared with the healthy control in both the AP and ML directions for the rigid and foam conditions. This finding indicates that to maintain balance, the LBP group altered their COP more than their healthy counterparts, which made them more reliant on the ankle proprioception strategy, thereby leading to increased COP variation. These changes were evident when the ankle vibrators were activated on the foam surface (σ_x=Healthy 18.82< Patient 28.91 and σ_{v_x}=Healthy 22.11 < Patient 29.21). **Table 4** shows the results of the statistical analyses with linear parameters (units in millimeters).

Table 4: Results of Three way Analysis of Variance (ANOVA) tests for the effects of Surface, Vibration and Group on the linear parameters of COP

Independent Variable	σ_x		σ_y		σ_{v_x}		σ_{v_y}		σ_{r_x}		σ_{r_y}		V_{Total}		σ_r	
	F	P	F	P	F	P	F	P	F	P	F	P	F	P	F	P
Main Effect																
Surface	11.06	P<0.05	81.75	P<0.05	199.67	P<0.05	162.43	P<0.05	246.19	P<0.05	521.18	P<0.05	277.97	P<0.05	163.57	P<0.05
Vibration	53.43	P<0.05	14.32	P<0.05	6.35	P<0.05	18.9	P<0.05	57	P<0.05	67.76	P<0.05	24.38	P<0.05	33.67	P<0.05
Group	69.02	P<0.05	259.8	P<0.05	36.56	P<0.05	84.57	P<0.05	157.6	P<0.05	583.19	P<0.05	72.53	P<0.05	118.54	P<0.05
Interaction																
Surface× Vibration	2.48	P=0.06	4.1	P<0.05	0.73	P=0.55	2.49	P=0.06	1.82	P=0.14	9.4	P<0.05	5.72	P<0.05	1.28	P=0.28
Surface× Group	3.38	P=0.06	47.1	P<0.05	9.74	P<0.05	16.32	P<0.05	1.657	P=0.19	108.51	P<0.05	1.035	P=0.31	4.39	P<0.05
Vibration× Group	12	P<0.05	8.8	P<0.05	1.21	P=0.3	5.79	P<0.05	11.61	P<0.05	26.74	P<0.05	3.27	P<0.05	7.72	P<0.05
Surface× Vibration× Group	1.66	P=0.17	3.5	P<0.05	0.05	P=0.98	2.21	P=0.08	0.98	P=0.39	7.77	P<0.05	0.58	P=0.62	0.25	P=0.85

The RQA parameters for both the AP and ML directions of COP are shown in **Table A4** and **Table A5** (**Appendix**). Note that the value of Recurrence in the LBP cohort, as compared to the healthy group, indicates the presence of repetitive points and more repetitive sway in motor behavior, especially on foam. This was evident in the trials performed with the active vibrators **(0.45 > 0.11)**. Furthermore, the value of Determinism was greater in the LBP group as compared to the healthy individuals. This was more remarkable when the triceps vibrators were activated, especially on foam **(99.52 > 96.44)**, suggesting the reliance on more repetitive patterns among the LBP group. The Entropy value, which expresses the complexity of determinism, was also calculated. Entropy was higher for the LBP group as compared to the healthy group across most of the trials **(4.69 > 3.9)**. The trend is also shown in **Table A4** and **Table A5** (**Appendix**), which helps explain the non-stationary behavior of the system. Specifically, the amplitude of this parameter was higher in the LBP group than the healthy individuals, especially on foam with muscles vibration **(-0.89 > -0.2)**. The full

