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Trunk Control during Standing Reach: A Dynamical System Analysis of Movement Strategies in Patients with Mechanical Low Back Pain

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Abstract

The purpose of this study was to quantify lumbo-pelvic control differences between patients with mechanical low back pain (MLBP) and asymptomatic controls using a dynamical systems approach to data reduction and interpretations. Subjects were 30 patients with chronic MLBP (age: 41.1 ± 8.9 years, body mass index: $26.2 \pm 5.2 \text{ kg/m}^2$) and 35 asymptomatic controls (age: 38.8 ± 9.2 years, body mass index: $25.3 \pm 4.8 \text{ kg/m}^2$). Kinematic data were collected from the femur, pelvis and lumbar spine during repeated trials of bilateral forward reaching under two loading conditions. Sagittal plane angular motion was filtered and time normalized. Continuous relative phases were then calculated for each data point. Mean absolute relative phase (MARP) and deviation phase (DP) parameters were derived to quantify intersegmental coordination and pattern variability. Mixed-model ANOVAs revealed that lumbo-pelvic coordination was more separated in time and more variable in the chronic MLBP group during this task. Trunk neuromuscular control was thus altered in our MLBP group. Unresolved extensor muscle dysfunction is suggested by a) preliminary analysis of phase plane trajectories, b) subjects' greater difficulty controlling aspects of the task that required the extensors to contribute to trunk stability and primary movement control.

Keywords

Chronic Low Back Pain; Trunk Control; Inter-segment Coordination; Kinematics; Reaching

Introduction

In patients with a primary complaint of low back pain (LBP), aberrant patterns of lumbo-pelvic motion have been reported both clinically [1-3] and in research studies employing standing trunk movements,[4-6] sit to stand activities [7] and gait [8,9] assessment. These aberrant patterns were characterized as limits in segment range of motion[5] and altered angular velocity

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[6] measured at discrete points during the movement. They imply an association between movement impairment of the lower back and symptoms of LBP. However, such discrete measures limit analysis of inter-joint coordination, movement variability and the different control mechanisms that underlie movement impairments in individuals with LBP. The continuous dynamic interaction between the lumbar spine and pelvis during active movement of the trunk and how it is altered in patients with LBP is not well understood; although, some investigators have examined this aspect.[7,10,11] Their results indicate that healthy asymptomatic individuals simultaneously move their lumbar spine and pelvis in the same direction during trunk bending. Healthy individuals show a high positive correlation between lumbar and pelvic angular motion.[10] In contrast, individuals with LBP significantly freeze the motion of their lumbar spine.[7] This indicates a need to also understand the coordination dynamics of the lumbo-pelvic region during other functional activities, and calls for higher order variables incorporating joint position and velocity in the analysis.[12-14] In this study we examined the nature of coordination and control between lumbar and pelvic segments in individuals with mechanical LBP (MLBP) and the extent of their ability to effectively stabilize the trunk during functional reaching, specifically, with application of loads.

To characterize movement of the lumbo-pelvic region we used the Dynamical Systems Theory (DST) approach. DST is used to study movement coordination and stability of coordinative structures within the human body.[13,15] In clinical research, DST is used to examine movement control parameters, measure sports performance, and explore changes in movement control in patients with primary neurological dysfunction. Sparto et. al [16] demonstrated the feasibility of using this approach to measure multi-joint kinematic coordination (knee, hip, lumbar spine) and the effects of muscular fatigue on a repetitive lifting test. They reported that muscular fatigue negatively affected coordination and stability of the lifting pattern. This suggests that these measurements may be useful in determining impairments in movement coordination and pattern stability in patient populations. In DST, movement is hypothesized to emerge from non-linear interactions of a network of several components (e.g., task, environment and performer). Patterns of motion develop through self-organization in the physical and biological systems.[15] Functionally preferred coordination states eventually cause system dynamics to become ordered and stable, and produce consistent movement and postural control patterns for specific tasks. Human movement organization in DST also incorporates naturally occurring “*movement variability*.” Coordination patterns vary when individuals perform tasks repeatedly. In a dynamic environment, such variability permits individuals to explore task and environmental constraints, and to acquire more efficient and stable patterns over time.[17] Therefore, during any repeated movement pattern some inherent variability could be viewed as healthy and essential for optimal flexibility and stability.[17] Similarly, significant reduction or increases in intrinsic variability could represent pathological states. Increased variability could result from a performer’s inability to discover a more stable motor solution following environmental perturbations or altered task demands. Similarly, greatly decreased variability could represent a pathological state with limited movement options.[17] An advantage of the DST methods we used to analyze spinal movement is that phase coordination differences can be assessed even if ranges of motion decrease in some degrees of freedom.

