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Quantifying Muscle Fatigue of the Low Back during Repetitive Load Lifting Using Lyapunov Analysis

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Abstract

Background: Occupational low back disorders are often associated with exposure to work-related physical risk factors such as muscle fatigue in the low back.

Objective: The objective of this study was to investigate the possible relationship between the divergence of the kinematic trajectories of the low back system and the different stages of fatigue during the execution of a repetitive lifting task.

Methods: The patterns of the low back system were recorded using markers on specific vertebras during the repetitive load lifting from the floor to a 0.75 m height table. The maximum Lyapunov exponent, λ_{max} of the recorded patterns was calculated from the x and y coordinates of the lower back markers using the algorithm proposed by Wolf.

Results: The results of the λ_{max} values determined three different sections of muscle fatigue which were also in agreement with the Borg's clinical scale of perceived fatigue results. The assessment of the λ_{max} values between the three different sections showed a descriptive point where the muscle fatigue accumulation may have resulted in a change of the low back control.

Conclusion: Lyapunov exponent methodology could be a reliable methodology for ergonomists to provide an index to design the work/rest ratio ergonomically.

Keywords: Posture; Biomechanics; Spinal control; Nonlinear dynamics; Lyapunov exponent; Ergonomics

Introduction

Occupational low back disorders (LBD) (low back pain, low back tissue injury, lumbar disk disorders) are a socioeconomic burden in numerous industrial countries [1,2] and are often associated with exposure to work-related physical risk factors such as forceful exertions, highly repetitive motions, prolonged static postures, ergonomically unfavorable working postures, and muscle fatigue in the low back [3-6]. The most frequently LBD are caused by ergonomically unfavorable working postures, such as the stoop and any other intermediate posture between the stoop and stand ones. These disorders have been hypothesized to occur when the equilibrium of the trunk forces is disturbed by internal (e.g., breathing) or external (e.g., being pushed) perturbations [7] as well as and more commonly by the transition from the neuromuscular non-fatigued to the fatigue stage leading to a change of the spine movement trajectories. Particularly, excessive small perturbations at the spine can lead to uncontrolled intervertebral movement with increased risk of injury [8]. Although a consensus of biomechanical and clinical definition of spinal stability is lacking in the literature, spinal stability is the basic requirement to protect the nervous system's structure and prevent the early mechanical deterioration of spinal components. Spinal stability is achieved and accomplished by the active and passive musculoskeletal system responses to successfully reconcile such perturbations with result to return and ensure to the equilibrium state [9,10]. The ability of the musculoskeletal system to deal with perturbations of the spine is crucial. This is based upon the principle that the lowest perturbation implies the highest mechanical spine stability in order to be able to perform reliably in a variety of tasks [11]. On the other hand it is also possible that too high or too small of perturbations are equal damaging and highest mechanical spinal stability is at an optimal medium [12].

Muscle fatigue has been shown to directly influence several of the spinal control systems [13,14] and therefore can influence the LBD risk [15,16]. Therefore, spinal motion analysis has become a useful method for quantifying the range of trunk motions and trunk pattern changes under different stages of fatigue in the low back. Additionally, it would be beneficial in ergonomics to study the relationship between the spinal mechanical behavior and the corresponding muscle fatigue, under dynamic conditions. In the lifting literature scientists have used different methodologies to determine the variability in kinematic and kinetic spinal characteristics such as: angular position/velocity/acceleration and torque of the ankle, knee, L5/S1, to describe different lift techniques, lifting speeds, and lifting loads [17,18]. Furthermore, motion characteristics such as trunk flexion/extension, velocity, acceleration [19], spine patterns, and Electro-myographic data (EMG) from specific muscles [20,21] have been suggested for identifying lower back disorders.

Several scientists have suggested that by analyzing the time-dependent behavior of kinematic variance about a target trajectory,

