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Original article

# A history of low back pain affects pelvis and trunk coordination during a sustained manual materials handling task

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## Abstract

**Purpose:** The purpose of this study was to compare the coordination between the trunk and the pelvis during a sustained asymmetric repetitive lifting task between a group with a history of low back pain (LBP; HBP) and a group with no history of LBP (NBP).

**Methods:** Volunteers lifted a 11-kg box from ankle height in front to a shelf 45° off-center at waist height, and lowered it to the start position at 12 cycles/min for 10 min. Lifting side was alternated during the trial. Continuous relative phase was used to calculate coordination between the pelvis and trunk rotation at the beginning (Min 1), middle (Min 5), and end of the bout (Min 9).

**Results:** While there were no main effects for group, a significant interaction between time and group indicated that, in the frontal plane, the NBP group coordination was more anti-phase toward the end of the bout, with no such differences for the HBP group. Analysis of sagittal-axial (bend and twist) coordination revealed the HBP group coordination was more in-phase at the end of the bout over the entire cycle and for the lifting phase alone, with no such differences for the NBP group.

**Conclusion:** Differences between groups demonstrate residual consequences of LBP in an occupational scenario, even though the HBP group was pain-free for >6 months prior to data collection. More in-phase coordination in the HBP group may represent a coordination pattern analogous to “guarded gait” which has been observed in other studies, and may lend insight as to why these individuals are at increased risk for re-injury.

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**Keywords:** Lifting; Lowering; Occupational biomechanics; Relative phase; Relative phase variability

## 1. Introduction

Low back pain (LBP) has long ago reached epidemic proportions in the US, with four out of five people experiencing LBP at least once in their lives.<sup>1,2</sup> LBP is also the most common reason for seeking medical care for civilians<sup>3</sup> and military alike.<sup>4,5</sup> In military cohorts, back pain-related medical issues were among the top three leading causes for lost duty days for U.S. soldiers as recently as 2011.<sup>5,6</sup> Issues related to back pain have also ranked among the highest risk factors for permanent disability within 5 years of onset at 20%.<sup>7</sup>

Symptoms resolve for most individuals who experience LBP, and these individuals return to pre-injury work and activity levels pain-free within 8 weeks.<sup>8</sup> While the majority of

healthcare resources are spent on those individuals for whom LBP lasts longer,<sup>1</sup> the others who return to occupational and recreational activity with a history of LBP (HBP) are more likely to experience recurring episodes of LBP. Within 1 year after initial LBP episode, epidemiological studies report recurring episodes at rates ranging from 24% to 50%.<sup>9,10</sup>

Research estimates that only 6%–15% of reported LBP episodes are first-time episodes;<sup>11</sup> with over 85% of annual LBP cases being recurrences. It is not surprising that HBP places individuals at increased risk for future episodes. This notion is supported by other studies which report 24%–50% of those who suffer initial LBP episodes have a recurring episode of LBP within 1 year,<sup>9</sup> and that chance of recurrence increases with age.<sup>9</sup> In collegiate athletes, one study reported that athletes with HBP were three to six times more likely to suffer a bout of LBP during their collegiate career than activity-matched athletes who never had LBP.<sup>12</sup> In the U.S. military, a high disability rate due to LBP, combined with a 19% disability rate leads to an estimate that approximately 80% of soldiers return to full duty

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after LBP, and that approximately 24% of the U.S. Army can be categorized as HBP.<sup>6,7,13</sup>

The athletic literature has demonstrated that there are functional consequences to having HBP. Collegiate athletes with HBP, who had returned to full activity levels within their sport for quite some time, ran significantly slower on the shuttle run when compared to sport-matched controls with no history,<sup>14</sup> suggesting that their performance-related residual effects were associated with HBP. Also differences have been observed in walking and running mechanics between those with and without LBP. When comparing runners with mild to moderate LBP vs. runners with HBP vs. runners who have never experienced LBP (NBP), research has documented increases in knee stiffness,<sup>15</sup> more in-phase pelvis–trunk coordination,<sup>16</sup> and decreases in coordination variability.<sup>17</sup> These disparities are consistent with the “guarded gait” typically associated with more severe LBP.