The purpose of this study was to identify differences in trunk movement patterns between patients with MLBP and asymptomatic controls during a sagittal plane functional task. We characterized coordination and pattern stability using techniques of DST. Additionally, we perturbed the task demands by loading the upper extremities. We tested the effects of this perturbation on coordination pattern and motion stability. The task selection was based on the utility and familiarity of the everyday activity of forward reaching. We expected asymptomatic controls to maintain normal lumbo-pelvic coordination with minimal pattern variability during all instances of the task, even after the application of a light load. The load used was not likely

challenging enough to require increased variability or exploration for more efficient coordination patterns. However, we hypothesized that light loads would cause the MLBP group to alter their movement patterns during the reaching task under all conditions. Further these altered patterns would accentuate asynchronous coordination of the lumbar spine and the pelvis with decreased pattern stability during task performance.

Subjects

Sixty-five subjects consented to be studied using a university-approved IRB protocol. Thirty subjects had primary complaints of chronic or recurrent MLBP and were experiencing pain at the time of testing. MLBP was defined as low back pain generated by injury or degeneration to spinal region musculoskeletal tissues and not the result of systemic disease. MLBP subjects were recruited from a university-based orthopedic surgery practice. All MLBP subjects had evidence of moderate to severe degenerative disc disease on MRI, as determined by the same spine surgeon. Sixty-seven percent of the MLBP group reported LBP symptoms only (no pain below the gluteal fold). Thirty-three percent reported low back and thigh pain. None had symptoms distal to the knee (Table 1). Control subjects reported no history of low back pain that required attention of a health care provider or that limited function for longer than 3 days. Individuals with a history of spinal or hip surgery, osteoporosis, inflammatory joint disease, frank neurological loss (i.e., lower extremity weakness and sensory loss), pain or paresthesia below the knee, pregnancy, scoliosis, leg length discrepancy or vestibular dysfunction were excluded from the study. Anthropometric and reach kinematic performance variables (target distance, peak segment motion, start position, task duration, and peak trunk velocity) are provided in the Table 1.

Methods

Subjects stood with feet shoulder width apart, shoulders in 90° flexion and elbows extended. Subjects kept the arms extended throughout. By this task specification strategy we examined trunk components of reaching motion in isolation from limb reaching motions. From the starting position they performed 3 consecutive and continuous movements of bilateral forward reach to a midline, shoulder height target and return to upright standing. The subjects were instructed to reach forward using their trunk and hips as if they were reaching over a counter into a cupboard, touch a stationary target and immediately return to upright standing. Subjects performed each repetition to a 6-second count (3 seconds forward, 3 seconds back). This movement was relatively slow as it amounted to taking 3-seconds to reach 15-20 cm forward to a target and 3 seconds to return. Subjects performed this task un-weighted and then holding 4.5 kgs. They were given 3 warm-up trials prior to each condition. Trials where the subject failed to touch the target or maintain the standardized pace of motions were repeated and re-recorded. The target distance for each subject was standardized to 50% of their functional reach. Each subject's functional reach distance was determined by the Functional Reach test. [18] For this test, the subjects stood with arms outstretched at shoulder height and were instructed to reach as far forward as they could without taking a step. The difference between their knuckle position on a ruler, secured to the wall at shoulder height, at the beginning and end of the reach was recorded. The test was performed following 2 practice trials. The mean of 3 trials was used to determine functional reach.