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it is possible to mathematically model local stability of the system in space using the maximum finite-time Lyapunov exponent (λ_{max}) [22-24]. Local stability is commonly defined as the "inverse of the rate of divergence from the intended trajectory after a small perturbation" [22,25-28]. However, this assumption is not in fully agreement with the mathematical framework from which the λ_{max} is produced. Mathematically, λ_{max} represents the average rate of exponential divergence of infinitesimally close trajectories (nearest neighbors) in state space, quantifying how the system responds to an extremely small (local) perturbation [28-30]. If the λ_{max} is low then it can be suggested that trunk movements follow a trajectory and remain close to this trajectory over time. In terms of neuromuscular control, this could mean that a system is using repeatedly the same control mechanisms due to fatigue and a minor perturbation could respond to loss of system control [31]. Perturbations of kinematics are sufficiently attenuated, because the system successfully deals with external mechanical disturbances and internal neuromuscular control errors [5]. A higher λ_{max} reflects faster divergence, which indicates that the system's kinematic trajectories are not overlapping. This finding could possibly indicate that the system is trying to recruit different neuromuscular mechanisms to maintain the spinal control or that the system is unable to recruit the appropriate neuromuscular patterns to maintain the spinal control. In studies on trunk control, λ_{max} has been shown to be increased (i.e., high divergence of system trajectories) by trunk muscle fatigue [5]. It was also found that lifting light loads coincided with higher λ_{max} compared to lifting heavier loads, possibly due to the lower muscle activity in lifting lighter loads [32].

In the index of the above literature we hypothesized that the divergence of the kinematic trajectories of the low back is associated with the muscle fatigue of the low back. Therefore, we addressed this hypothesis and we studied changes of the λ_{max} values of the low back trajectories during a lightweight repetitive lifting task as a function of the number of lifting repetitions. The main purpose was to identify a possible correlation between the divergence of the kinematic trajectories of the low back system and the different stages of fatigue in comparison with the corresponding Borg's scale measurements in order to detect the stage when the fatigue accumulation becomes substantial. In addition, we aimed to determine the Time to Substantial Fatigue Onset - TSFO [33]. This objective might be important in order to organize the work/rest ratio of the particular task in the workplace.

Material and Methods

Subjects

Five healthy male subjects voluntarily participated in this study. The average age was 23.32 years (SD=1.28 years) and the average Body Mass Index (BMI) was 25.4 (SD=0.9). The volunteers had similar body shape characteristics namely similar weight and height. None of the participants had a low back injury history, physical disability or discomfort problem and they reported no symptoms of pain during the experiment. The study protocol has been approved by the Research Ethics Committee of University of Patras and all volunteers read and signed an informed consent before participating.

Experimental protocol

The protocol consisted of the video recording of markers, which were placed on specific vertebras, during the procedure of repetitive load lifting from the floor to a 0.75 m height table (lifting was performed vertically). The volunteers stood at a distance of 30 cm from the table and the lifting frequency was set to 4 lifts per minute. They lifted a metal box with dimensions (50 × 30 × 25) cm and the lifting weight was set as the 15%*(Maximum Voluntary Weight Lift) (MVWL) for each volunteer correspondingly. They performed a symmetric, stoop lifting in the sagittal plane by coupling the box from its handles using industrial gloves as shown in Figure 1.

Maximum Voluntary Weight Lift – Lifting cycles

MVWL was measured for each volunteer and the lifting weight, used in this protocol, was set as the 15%*MVWL (Nt) for each volunteer correspondingly. In order to measure the MVWL value, the following experimental setup was used. A dynamometer was connected to the ground. A lifting belt was adjusted to the volunteer and to the dynamometer in order to allow the vertical lifting of the dynamometer by the use of their trunk. Volunteers were asked to pull the dynamometer three times, exerting their maximum without using their hands. There was 1.5 h rest period before each of the three MVWL trials in order to measure the non-fatigued maximum. MVWL value was calculated as the average value of the three MVWL values for each volunteer correspondingly. Therefore, the mean lifting weight value was found to be 9.9 ± 2.25 Nt (Table 1). The numbers of the executed lifting cycles are also shown in Table 1 for each volunteer correspondingly.

Questionnaire study

Each participant self-evaluated his fatigue level as Perceptible Fatigue (PF) which expressed their discomfort level using Borg's clinical rating scale of general and local fatigue (CR-10), every 1 load lift (LL) [34]. Under this ten-grade scale, '1' represented total absence of fatigue and '10' complete inability to continue the lifting task (Table 2). The volunteers began to execute the lifting task without any warm-up and stopped when they called inability to continue the task, which corresponded to '10' on the Borg's scale.

Video data acquisition

Ten markers were attached on certain vertebras (S1, L5, L4, L3, L1, T9, T6, T4, T2 and C7) as shown in Figure 2. The experimental procedure was recorded using a video camera (Sony Handycam DCR-HC90E 3.05 mega pixels, 25 frames/sec) and the recorded data was analyzed using Biokin 2D software version 4.7 (Darras Software Development - DSD). The origin of the coordinate system was set at the S1 marker. The x and y coordinates were calculated for each marker correspondingly and for every time step of 0.04 sec. For the demands of the present study only the markers that corresponded to the lower back (S1, L5, L4, L3, L1) were analyzed.