In the ergonomic literature, studies have implied that participating in manual materials handling tasks is among the work-related factors associated with LBP.<sup>18–21</sup> There is also an increased risk of occupational LBP with any job task which involves the motion combinations of bending and twisting from the waist (trunk sagittal lean and rotation).<sup>3,22,23</sup> Such factors are also a consideration in the military, where one report indicates that slightly more than 2/3 of U.S. soldier occupational tasks involve lifting and lowering between the ground and waist height.<sup>24</sup> However, few studies have explored differences in lifting mechanics between individuals with and without HBP; insight into these differences could elucidate adaptations due to LBP. A recent study has reported differences in lifting mechanics between soldiers with and without HBP; specifically, individuals with HBP maintained more consistent mechanics (range of motion and angular velocity) during a 10-min lift/lower task than those with NBP.<sup>25</sup>

Dynamical systems measures, such as continuous relative phase (CRP) analysis, have been able to provide information on how segments interact relative to each other. Relative phase has been utilized in the past to incorporate angular position and angular velocity information over an entire motion cycle which compliments kinematic analyses.<sup>26</sup> Data analyzed using relative phase angle (CRP $\theta$ ) and CRP $\theta$  variability have demonstrated differences in lower limb<sup>27,28</sup> and pelvis–trunk coordination<sup>17,29</sup> between individuals with and without LBP. Additionally, these measures can be adapted to analyze segmental interactions which incorporate asymmetric motions, such as trunk bend and twist (sagittal bend and axial rotation) during running.<sup>30</sup> Using such techniques to analyze interactions between the pelvis and trunk during a manual materials handling paradigm will allow for additional insights into the “bend and twist” motions associated with occupational LBP.

The purpose of this study was to compare the coordination and coordination variability profiles of the trunk and the pelvis during a sustained asymmetric repetitive lifting task between an HBP and an NBP group during a repeated box lift/lower paradigm. We chose a 10-min asymmetric lift/lower paradigm in order to simulate a typical time-modulated occupational scenario. We chose a box mass of 11 kg and cadence of 12 lift/

lower cycles/min in order to provide sufficient physical stress to elicit any time-related differences between the groups and to ensure that all participants were performing the same amount of work at the same rate, while maintaining the safety of our participants with HBP. We hypothesized that the HBP group would demonstrate different coordination mechanics over time as compared to the NBP group. Specifically, we expected the HBP group to display more in-phase coordination (CRP $\theta$ ; values closer to 0), which would represent “guarded mechanics” often associated with LBP during gait. Consistent with previous coordination findings,<sup>29</sup> we also hypothesized that the HBP group would demonstrate decreased coordination variability, demonstrating a decreased ability to adapt after the resolution of LBP and/or over time.

## 2. Materials and methods

### 2.1. Participants

Twenty healthy male soldiers gave informed consent to participate in this study. Ethical approval was granted by the U.S. Army Research Institute of Environmental Medicine’s institutional review board. The investigators adhered to the policies for protection of human subjects as prescribed DoD Instruction 3216.02 and the research was conducted in adherence with the provisions of 32 CFR Part 219. Participants were asked about their history with LBP. LBP was defined as pain, soreness, or tightness that prevented a person from performing their usual duty or training regimen for more than 3 days. Because we were interested in non-specific LBP, participants were excluded from participation if they reported that their LBP was the result of traumatic injury, or if they were medically diagnosed with a slipped or bulging inter-vertebral disc. Those who had never experienced a bout of LBP were placed in the NBP group ( $n = 11$ ;  $176.8 \pm 5.2$  cm;  $81.6 \pm 14.0$  kg;  $26 \pm 6$  years). If a participant had experienced a bout of LBP that lasted less than 6 weeks and have had no symptoms for at least 6 months, then they were placed in the history of back pain group ( $n = 9$ ;  $176.4 \pm 5.1$  cm;  $81.0 \pm 11.4$  kg;  $24 \pm 5$  years). Participants were also excluded from participation if they reported any current or prior musculoskeletal injuries or medical conditions that would either interfere with their completion of the testing or that would predispose them to injury during the testing.

### 2.2. Equipment

A detailed description of the methods used in this study has been published previously.<sup>25</sup> A custom 3-shelf station was constructed for this experiment. Two platforms were affixed to the left and right of a central vertical channel, angled at 45°. Within the central channel a small step was built atop an adjustable floor (Fig. 1). Foam blocks could be inserted to adjust the floor height so that the two platforms would be at waist height of the participant standing on the flooring. The low central platform shielded the participant’s feet, while creating an ankle height shelf for an 11-kg box with handles to be placed directly in front of the participant. The box was lifted and lowered from shelf to shelf at a fixed cadence maintained using a metronome (KDM-2; KORG USA Inc., Melville, NY, USA).