Standardizing subjects reaching distance to 50% of their functional reach allowed us to assess control of trunk motion in midrange where the neuromuscular system is primarily responsible for trunk dynamic stability. The “no load” condition tested the neuromuscular system's ability to provide general trunk dynamic stability during a common functional task. The “load” condition increased the stability challenge. A load of 4.5 kgs (e.g., gallon of milk, pot of water, bag of groceries) was chosen as it approximates upper extremity loading experienced during

daily activities. Three-dimensional kinematic data were collected from sensors placed on the femur (lateral epicondyle), pelvis (S2 spinous process) and lumbar spine (L1 spinous process). Each sensor's data were collected (40 Hz) using an electromagnetic tracking device (3 Space Fastrak, Polhemus Inc., Colchester, VT). Subjects were calibrated to their neutral (0°) standing position.[19] Sensor positional data were converted to segment angular rotations using Euler angles in Cardan sequence (x, y, z)(see Figure 1). Sagittal plane data were filtered at 5 Hz (zero lag, 4th order Butterworth). The 5 Hz cut-off frequency was determined using residual analysis. [20] Data collection and reduction were completed using custom LabView programs (National Instruments, Austin, TX)

Data Analysis

Lumbar spine and pelvis angular displacement data were time-normalized to 101 data points. To quantify coordination, phase portraits were generated for each segment by plotting angular displacement versus velocity. From the resulting phase plane trajectories, a phase angle $\phi = \tan^{-1}(\text{velocity} / \text{displacement})$ was calculated for each data point through the entire motion. A continuous relative phase (CRP) curve was derived from the difference between the phase angles of the pelvis (ϕ_{pelvis}) and lumbar spine (ϕ_{lumbar}) given as $|\phi_{\text{lumbar}} - \phi_{\text{pelvis}}|$ at each data point and averaged across 3 trials. Coefficient of multiple correlation (CMC)[21] values revealed that repeatability of the subjects movement patterns for the “no load” and “load” condition were excellent to good for range of motion (0.95 ± 0.02 CMC), phase angles (0.95 ± 0.01 CMC) and relative phase (0.79 ± 0.01 CMC). The Root Mean Square (RMS) error for the angular time series was $1.8 \pm .95^\circ$ for the pelvis and $1.9 \pm 2.0^\circ$ for the lumbar spine.

Mean Absolute Relative Phase (MARP) was calculated by averaging the relative phase values over the CRP curve using the equation from Stergiou et al.[22],

$$\text{MARP} = \sum_{i=1}^p |\Phi \text{ Relative Phase}|_i / p$$

where “p” equals 101, the total data points through the full motion. Functionally, MARP values close to 0° indicated a more “in phase” relationship or segments moving in a similar manner. Values closer to 180° indicate an “out of phase” relationship, or segments moving in the opposite direction. Pattern stability, or trial-to-trial variability, was quantified using Deviation Phase (DP). DP was calculated by averaging the standard deviations of the 3 CRP curves using the equation from Stergiou et al.,[22]

$$\text{DP} = \sum_{i=1}^p \text{SD}_i / p$$

where “p” is 101, the number of data points in the motion and SD the standard deviation. DP values closer to 0° indicate pattern stability, or less pattern variability. Within-session reliability for our dependent variables (MARP, DP) ranged from .64 to .82 (ICC (3, 3)).[23] Average standard error of measurement (SEM) was 12.7° for MARP and 7.3° for DP. A custom Excel program (Microsoft Corporation, Redmond, WA) was used for data reduction and calculation of the variables.