The markers were placed on the volunteers' body and especially in the back groove using appropriate spring and belt for fasten. In

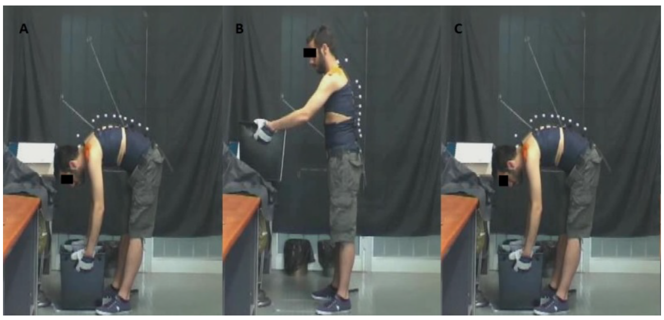

Figure 1: The volunteers performed a symmetric, stoop lifting in the sagittal plane. Different postures during the execution of the task.

Volunteers	MVWL (Nt)			$MVWL_{mean}$ (Nt)	15%*$MVWL_{mean}$ (Nt)	Lifting cycles
	Trial 1	Trial 2	Trial 3			
1	842	879	981	900.66	135.1	30
2	585	603	639	609	91.35	42
3	517	594	792	634.33	95.15	37
4	473	583	601	552.33	82.85	35
5	540	530	550	540	81	29
					Mean=97.1±22.05Nt	

Table 1: Statistics on the weights lifted by volunteers and the number of the executed lifting cycles.

Figure 2: Markers on the volunteer. Ten markers were attached on the S1, L5, L4, L3, L1, T9, T6, T4, T2 and C7 vertebras.

1–10 Borg rating of perceived fatigue level	
0	Rest
1	Really easy
2	Easy
3	Moderate
4	Sort of hand
5	Hard
6	
7	Really hard
8	
9	Really, really, hard
10	Maximal

Table 2: Borg's clinical rating scale of general and local fatigue.

particular, a proper spring was fitted on the volunteer's back groove, from the neck to the tailbone, with a diameter of 1.5 cm, in order to adjust to all the volunteer's types of spinal curvature. The markers were adapted on the spring as shown in Figure 3b. The spring was stabilized on the volunteer's body using elastic straps which were attached on textile belts (Figure 3c). The markers consisted of a 4.5 cm height metal shaft which was fixed on a circular metal base of 2 cm diameter (Figure 3a) and the base was adapted on the top of the corresponding, to any vertebra, coil. On the top of the metal shaft a reflective sphere of diameter of 2 cm was attached. The marker's height was set to be 5 cm in order not to get hidden by the paraspinal muscles.

The volunteers did not wear any clothes on their upper body in order to eliminate the errors on the coordinate's data that is produced by the clothes movement. Furthermore, with the use of this experimental setup the marker's displacement (x and y coordinates) is not impeded by the skin's movement since the marker is attached on the spring and not directly on the skin. Otherwise, if the marker was attached directly on the skin, the use of adhesive tape on the skin would produce a high error to the coordinate's data that is produced by the skin's movement.

Lyapunov exponent analysis

The x and y coordinates of the lower back markers (S1, L5, L4, L3, L1) were evaluated using the Lyapunov Exponent (LyE). Joint kinematic data exhibit patterns that present a limit cycle behavior. LyE is ideal in evaluating limit cycle signals, such as low back kinematic data (Figure 4) and has the ability of evaluating the divergence of movement trajectories in state space. To investigate the fatigue effects of loading we examined the first 10, 12 and 14 cycles of lifting and the last 10, 12 and 14 cycles of lifting for the LyE values where we assumed that the first 10 cycles of lifting represented the non-fatigued state. The LyE is calculated as the slope of the average logarithmic divergence of the neighboring trajectories in the state space. For the present study, for the calculation of LyE we used the algorithm proposed by Wolf (1985). A LyE value of zero will be produced for periodic systems (such as a sine wave) because the trajectories plotted in the state space would completely overlay. A positive LyE may indicate the presence of determinism (order) within a time series. For more details on the algorithm and calculation of LyE please refer to Wurdeman, Myers and Stergiou, 2012 [35].