296   statistical analysis of the RQA parameters is shown in **Table A6** (**Appendix**), where most of these
297   parameters indicate significant differences between the LBP and Healthy cohort **(P<0.05)**. Results for
298   the RQA parameters of the trunk data are provided in **Table A7** and **Table A8** (**Appendix**). RQA
299   measures based on diagonal lines including Recurrence, determinism, entropy, and trend for each
300   group of the COP time series were calculated from the recurrence plots, as shown in **Figure 5** for both
301   cohorts (Trial #6). The concept of RQA parameters and their relationship with the diagonal lines can
302   be found in (van den Hoorn et al., 2018). The results of the statistical analyses are provided in **Table**
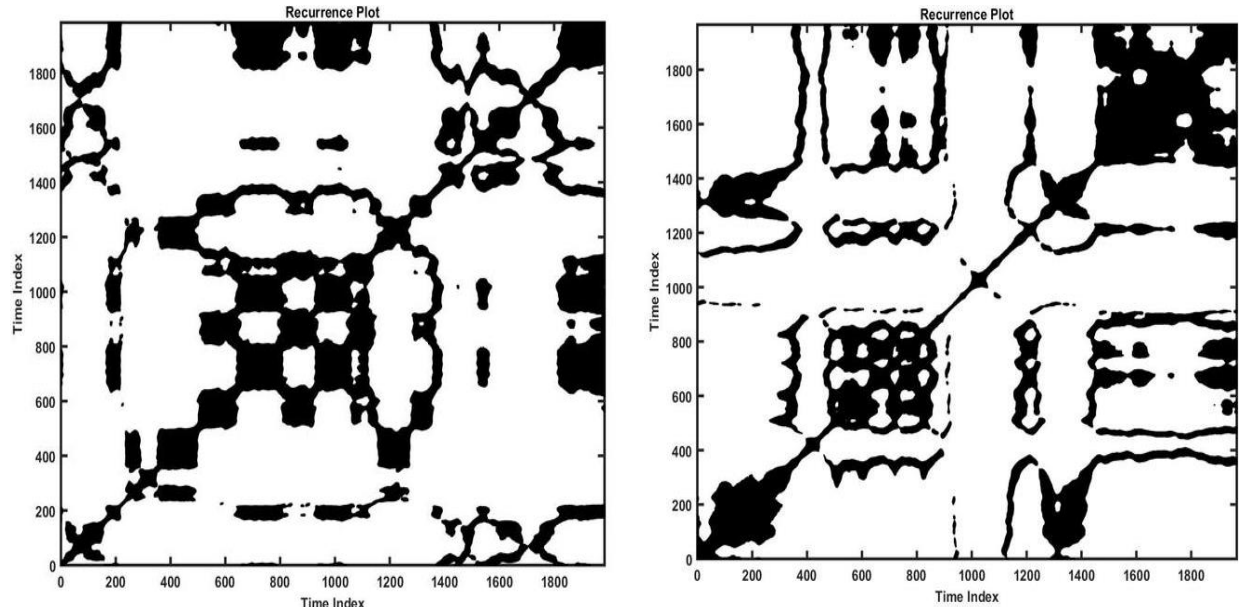303   **A9**.

304
305   **Figure 5: recurrence plot for a healthy (left) and a LBP (right) individual in Trial #6 (ankle vibration on**
306   **foam surface**

307   Short-term and long-term Lyapunov exponents are shown in **Table A10** and **Table A11** (**Appendix**)
308   for the COP and trunk angle data. For all the trials, the phase space path stability of the healthy cohort
309   was higher than that of the LBP cohort (less Lyapunov exponents value). These results are consistent
310   with the results of the velocity deviation parameters for both the AP and ML directions as shown in
311   **Table A2** and **Table A3** (**Appendix**). Moreover, a direct relationship was observed between
312   instability and the increase of velocity deviation in both cohorts. It can be seen from the short and
313   long-term Lyapunov exponents that the LBP individuals experienced greater problems with stability
314   in comparison with the healthy group under the same testing conditions. Moreover, when the same
315   tests were conducted on the softer surface (foam), those instability differences became more
316   pronounced (λ_s=**Healthy 2.5 < Patient 3.2 and** σ_{v_x}=**Healthy 22.11 < Patient 29.21**). Statistical
317   analysis of Lyapunov Exponents are provided in **Table A12** (**Appendix**), where short-term Lyapunov
318   shows more significant differences between LBP and Healthy cohorts as compared to long-term
319   Lyapunov **(P<0.05)**.

4. Discussion

321   This work presents a quantitative methodology that leverages both linear and nonlinear dynamic tools
322   to delineate and discriminate proprioception control in non-specific low back pain patients as
323   compared to healthy individuals.
324   The linear analysis employed here revealed that the standard deviation of amplitude and velocity of
325   the COP were higher among the LBP group as compared to the healthy controls in both AP and ML
326   directions, suggesting that the LBP patients experienced a greater challenge in using the hip control
327   strategy to maintain stability instead of the ankle strategy. This was most apparent in the trials during
328   which the vibrators were active (Trials 8, 7, 6, 4, 3 and 2) and while standing on the foam surface.
329   These findings are consistent with previous research (Brumagne et al., 2008). However, it is not clear