Independent and paired t-tests were used to determine whether the subjects demonstrated differences in their characteristics or task performance within and between conditions. Descriptive statistics were calculated for the dependent variables, MARP and DP. Data met the assumptions for ANOVA. The independent variables were *Group* (MLBP and control),

Load (no load and load) and *Movement direction* (forward trunk flexion and return to erect standing). Separate 3-way mixed model ANOVAs were conducted to assess differences in MARP and DP for both *between* (Group) and *within subject* factors (Load, Movement Direction). The Greenhouse-Geisser correction was required as the assumption of homogeneity of variances (sphericity) was violated [24]. Parameter estimates (independent t-tests) were used to determine how the dependent variables were weighed in the equation that maximally distinguished the groups. Significance level for all tests was set at $\alpha \leq .05$. Data analysis was performed using SPSS for Windows (Version 15, Chicago, IL).

Results

Task Performance

The groups did not demonstrate significant differences in target distance, segment start position, peak segment range of motion or discrete relative phase parameters (see Table 1). The control group did demonstrate a significantly higher peak trunk velocity during the forward portion of the reach, but only in the loaded condition. The target distance and cycle duration time were not altered for the loaded condition. Segment start positions, peak trunk motion, peak angular velocity in forward reach and return were not significantly different between load conditions for either group. The MLBP subjects were able to complete the task under both conditions and did not report increased pain intensity.

Group Differences

The MLBP group demonstrated more asynchronous coordination of the lumbar spine and pelvis than the control group in both the no load and load conditions despite the similarity of the other parameters of their motion $\{F_{(1, 63)} = 4.62, P = .04, \eta = .26, 1 - \beta = .56\}$. The main effects for Load $\{F_{(1, 63)} = .021, P = .89\}$, and Movement Direction $\{F_{(1, 63)} = 2.82, P = .10\}$, and all interactions were not significant. Higher MARP values in the MLBP group indicated less “*in phase*” movement between their lumbar spine and pelvis (see Figure 2, A). Subjects in the control group maintained their mean MARP across conditions, showing consistently more “*in phase*” coordination, irrespective of change in loading and movement direction. Parameter estimates revealed that forward ($B = -15.29, P = .04$) and return ($B = -15.64, P = .02$) movements of the loaded condition accentuated the asynchronous coordination in the MLBP group. The *eta* (η) for Group differences indicated a medium effect size (.26).

Qualitative analysis of the group’s coordination dynamics offers a picture of how movement coordination occurred during the reaching task (see Figure 3). The CRP patterns demonstrate that the groups chose different coordination patterns to complete this task. In the control group, the first 5% of movement predominantly occurred at the pelvis with minimal contribution from the lumbar spine. This was followed by a gradual increase in lumbar segmental velocity, enabling this segment to move synchronously with the pelvis and reducing the absolute relative phase (ARP) value. The result was a tightly coordinated movement pattern that continued through the remainder of movement toward the target (first 50% of pattern). In general, the lumbar segment led the pelvis during the forward reach. Upon reversal to return to upright standing, controls continued to demonstrate the relatively tightly locked coordination, but progressed toward a less tightly correlated pattern with the lumbar spine again moving at a greater rate than the pelvis. Qualitatively, the control group pattern could be described as Lumbar-Synchronized-Lumbar. In contrast, the chronic MLBP group demonstrated almost the opposite pattern. The pelvis led the lumbar spine in position and velocity through most of the forward reach. Then at 40% of the total movement time the pattern sharply altered to the lumbar segment leading. This change greatly improved synchronization during the early return movement, when the lumbar spine continues to lead, altering the segment relationship into opposition over the first 10% of return motion. The phase relationship then remained steady

for the next 25% of the return movement (55-80% total motion). The pelvis gradually started to move at a higher rate through the end of motion, resulting in a more pelvis-dominated movement. The MLBP pattern could be described as Pelvis-Lumbar-Pelvis. Apart from the altered movement patterns, another notable difference existed. The MLBP group did not demonstrate as consistent a group behavior as the control group. Their standard error was considerably higher. This may be an indication that more than one altered pattern of motion is present in the MLBP group.