Results

The results of the Lyapunov exponent analysis are presented in Figure 5. In this figure the values of λ_{max} in the first 10, 12 and 14 cycles of lifting as well as the corresponding values of λ_{max} in the last 10, 12 and 14 cycles of lifting are shown for the analyzed markers (L1, L3, L4, L5, S1) and for all the participants. The results of the Borg's clinical scale values are presented in Figure 6. It was observed that three different sections appeared based on the three different stages of muscle fatigue (no-fatigue, transition to fatigue, fatigue). These observed sections were combined with the Lyapunov exponent results as shown in Figure 7. The first section consisted of the values of λ_{max} in the first 10 and 12 cycles of lifting. This section represented the non-fatigued stage of lifting. The second section consisted of the values of λ_{max} in the first 14 cycles of lifting until the last 14 cycles of lifting where it was observed that the values of λ_{max} decreased compared to the corresponding values of the non-fatigued stage area. It was also observed that the values of λ_{max} were the lowest in the last 14 cycles of lifting and in the last 12 cycles of lifting for most of the participants and for almost all of the analyzed markers. These λ_{max} values corresponded to values 5 and 6 of the Borg's clinical scale of perceived fatigue. Table 3 shows the results of the statistical analysis between the values of λ_{max} in the first 10 cycles of lifting and the corresponding values of λ_{max} in the last 14 cycles of lifting. These results showed high correlation between the values of λ_{max} in the first 10 cycles of lifting and the values of λ_{max} in the last 14 cycles of lifting for markers L1, L3 and L4. It was also observed a decreased correlation between the above mentioned values of λ_{max} for the markers L5 and S1. High correlation was also observed between the values of λ_{max} in the first 10 cycles of lifting and the proposed TSFO points for the markers L1, L3, L4 and L5 as shown in Table 4.

	Marker L_1 $λ_{max}$ last 14 cycles	Marker L_1 $λ_{max}$ last 10 cycles	Marker L_3 $λ_{max}$ last 14 cycles	Marker L_3 $λ_{max}$ last 10 cycles	Marker L_4 $λ_{max}$ last 14 cycles	Marker L_4 $λ_{max}$ last 10 cycles	Marker L_5 $λ_{max}$ last 14 cycles	Marker L_5 $λ_{max}$ last 10 cycles	Marker S_1 $λ_{max}$ last 14 cycles	Marker S_1 $λ_{max}$ last 10 cycles
Marker L_1 $λ_{max}$ first 10 cycles	0.905 p=0.035	0.940 p=0.017	-	-	-	-	-	-	-	-
Marker L_1 $λ_{max}$ last 14 cycles	1	0.941 p=0.017	-	-	-	-	-	-	-	-
Marker L_3 $λ_{max}$ first 10 cycles	-	-	0.927 p=0.023	0.904 p=0.035	-	-	-	-	-	-
Marker L_3 $λ_{max}$ last 14 cycles	-	-	1	0.955 p=0.012	-	-	-	-	-	-
Marker L_4 $λ_{max}$ first 10 cycles	-	-	-	-	0.727 p=0.164	0.412 p=0.491	-	-	-	-
Marker L_4 $λ_{max}$ last 14 cycles	-	-	-	-	1	0.583 p=0.302	-	-	-	-
Marker L_5 $λ_{max}$ first 10 cycles	-	-	-	-	-	-	0.086 p=0.891	0.264 p=0.668	-	-
Marker L_5 $λ_{max}$ last 14 cycles	-	-	-	-	-	-	1	0.789 p=0.112	-	-
Marker S_1 $λ_{max}$ first 10 cycles	-	-	-	-	-	-	-	-	-0.372 P=0.537	-0.278 P=0.651
Marker S_1 $λ_{max}$ last 14 cycles	-	-	-	-	-	-	-	-	1	0.762 p=0.135

Table 3: Correlation analysis between the values of $λ_{max}$ in the first 10 cycles of lifting and the corresponding values of $λ_{max}$ in the last 14 cycles of lifting for all the markers ($p<0.05$).

	Marker L_1 TSFO point	Marker L_3 TSFO point	Marker L_4 TSFO point	Marker L_5 TSFO point	Marker S_1 TSFO point
Marker L_1 $λ_{max}$ first 10 cycles	0.955 p=0.012	-	-	-	-
Marker L_3 $λ_{max}$ first 10 cycles	-	0.976 p=0.005	-	-	-
Marker L_4 $λ_{max}$ first 10 cycles	-	-	0.865 p=0.058	-	-
Marker L_5 $λ_{max}$ first 10 cycles	-	-	-	0.781 p=0.119	-
Marker S_1 $λ_{max}$ first 10 cycles	-	-	-	-	0.323 p=0.596

Table 4: Statistical analysis between the values of $λ_{max}$ in the first 10 cycles of lifting and the proposed TSFO points for all the markers ($p<0.05$).