330 whether this change of strategy in the LBP cohort is due to a disorder in lumbar proprioception
331 receptors making them unable to send the proprioception data to the brain correctly, or whether the
332 control scheme of the brain is actually altered by the LBP, causing the brain to use less of these data
333 (della Volpe et al., 2006).
334 The nonlinear dynamic analysis, including the analysis of the COP data in terms of recurrence,
335 determinism and entropy in the both directions showed that the LBP individuals have more repetitive
336 patterns and sway as compared to the healthy group. This renders them less able to adapt to the
337 environmental conditions and use prior repetitive sway behavior to maintain stability, particularly
338 while on the foam surface which requires more flexibility and adaptive control behavior. Trend, or
339 the measure of the non-stationary behavior of a system, was shown to be higher among the LBP group
340 reflecting failure to achieve a balance point. In conjunction with an increase in the standard deviation
341 of COP, this may be interpreted as functional brain changes that occur during proprioceptive
342 processing in LBP patients contributing to their postural control impairments. Thus, the brain may be
343 able to obtain different data and identify the equilibrium point by increasing the change in COP
344 (Ghomashchi et al., 2011).
345   Functional stability analyses (**Table A10** and **Table A11** (Appendix)) based on short-term and
346 long-term Lyapunov stability components demonstrated a higher short-term exponent in the LBP
347 cohort as compared to the healthy group for the COP and trunk data. This indicates reduced stability
348 in LBP individuals, suggesting that these patients are less likely to use their full body potential to
349 maintain stability and instead rely more on their ankle joints. This adaptive control strategy is
350 probably due to the less flexible lumbar area as compared to healthy people.
351   Statistical analyses indicated that for most of the parameters used in this study (linear parameters,
352 RQA and Lyapunov components), there were significant differences between the LBP cohort and the
353 healthy group. This suggests that the methodology introduced here along with the various quantitative
354 parameters could be incorporated in the diagnosis and treatment/rehabilitation of individuals with
355 proprioception disorders, including LBP patients. Specifically, physiotherapists should consider the
356 increased use of therapeutic exercises that encourage the use of hip strategy for maintaining stability
357 and to prevent LBP recurrence. The less complexity in NSLBP behaviors (**Table A4** and **Table A5**)
358 can be explained by their higher muscle coactivation (Guthart and Salisbury, 2000) and higher
359 reliance on the ankle strategy (Brumagne et al., 2008) that may reduce the stabilizing control in the
360 ML direction.

361   A number of limitations must be acknowledged. First, in the absence of a device such as
362 gyroscope and accelerometer to obtain direct angular velocity and angular acceleration of the
363 trunk, we relied on a derivative method for calculating these two parameters, which could
364 have led to unreliable results in analyzing and interpreting the data. Second, we did not
365 employ a direct questionnaire or experimental trial that could have unequivocally identified those
366 with proprioception disorders, the patients self-identified which may have affected the results. While
367 motor control adaptation in LBP has been extensively studied from a motor output perspective, much
368 less attention has been paid to changes in sensory input, specifically proprioception. Future studies are
369 needed to use the quantitative tools proposed here to further investigate the adaptive strategies and
370 their impact on the chronification of LBP.

5. Conclusion

372   This study developed a methodology that leverages linear and nonlinear dynamic tools to
373 quantitatively study proprioception impairment in a cohort of LBP patients. The linear analyses
374 results indicated an increase of the standard deviation of amplitude and velocity among the LBP
375 participants, reflecting that these patients were mechanically challenged while using a hip control
376 strategy to maintain stability, and hence opted for an ankle control strategy instead. Nonlinear
377 analyses of recurrence, determinism, and entropy from the COP in both directions, coupled with the
378 trunk kinematic data, demonstrated that the LBP participants used more repetitive sway kinematics, as
379 compared to their healthy counterparts, reflecting diminished adaptive capability to environmental

380 conditions. Higher trend values in the LBP group indicated that they engage in more non-stationary
381 sway behaviors. The short-term Lyapunov component was greater in the LBP group suggesting
382 greater physical instability. From a short term perspective, our work suggests that LBP patients tend
383 not to use their full body potential to maintain stability and instead rely on the ankle control strategy,
384 possibly due to a compromised or less flexible lumbar area and/or fear of further injury. Future studies
385 are needed to investigate the long-term impact of impaired proprioceptive signaling and its role in
386 postural control.