Stability, or variability of each individual's pattern of coordination, was assessed using the parameter of deviation phase. Pattern stability was significantly reduced in the MLBP group during all conditions $\{F_{(1, 63)} = 5.26, P = .03, \eta = .28, 1 - \beta = .62\}$. Thus, individuals in the MLBP group demonstrated more variable coordination patterns, higher DP values, during repeated performance of the reaching task (see Figure 2, B). Additionally, in the MLBP group, the pattern variability during the return motion was further increased compared to forward motion $\{\text{Group} \times \text{Movement Direction}; F_{(1, 63)} = 6.79, P = .01, \eta = .31, 1 - \beta = .73\}$. This increase occurred during both the "no load" and "load" conditions. In contrast, mean DP was lower and pattern variability relatively low during return in the control group for both load conditions (Figure 3, B). There was a no significant main effect of Load $\{F_{(1, 63)} = .37, P = .55\}$ or Movement Direction $\{F_{(1, 63)} = 1.34, P = .25\}$. Pattern variability was increased in the MLBP group during the return phase of the reaching motion as revealed by significant parameter estimates in the no load ($B = -10.13, P = .04$) and the 4.5 kg loaded condition ($B = -15.30, P = .005$). The *eta* (η) for group differences indicated a medium effect size (.28), while the group by load interaction demonstrated a slightly larger effect size (.31).

An example of how the coordination dynamics and underlying control mechanisms differs between individuals with and without MLBP is offered in Figure 4. The differences demonstrated by these matched subjects (age, gender, body mass index) resemble the previously reported changes in segment range of motion and velocity found in the MLBP population. Qualitatively, the angle-angle plots (Figure 4, A) and phase plane plots (Figure 4, B) indicate considerable differences in segment contribution and coordination to the reaching task. The lack of smooth movement patterns and sharp dips in the phase angle trajectories of the MLBP patient (Figure 4, B; marked by "**") indicate periods of cessation and resumption of segmental velocity. This often causes decoupling of segment coordination and higher MARP values, as suggested by the graphs of segment phase angle relationships (Figure 4, C). In this MLBP subject, lack of smooth movement control and limited lumbar spine motion contributed to the features in the altered control pattern (Figure 4, B).

Discussion

We investigated neuromuscular control of the lumbar spine and pelvis in individuals with chronic MLBP using a dynamical systems approach to quantify segment coordination and pattern stability, independent of changes in segment range of motion. As per expectation, to accomplish the task, both groups used their lumbar spine and pelvis albeit to different extents. Phase analysis showed altered segment coordination in MLBP. The higher MARP values in the MLBP group support our hypothesis that patients with chronic MLBP demonstrate decreased inter-segment coordination between their lumbar spine and pelvis during a bilateral reaching task. This finding is consistent with previous reports of altered trunk and pelvis coordination in patients with LBP during other functional tasks.[5-8] Further, the additional demand on the trunk musculature following light loading made the differences in lumbo-pelvic coordination still more prominent between the groups. Because there were no significant differences in the group's task performance (target distance, peak segment motion) or initial alignment (start position), we attributed these alterations to differences in inter-segmental coordination. One plausible explanation for the pattern change is an adapted motor plan of co-

contraction that restricts motion at the lumbar spine. This adaptation pattern was demonstrated by our representative MLBP subject (Figure 4, B) and has been reported in the literature.[7, 25,26]