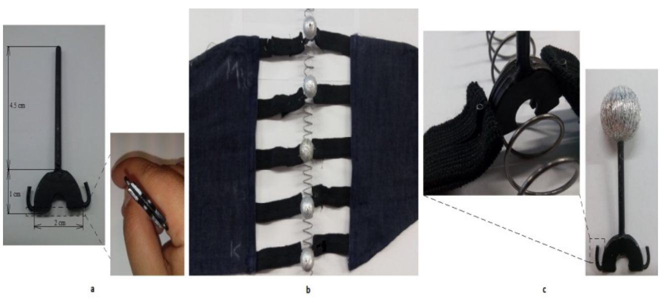

Figure 3: a) Dimensions of the marker's base and the marker's shaft, b) Markers adapted on the spring and attached on the textile belt, c) Markers' attachment through the elastic straps.

Discussion

The purpose of the present study was to assess the $λ_{max}$ of the low back trajectories as a function of the number of lifting repetitions and to investigate if there is a possible connection between the divergence of the kinematic trajectories of the low back system and the different stages of fatigue. Lyapunov exponent analysis is becoming an increasingly popular measure for examining the response of the neuromuscular system to small perturbations and therefore it could be a reliable tool for injury prevention and for the design of the work/rest ratio. Scientists have used the kinematic trajectory divergence technique as an early identification tool for individuals who are at risk of falling and to study the ability to resist perturbations in passive dynamic walking models [36-39]. However, the possible relationship between the low back trajectories divergence and muscle fatigue has not been widely investigated during repetitive lightweight lifting tasks.

The present experimental protocol was designed to assess the effect of muscle fatigue on $λ_{max}$ during the execution of lightweight (15%*MVWL (Nt)) lifting. Figure 6 shows three different sections which correspond to the different stages of fatigue based on the Borg's clinical scale of perceived fatigue. These sections were also observed in the $λ_{max}$ values diagram implying three corresponding sections

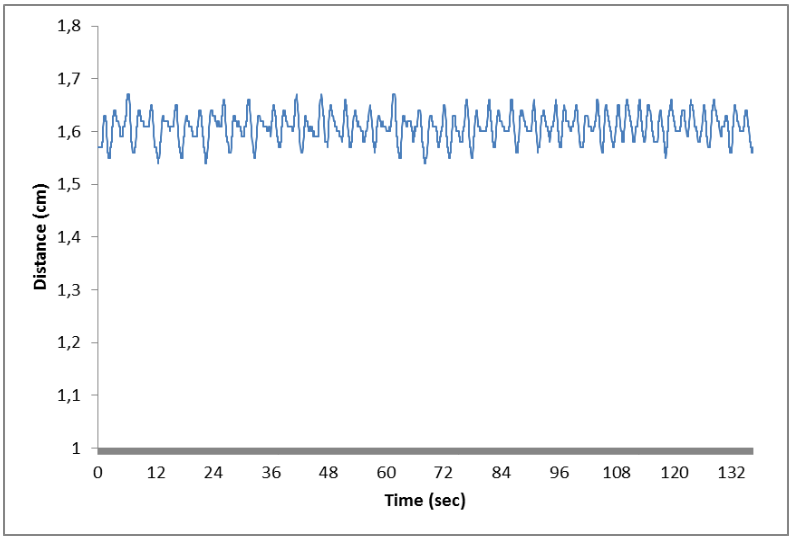

Figure 4: Example of the limit cycle behavior of low back kinematic data from one of our participants. Specifically, this is the x coordinate of the L5 marker.