Acknowledgment

393

Conflict of interest

395 None.
396

References

398 Brumagne, S., Janssens, L., Knapen, S., Claeys, K., and Suuden-Johanson, E. (2008). Persons
399   with recurrent low back pain exhibit a rigid postural control strategy. *European Spine
400   Journal* 17(9), 1177-1184. doi: 10.1007/s00586-008-0709-7.
401 Burton, A.K., Tillotson, K.M., Main, C.J., and Hollis, S. (1995). Psychosocial predictors of
402   outcome in acute and subchronic low back trouble. *Spine* 20(6), 722-728. doi:
403   10.1097/00007632-199503150-00014.
404 Claeys, K., Brumagne, S., Dankaerts, W., Kiers, H., and Janssens, L. (2011). Decreased
405   variability in postural control strategies in young people with non-specific low back
406   pain is associated with altered proprioceptive reweighting. *European journal of
407   applied physiology* 111(1), 115-123.
408 Claeys, K., Dankaerts, W., Janssens, L., and Brumagne, S. (2012). Altered preparatory pelvic
409   control during the sit-to-stance-to-sit movement in people with non-specific low back
410   pain. *Journal of Electromyography and Kinesiology* 22(6), 821-828. doi:
411   10.1016/j.jelekin.2012.04.007.
412 Claeys, K., Dankaerts, W., Janssens, L., Pijnenburg, M., Goossens, N., and Brumagne, S.
413   (2015). Young individuals with a more ankle-steered proprioceptive control strategy
414   may develop mild non-specific low back pain. *Journal of Electromyography and
415   Kinesiology* 25(2), 329-338.
416 Clark, S., and Horton, R. (2018). Low back pain: a major global challenge. *Lancet (London,
417   England)* 391(10137), 2302. doi: 10.1016/S0140-6736(18)30725-6.
418 Cordo, P.J., and Gurfinkel, V.S. (2004). "Motor coordination can be fully understood only by
419   studying complex movements," in *Progress in brain research*. Elsevier), 29-38.
420 Dagenais, S., Caro, J., and Haldeman, S. (2008). A systematic review of low back pain cost
421   of illness studies in the United States and internationally. *The spine journal* 8(1), 8-20.
422   doi: 10.1016/j.spinee.2007.10.005.
423 della Volpe, R., Popa, T., Ginanneschi, F., Spidalieri, R., Mazzocchio, R., and Rossi, A.
424   (2006). Changes in coordination of postural control during dynamic stance in chronic
425   low back pain patients. *Gait & posture* 24(3), 349-355. doi:
426   10.1016/j.gaitpost.2005.10.009.

Fairbank, J.C., and Pynsent, P.B. (2000). The Oswestry disability index. *Spine* 25(22)**,** 2940-2953. doi: 10.1097/00007632-200011150-00017.

Field, A. (2013). *Discovering statistics using IBM SPSS statistics.* sage.

Filiz, M., Cakmak, A., and Ozcan, E. (2005). The effectiveness of exercise programmes after lumbar disc surgery: a randomized controlled study. *Clinical rehabilitation* 19(1)**,** 4-11. doi: 10.1191/0269215505cr836oa.

Ghomashchi, H., Esteki, A., Nasrabadi, A.M., Sprott, J.C., and BahrPeyma, F. (2011). Dynamic patterns of postural fluctuations during quiet standing: A recurrence quantification approach. *International Journal of Bifurcation and Chaos* 21(04)**,** 1163-1172.

Goodwin, G.M., McCloskey, D.I., and Matthews, P.B. (1972). Proprioceptive illusions induced by muscle vibration: contribution by muscle spindles to perception? *Science* 175(4028)**,** 1382-1384. doi: 10.1126/science.175.4028.1382.

Gpower (2019).

Guthart, G.S., and Salisbury, J.K. (Year). "The Intuitive/sup TM/telesurgery system: overview and application", in: *Proceedings 2000 ICRA. Millennium Conference. IEEE International Conference on Robotics and Automation. Symposia Proceedings (Cat. No. 00CH37065)*: IEEE), 618-621.

Hashemi, L., Webster, B.S., and Clancy, E.A. (1998). Trends in disability duration and cost of workers' compensation low back pain claims (1988-1996). *Journal of Occupational and Environmental Medicine* 40(12)**,** 1110-1119. doi: 10.1097/00043764-199812000-00011.