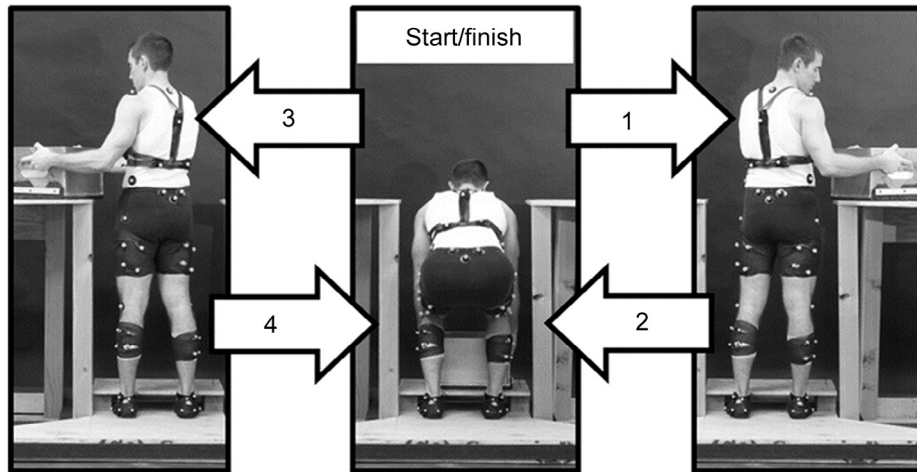


Fig. 1. Representation of a complete lift/lower cycle. The 11-kg box lift was initiated from the center position and completed on the right platform. The box was then returned to the center before repeating the pattern to the left side. Each step (1, 2, 3, 4) is allotted 2.5 s. Trunk motion was tracked using the three markers on the torso harness and pelvic was tracked using the sacral triad. During actual data collection, sacral markers were secured with tape.

For purposes of recording movement, reflective markers were placed bilaterally on skin and clothing locations corresponding to the participants' body segments.<sup>25</sup> Three-dimensional (3D) motion of these reflective markers were captured using 12 Motion Capture Unit (MCU) cameras (Qualisys AB, Goteborg, Sweden) surrounding the lifting station. The reflective markers defining the local segment coordinate systems for the pelvis were placed bilaterally on the anterior superior iliac spines (ASIS), posterior superior iliac spines (PSIS), sacrum, greater trochanter (GT), and iliac crest (ILCR, directly superior to the GT during quiet standing). The trunk segment was defined using calibration markers placed bilaterally on the iliac crest and on the acromioclavicular joints (Fig. 1). The PSIS and sacrum markers were used to track pelvic movement. Markers on a rigid lightweight molded plastic frame secured to the posterior aspect of the trunk were used to track the motion of the trunk (Fig. 1).

### 2.3. Procedures

Once a participant gave informed consent and medical clearance was granted, data were collected in a single session. Upon arrival to the lab, the participant's anthropometrics were recorded. Next the participant was given instructions for the session. Specifically, participants were told to perform the lift while maintaining the pace set by the metronome, to keep their feet stationary during the entire bout, and to fully release their fingers from the box at each platform. No additional lifting technique instructions were provided.

Following the instructions, the participant was asked to practice the box lifting task. Once the participant was comfortable with the movement and felt sufficiently warmed up, and the investigator was satisfied with the participant's ability to maintain the cadence, the reflective markers were placed as previously described.<sup>25</sup>

The lifting task itself required the participant to first lift the 11-kg box from the low platform to the right elevated shelf and back before going to the left side. The box lift was performed

without stopping for 10 min at a rate of 12 lift/lower cycles per minute alternating between the elevated platforms. Kinematic data were collected at Min 1, Min 5, and Min 9 for 65 s to ensure six lift/lower cycles to each side were captured.

### 2.4. Data processing

Marker data were tracked using Qualisys Track Manager software (Qualisys AB). Visual 3D motion analysis software (C-Motion Inc., Germantown, MD, USA) was used to filter motion data (low pass, second order Butterworth filter at 15 Hz) and calculate 3D segmental angles and velocities for the pelvis and trunk segments. For the purposes of analysis, custom MATLAB software (The MathWorks, Inc., Natick, MA, USA) was used to divide the data into lifting and lowering phases of the cycle for both left (lifting to the left, lowering from the left) and right sides (lifting to the right, lowering from the right). Four points on the front of the box were averaged to ascertain box position, which was used to define lifting and lowering phases based on position and acceleration profiles of the box, and excluded portions of the lift where the box was at rest (i.e., zero acceleration). This allowed for examination of both phases separately and excluded periods of time during which the box was resting on any of the shelves.