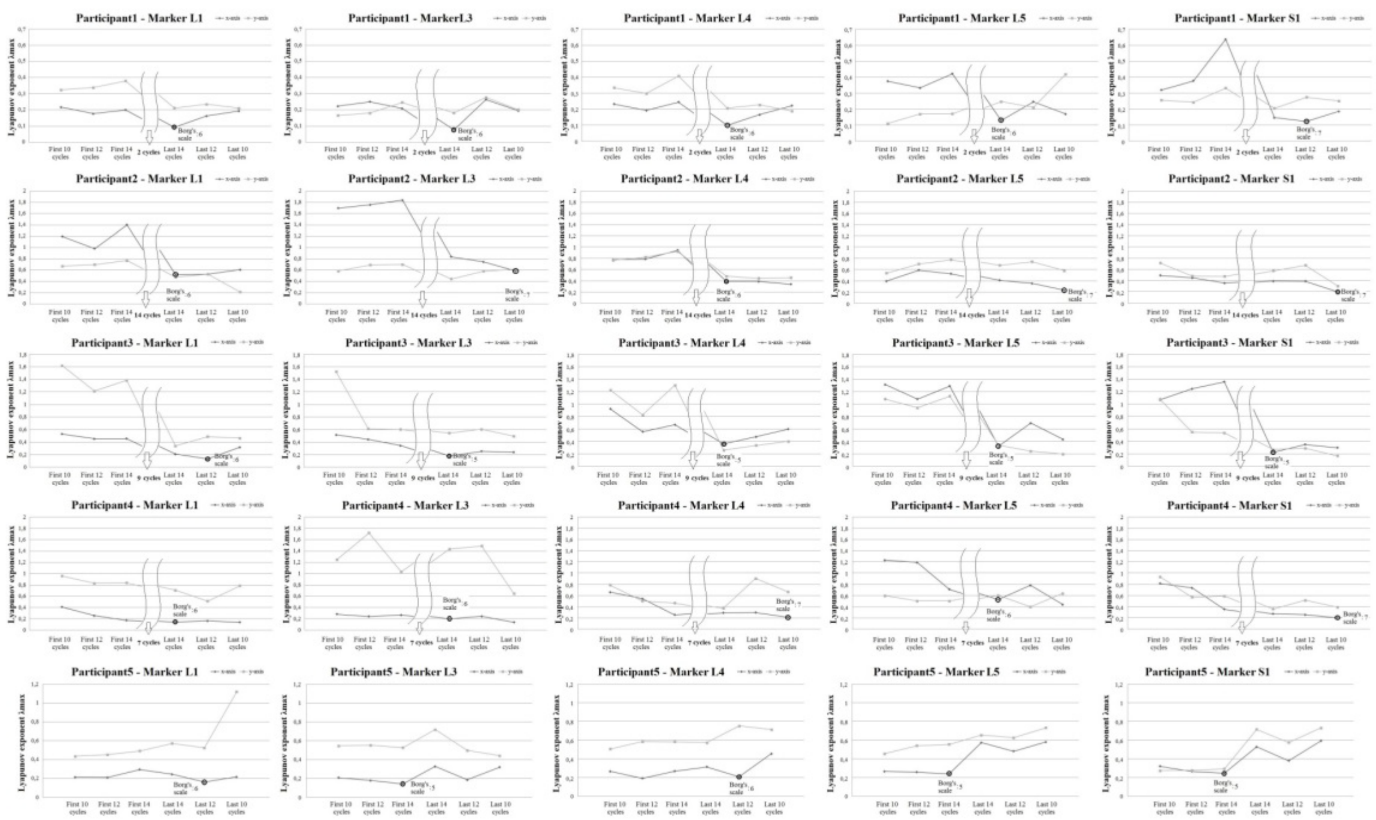

Figure 5: Lyapunov exponent analysis, λ_{max}, values in the first 10, 12 and 14 cycles of lifting as well as the corresponding values of λ_{max} in the last 10, 12 and 14 cycles of lifting for the analyzed markers (L1, L3, L4, L5, S1) and for all the participants. Crucial λ_{max} values and the corresponding values of Borg's clinical scale of perceived fatigue.

of different levels of low back control as shown in Figure 7. These findings were strengthened by the statistical analysis which compared the λ_{max} values between the initial and the last stages of the task (Table 3). In the first section the values of λ_{max} were higher compared to the corresponding values of λ_{max} in sections 2 and 3. In section 2, the values of λ_{max} were decreased indicating that there was increased convergence of the low back kinematic trajectories during the execution of the lifting task according to our hypothesis. This observed difference of λ_{max} values which implied increased low back control from the beginning to the progressive execution of the task between sections 1 and 2 may be ought to the lack of warm up. The volunteers began to execute the task without any previous warm up which may resulted in a time delay of the activation of the neuromuscular mechanisms of the spine control, such as the paraspinal muscles, in order to achieve maximal spinal control