Our results partially support the hypothesis that individuals with MLBP would demonstrate decreased pattern repeatability during all conditions. While there was an overall difference in trial-to-trial pattern variability between the groups during all conditions, those with MLBP also demonstrated significantly greater individual variability (indicated by DP) during return portions of the movement. The control group, however, maintained a constant pattern during forward reach and mirrored the kinematics on return. We expected, the control group's response to the introduction of a higher task demand (increased flexion moment, dual role of stabilization and movement control by extensor muscles) to be unchanged, as the task was neither novel nor demanding enough to their neuromuscular system. This proved to be the case. However, increased variability demonstrated by a majority of subjects with MLBP, when loaded, indicated lack of ability to maintain a consistent coordination pattern when task demands increased. We cannot rule out that the demand was not comparatively greater for the MLBP group. To this point, it has been reported that more strenuous exertion and muscle fatigue increases force variability and this may have resulted in the increased kinematic variability demonstrated by the MLBP group.[27] If we assume that optimal variability is demonstrated by the control group, patients with recurrent or chronic MLBP have a system that is less stable and somewhat noisy. Therefore, when faced with a perturbation, the system is less adaptable and coordination and stability of the movement pattern deteriorates.[17] This may put them at an increased risk for a prolonged episode or further injury.

The bilateral reaching task, as performed by the control subjects, requires predominant contribution from back and hip extensors both eccentrically in the later half of the forward reach and concentrically during the return phase. Given the almost opposite continuous relative phase pattern demonstrated by the MLBP group (Figure 3), we believe they were unable to adequately control the inter-segmental movement with their trunk extensors and thus switched to pelvic-dominated reaching and hip extensor control. Thus, our data suggest trunk extensor muscle dysfunction in chronic MLBP patients. This, in conjunction with previously reported findings of reduced cross-sectional area, strength and endurance of trunk extensors in the MLBP population, stresses the likely importance of this muscle group in rehabilitation of patients with MLBP.[28-31] This finding is consistent with our previous findings of altered trunk extensor muscle activation patterns in a subset of patients with MLBP.[19] The altered activation pattern is also a plausible explanation for the increased trial-to-trial variability most evident during the return phase of movement. We cannot rule out fatigue of the trunk muscles as a source of the pattern differences, although we kept the number of repetitions low to minimize the effects of muscle endurance on coordination patterns.[16,27] In addition, evidence of poor proprioception in the chronic MLBP population [32,33] leads to the possibility that musculoskeletal changes in our MLBP subjects reduced their ability to monitor and incorporate timely sensory feedback into movement adjustments during increased task demands. Such changes could force the neuromuscular system into altered inter-segmental dynamics, or control pattern, in an attempt to optimize dynamic stability. However, further research is required to investigate these hypotheses.

Our results should be interpreted in light of the limitations of our study. First, analysis was limited to the sagittal plane, and trunk movement is 3-dimensional; thus, our findings provide a partial picture of movement adaptation. Further, we chose a task that minimized kinetic effect of arms on trunk motion by having subjects keep the arms extended and level. Second, we did not standardize postural alignment of the trunk and pelvis, but instead used the subject's relaxed standing posture as the reference position. While our groups did not differ in their segment angle start positions, alignment may have an effect on individual movement patterns. Third,

the use of a limited number of trials to determine pattern stability may affect results. However, every subject performed the functional reach test and practice trials prior to the recorded trials. In addition, we believe this task was not novel to our subjects; therefore any learning effect should have minimal influence on the results. Despite our attempt to minimize learning effect, differences in learning rates may still exist between the groups. Future investigators should consider this point in their attempt to control for confounding effects of fatigue and learning. Fourth, large between-subject variability in the MLBP group may indicate that subgroups of patients with MBLP exists each with a different adaptive patterns, some perhaps more dysfunctional than others. When data are averaged across subjects, information about underlying control mechanisms can be lost. Therefore, qualitative analysis of individual angle-angle plots, continuous relative phase curves and phase portrait trajectories may assist in further interpretation of these data and with identification of details of adaptive movement patterns associated with this task in MLBP patients. Finally, the design of this study does not directly determine which impairment(s) might be responsible for the altered inter-segmental control or whether these changes were a cause or effect of their MLBP. Further research using prospective study designs and concurrent EMG and kinematics may offer additional insight into the impaired control mechanisms in the MLBP population. In addition, correlating these findings with specific clinical signs and symptoms would assist clinicians in determining which patients demonstrate these movement impairments.