Once the sides and action were determined, continuous relative phase (CRP $\theta$ ) calculations were initiated by combining the segmental angles and velocities to create a position-velocity phase plane. The phase plane was normalized to the unit circle to later correct for any frequency and amplitude differences between the pelvis and trunk segments.<sup>31</sup> Next phase angles were generated from the phase plane through the use of the arctangent function. CRP $\theta$  was then calculated as the absolute value of the difference between the phase angles of each segment. CRP $\theta$  was calculated for each of the six complete lifting and lowering cycles to/from the right and left sides. CRP $\theta$  variability (CRPvar) could now be calculated as the average of each cycle's deviation from the mean CRP $\theta$  value within a given time point (Min 1, Min 5, or Min 9).

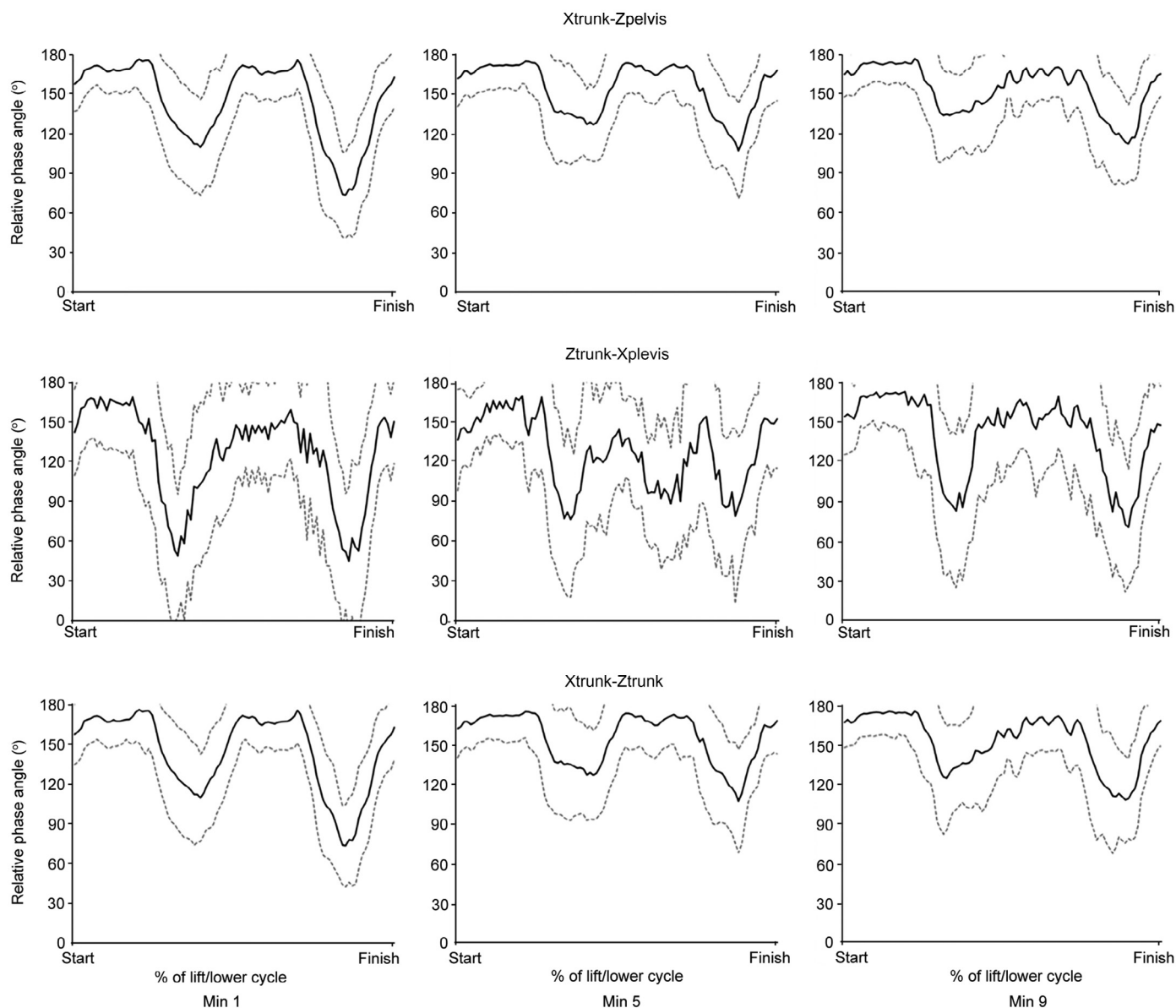


Fig. 2. Exemplar plots of CRP $\theta$  (solid dark line) and CRPvar (lighter dashed lines) for sagittal–axial for one exemplar subject. CRP = continuous relative phase.