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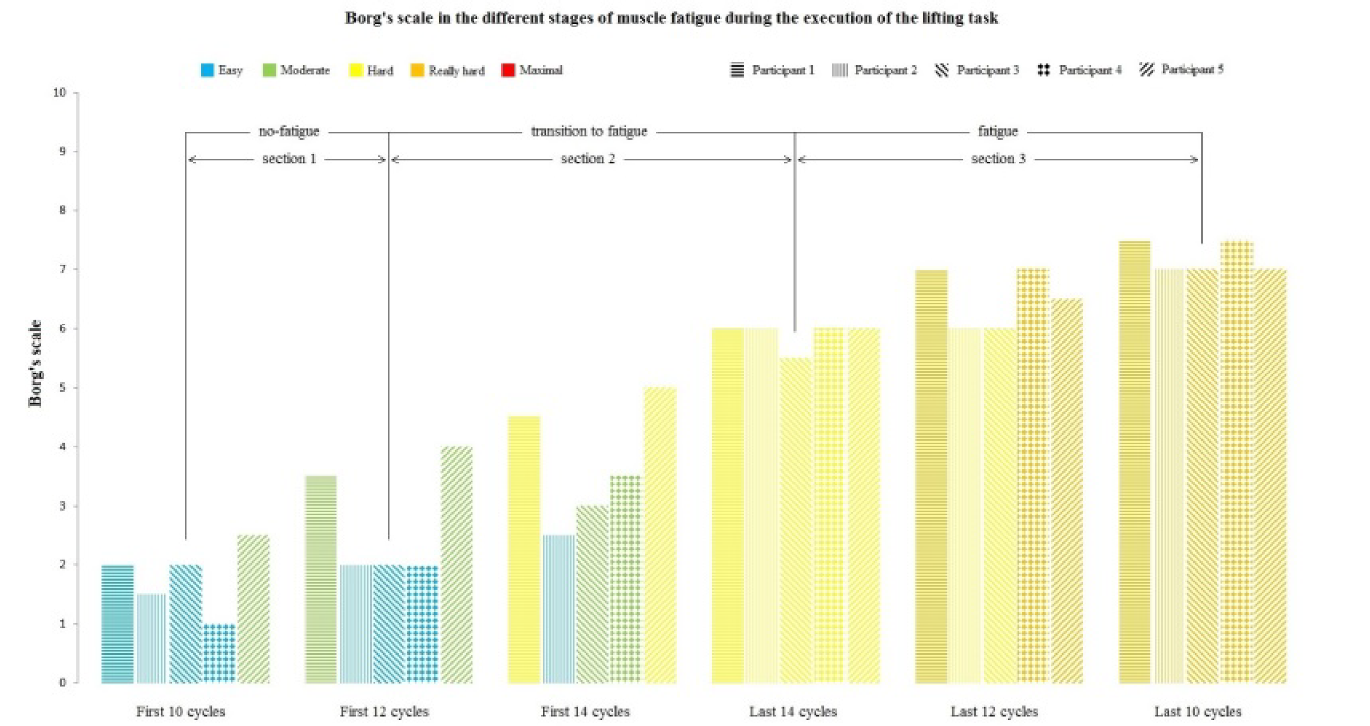

Figure 6: Borg's clinical scale values during the execution of the lifting task for each volunteer. Three different stages of muscle fatigue (no-fatigue, transition to fatigue, fatigue).