Despite these limitations, use of a dynamical systems approach to understand coordination patterns and organization of the neuromuscular system in the MLBP population offers insight that may not be evident when using analysis of time series or discrete data alone. This tool could be applied to determining the efficacy of trunk motor control exercises for treatment of patients with MLBP attributed to poor neuromuscular control. Our data indicate that inter-segmental coordination was altered and more variable in the chronic MLBP group during this specific functional task. Given the current evidence of neuromuscular dysfunction in this patient population and the findings here, we recommend that clinicians assess trunk extensor muscle function with tests that challenge both postural stability and inter-segmental movement control. Rehabilitation programs might also be improved by incorporating exercises that provide practice for a sufficiently rich repertoire of trunk movement strategies, and repeat them more frequently to allow a system, in the process of rehabilitation, to become more stable in its response to associated perturbations across strategies.

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Figure 1.

Figure demonstrating the bilateral reaching task. Subjects stood with feet shoulder width apart, knees straight. Arms were elevated to approximately 90° of shoulder flexion, elbows extended with elevation maintained during the reaching task. Reaching distance was standardized to 50% of subject's functional reach distance. Subjects were instructed to "reach for the target by using their trunk and pelvis to move their arms forward, like reaching over a counter to get a bowl off of a cabinet shelf." Subjects were instructed to touch target and immediately return to upright standing. Reach and return motion standardized to 6-seconds (3-seconds forward, 3-second return). The graph represents a normalized time series of the segment movements of the control group (50% represents target contact). Trunk motions were smooth and continuous.

Figure 2.

Graphs of the group mean (with standard error) of the (a) *mean absolute relative phase* (MARP) representing “in phase” coordination and (b) *deviation phase* (DP) representing movement pattern variability across all conditions. The higher MARP (a) in the mechanical low back pain (MLBP) group indicates they demonstrated poorer coordination between their lumbar spine and pelvic segments particularly during the loaded condition. The higher DP in the MLBP group indicates greater individual trial-to-trial variability during their movement pattern. In contrast to the control group which maintains stability across conditions, the MLBP demonstrates greater variability during the return movement. * $P < .05$.

Figure 3.

Figure of group means (bounded by standard error, in gray) for continuous relative phase (CRP) versus time. Forward reach encompasses the first 50% of the motion and return to upright the last 50%. During forward reach an increase in the RP indicates the pelvis is leading or moving faster and a RP decrease means the lumbar spine is leading. During the return motion an increase in RP indicates that the lumbar spine is leading, while a decrease indicates the pelvis leads. In general control and mechanical low back pain (MLBP) subjects demonstrate contrasting patterns of inter-segment coordination. The bracketed area (29% - 76% of movement) indicates the region of significant group difference in RP values ($P \leq .05$). In addition, the variability in the movement pattern displayed by the control group is less than that of the MLBP with a generally smoother transition from forward reach to return motion.

Control Subject

MLBP Subject

Figure 4.

This figure provides example data from the loaded condition for a matched (age, gender, body mass index) mechanical low back pain (MLBP) and control subject. The figure includes 4 different plots (a) pelvis vs. lumbar spine angle-angle, (b) phase plane (segment displacement vs. velocity), (c) continuous relative phase angles, and (d) phase angle vs. phase angle. Angle-angle plots (a) the control subject (left panel) demonstrated a highly coordinated movement pattern that is consistent in forward reach and in return. The MLBP subject (right panel) demonstrated less inter-segment coordination and different patterns of movement in forward reach and return. In the phase plane plots (b), asterisks (*) mark the cusps indicating large velocity changes during movement and arrows (→) indicate the region representing the reversal of direction. The decreased excursion of the lumbar spine segment and abrupt velocity shifts demonstrated by the subject with MLBP (right panel) are reflected in a higher mean absolute relative phase value, signifying less coordinated movement between the segments and poor temporal control primarily during the return phase. The continuous relative phase plots (c) reveal qualitatively different patterns of inter-segment coordination between the 2 subjects.