Hashemi, L., Webster, B.S., Clancy, E.A., and Volinn, E. (1997). Length of disability and cost of workers' compensation low back pain claims. *Journal of occupational and environmental medicine* 39(10)**,** 937-945. doi: 10.1097/00043764-199710000-00005.

Horak, J., Ladislav, K., & Raidl, A (2003). Deterministic chaos and its physical application. Academia.

Hoy, D., Bain, C., Williams, G., March, L., Brooks, P., Blyth, F., et al. (2012). A systematic review of the global prevalence of low back pain. *Arthritis & Rheumatism* 64(6)**,** 2028-2037. doi: 10.1002/art.34347.

Joos, E., Peretz, A., Beguin, S., and Famaey, J.P. (1991). Reliability and reproducibility of visual analogue scale and numeric rating scale for therapeutic evaluation of pain in rheumatic patients. *The Journal of rheumatology* 18(8)**,** 1269-1270.

Katz, J.N. (2006). Lumbar disc disorders and low-back pain: socioeconomic factors and consequences. *JBJS* 88(suppl_2)**,** 21-24. doi: 10.2106/JBJS.E.01273.

Liebenson, C. (1996). Rehabilitation and chiropractic practice. *Journal of manipulative and physiological therapeutics* 19(2)**,** 134-140.

Méndez, F.J., and Gómez-Conesa, A. (2001). Postural hygiene program to prevent low back pain. *Spine* 26(11)**,** 1280-1286.

Riley, M., Balasubramaniam, R., and Turvey, M. (1999). Recurrence quantification analysis of postural fluctuations. *Gait & posture* 9(1)**,** 65-78. doi: 10.1016/s0966-6362(98)00044-7.

Roll, J., and Vedel, J. (1982). Kinaesthetic role of muscle afferents in man, studied by tendon vibration and microneurography. *Experimental brain research* 47(2)**,** 177-190. doi: 10.1007/BF00239377.

Rosenstein, M.T., Collins, J.J., and De Luca, C.J. (1993). A practical method for calculating largest Lyapunov exponents from small data sets. *Physica D: Nonlinear Phenomena* 65(1-2)**,** 117-134.

Rubin, D.I. (2007). Epidemiology and risk factors for spine pain. *Neurologic clinics* 25(2)**,** 353-371. doi: 10.1016/j.ncl.2007.01.004.

477   Salavati, M., Hadian, M., Mazaheri, M., Negahban, H., Ebrahimi, I., Talebian, S., et al.
478   (2009). Sohani SM, Parnianpour M. Test–retest reliably of center of pressure
479   measures of postural stability during quiet standing in a group with musculoskeletal
480   disorders consisting of low back pain, anterior cruciate ligament injury and functional
481   ankle instability. *Gait & posture* 29**,** 460-464.
482   Sarker, K.K., Mohanty, U., and Sethi, J. (2017). Effect of spinal manipulation on postural
483   instability in patients with non specific low back pain. *Int J Pharm Bio Sci* 7(3)**,** 992-
484   999.
485   software, S. (2019).
486   Sprott, J.C. (1998). RQA software.
487   Truchon, M. (2001). Determinants of chronic disability related to low back pain: towards an
488   integrative biopsychosocial model. *Disability and Rehabilitation* 23(17)**,** 758-767.
489   doi: 10.1080/09638280110061744.
490   van den Hoorn, W., Kerr, G.K., van Dieën, J.H., and Hodges, P.W. (2018). Center of pressure
491   motion after calf vibration is more random in fallers than non-fallers: prospective
492   study of older individuals. *Frontiers in physiology* 9**,** 273.
493   Waddell, G. (1987). 1987 Volvo award in clinical sciences. A new clinical model for the
494   treatment of low-back pain. *Spine* 12(7)**,** 632-644. doi: 10.1097/00007632-
495   198709000-00002.
496   Webber Jr, C. (2009). "Introduction to recurrence quantification analysis RQA version 13.1
497   README. PDF".).
498   Webber Jr, C.L., and Zbilut, J.P. (2005). Recurrence quantification analysis of nonlinear
499   dynamical systems. *Tutorials in contemporary nonlinear methods for the behavioral*
500   *sciences* 94**,** 26-94.
501