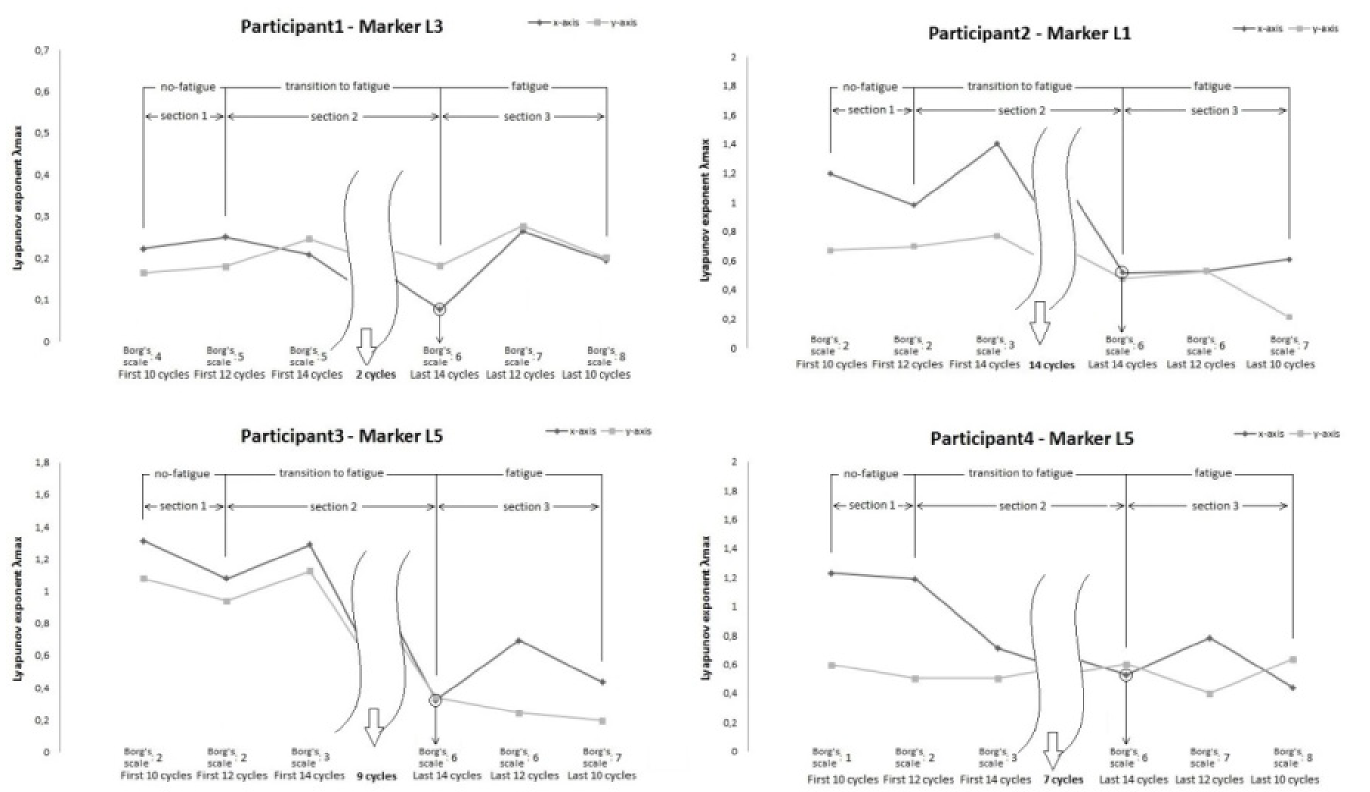

Figure 7: Lyapunov exponent, λ_{max}, values in the different stages of fatigue. Characteristic diagrams of four participants. Minimum λ_{max} values were proposed as TSFO points.

(i.e., when the volunteers warmed up during the execution of the task it is possible that they possessed a greater ability to resist external perturbations resulting in a decrease in the values of λ_{max}). Additionally the existence of the lifting weight speeded up the activation of the above mentioned neuromuscular mechanisms. Scientists showed that while lifting heavier loads there is an increase in both mean and peak muscle activation which is due to higher levels of steady-state muscle activation and results into lower kinematic trajectory divergence of the spine system [40-42]. In other words, our participants adopted a co-contracting and rigid pattern of movement behavior as fatigue accumulated.

Furthermore, our findings showed that section 2 is characterized by the decreasing λ_{max} values implying greater trajectory convergence except a distinctive point at the end of the section where an inversion of the λ_{max} values was observed. This point corresponded to the lowest value of λ_{max} and possibly defines the change of the status of the low back control during the execution of the lifting task. In the most diagrams of Figure 5 after this lowest λ_{max} point (section 3) an increase of the λ_{max} values was observed implying greater kinematic trajectory divergence. This finding is very important as it probably indicates a substantial muscle fatigue accumulation, which is such that forces the spinal system to adopt a different movement strategy. Scientists using surface electromyography methodology have shown that during the execution of repetitive lightweight lifting tasks there is a time period at which the muscles reduce their maximal capacity to generate force or power output probably as a result of muscle fatigue accumulation which likely translates into a change in the patterns of the observed movement behavior [41,43-45]. It is possible that the substantial accumulation of fatigue results in the adoption of an alternative movement strategy which requires the recruitment of neighboring muscular systems to aid for the completion of the task. Thus, we observe the increase in the λ_{max} values. It is also possible, that at the inflection point, where we observe the transition to a greater λ_{max} the spine is at each most vulnerable point, unable to respond to perturbations, and likely at increased risk for injuries. The above mentioned inflection point which we proposed as the TSFO point corresponded to values 5 or 6 of the Borg's clinical rating scale of perceived fatigue (Figure 5) which indicates that the volunteers did not perceive early enough the onset of substantial fatigue and continued to execute the lifting task probably leading to an increase injury risk.

Conclusion

Lyapunov exponent methodology could be a reliable methodology for ergonomists to investigate the effects of fatigue accumulation on low back control, in the work field, as it is a non-invasive technique which allows the researcher to calculate the maximum LyE, λ_{max}, from kinematic data only. LyE is a promising tool that could provide an index, as TSFO, which could be considered to the design of the work/rest ratio to avoid muscle injury. The next investigation for continuing this research work could be the study of a heterogeneous group of volunteers with different body characteristics. It would be also interesting to investigate the effect of training between groups of experienced industry workers versus an inexperienced volunteer's one.

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