Table 1

Group demographics, clinical characteristics and kinematic task parameters.

Demographics + Characteristics	Control	MLBP		
Subjects (female/total)	12/35	11/30		
Age (years)	38.8 (9.2)	41.1 (8.9)		
Height (m)	1.7 (0.1)	1.8 (0.1)		
BMI* (kg/m ²)	25.3 (4.8)	26.2 (5.2)		
Pain Location (% with LBP only)	--	67%		
Symptom Duration (months)	--	3.1 (4)		
RMQ** (0-24)	--	8.1 (5.2)		
NPRS*** (0-10)	--	3.8 (2.2)		
Target Distance [¶] (cm)	19.2 (4.7)	17.5 (4.2)		
Kinematic Task Parameters	No Load	Load	No Load	Load
Peak Trunk Velocity ^{¶¶} (°/s)	29.5 (14.2)	30.9 (13.8)	28.5 (34.1)	25.9 (17.8)
Forward Reach (°/s)	27.2 (13.9)	27.8 (12.6)	25.5 (30.9)	21.6 (12.5)
Return to Upright (°/s)	26.2 (12.6)	29.4 (13.2)	27.0 (34.3)	25.2 (18.1)
Start Position ^{¶¶¶} Pelvis (°)	-4.8 (8.5)	-6.0 (7.3)	-3.7 (11.1)	-3.9 (11.7)
Start Position Lumbar Spine (°)	-12.4 (14.0)	-10.2 (12.6)	-9.3 (16.9)	-8.0 (18.0)
Peak Trunk Motion [€] (°)	45.3 (17.3)	47.0 (18.3)	41.5 (25.8)	40.5 (23.3)
Peak Pelvis Motion (°)	26.4 (11.8)	27.5 (10.1)	21.7 (11.5)	22.4 (11.7)
Peak Lumbar Motion (°)	21.0 (12.3)	20.9 (12.4)	18.5 (14.4)	18.9 (16.5)
Discrete RP ^{€€} Max Forward (°)	46.5 (53.1)	48.3 (48.7)	47.5 (55.1)	30.7 (40.8)
Discrete RP Min Forward (°)	-52.1 (50.8)	-53.0 (50.2)	-57.6 (62.0)	-75.6 (56.6)
Discrete RP Max Return (°)	53.0 (46.2)	51.1 (43.7)	63.2 (49.5)	72.9 (60.5)
Discrete RP Min Return (°)	-53.9 (50.9)	-45.5 (50.5)	-52.1 (51.8)	-49.9 (47.1)

Data represent mean (standard deviation).

Bold: significant group differences, $P < .05$.

* BMI: Body Mass Index is a measure of body fat based on weight and height; higher values indicate higher percentage of body fat.

** RMQ: Self-report Roland Morris Disability questionnaire, lower score, less disability.

*** Numeric Pain Scale: Higher value indicates more pain.

[¶] Target Distance represents 50% of the subject's functional reach. Functional reach was determined using *The Functional Reach Test*. [18] This is a measure of balance and is the difference between arm length and maximum forward reach (in centimeters), without the subject changing their standing base of support. Individual subject value is based on mean of 3 trials.

^{¶¶} Peak Trunk Velocity represents the peak angular velocity of the lumbar spine relative to the femur in degrees/second.

^{¶¶¶} Start Position represents the initial orientation of the pelvic and lumbar segments, relative to relaxed standing position, when the subject is standing with the shoulders at 90° of flexion and elbows extended.

[€] Peak Trunk Motion represents the peak angular motion achieved between the femur and lumbar spine in degrees during the reaching task.

^{€€} Discrete Relative Phase (RP) maximum (Max) and minimum (Min) values for both forward reach and return to standing.