We analyzed single plane interactions in the sagittal and transverse planes. In order to examine pelvis–trunk coordination during the bending and twisting motion, we analyzed three additional segmental interactions. Within the trunk segment we examined the sagittal plane and transverse plane interactions (Xtrunk–Ztrunk). While this combination has been utilized previously to demonstrate differences in pelvis–trunk coordination between runners with and without LBP,<sup>30</sup> it does not involve the pelvis, which is more integral to lifting during a manual materials handling task. Therefore, we decided to examine the interaction between pelvis anterior–posterior tilt and trunk axial rotation (Xpelvis–Ztrunk) and trunk anterior lean with respect to pelvis rotation (Xtrunk–Zpelvis). Fig. 2 represents an exemplar sagittal–axial relative phase resultant plot for one exemplar subject.

### 2.5. Statistical analysis

Group means were reported for CRP $\theta$  and CRPvar in both groups during the lifting and lowering portions of the total cycle at the beginning (Min 1), middle (Min 5), and end (Min 9) of the trial, and for both the right and left sides. Initially a 3-way analyses of variance (ANOVA) was conducted to examine the relationship between group (HBP, NBP), time (Min 1, Min 5, Min 9) and side (L, R). While the results of this analysis revealed no significant interactions involving side (group  $\times$  side, time  $\times$  side, or group  $\times$  time  $\times$  side), several main effects for time did emerge. Two-way repeated measures ANOVA were conducted to examine the relationships between LBP group (HBP, NBP) and time (Min 1, Min 5, Min 9) for each variable examined for each side of the body. Holm–Sidak

*post hoc* analysis was performed when significant interactions or main effects ( $p \leq 0.05$ ) were reported. In order to supplement the interpretation of statistically significant results, effect sizes (ES) were calculated to assess the practical importance of a difference between means, estimated as the difference between two means over a pooled standard deviation. Cohen<sup>32</sup> proposed that  $ES > 0.8$  represent large practical differences and that  $ES > 0.5$  is clinically meaningful when comparing two means within biological systems. Data were analyzed using SigmaPlot (version 12.0; Systat Software, Inc., San Jose, CA, USA).

### 3. Results

#### 3.1. Single-plane analyses

In the sagittal plane there was a main effect for time for CRPvar while lifting to the right side ( $p = 0.013$ ). When averaged across groups, CRPvar was greater at Min 1 than Min 5

( $p = 0.01$ ) ( $ES = 0.7$ ). There were no interactions or other main effects, nor were there any significant findings while lifting to the left side (Table 1).

Transverse plane comparisons revealed a group  $\times$  time interaction for CRP $\Theta$  while lifting to the right side ( $p = 0.024$ ), with *post hoc* analyses revealing that, within the NBP group, CRP $\Theta$  was significantly greater at the end of the bout than at the beginning or the middle ( $p < 0.001$  and  $p = 0.009$ , respectively). There were also main effects for time while lowering from the right for CRP $\Theta$  ( $p = 0.03$ ) and CRPvar ( $p = 0.04$ ) (Table 1). CRP $\Theta$  values were significantly greater at the end of the bout (Min 9) than in the middle (Min 5,  $p = 0.05$ ). However, all significant results were translated to small practical differences, with  $ES < 0.4$ . While lifting to the left there was a main effect of time for CRPvar, with *post hoc* analyses revealing that CRPvar at Min 1 was significantly less than at Min 5 and Min 9 (both  $p \leq 0.05$ ). There were also main effects of time for CRP $\Theta$

Table 1  
Single-plane coordination (CRP) and coordination variability (CRPvar) results.

Single-plane coordination			Min 1	Min 5	Min 9
<b>Right side</b>					
<i>Xtrunk-Zpelvis</i>					
CRP $\Theta$	Lift	HBP	35.34 $\pm$ 28.15	29.66 $\pm$ 21.21	39.02 $\pm$ 35.07
		NBP	22.13 $\pm$ 6.65	17.75 $\pm$ 5.93	18.53 $\pm$ 6.58
Lower		HBP	35.96 $\pm$ 27.62	35.26 $\pm$ 27.34	39.76 $\pm$ 39.96
		NBP	20.24 $\pm$ 7.06	18.33 $\pm$ 8.41	18.22 $\pm$ 4.92
CRPvar	Lift	HBP	50.83 $\pm$ 36.53	40.69 $\pm$ 24.10*	49.67 $\pm$ 32.30
		NBP	31.37 $\pm$ 10.32	25.52 $\pm$ 7.23	28.45 $\pm$ 8.87
Lower		HBP	52.38 $\pm$ 34.57	46.84 $\pm$ 23.06	42.24 $\pm$ 21.79
		NBP	33.23 $\pm$ 8.38	31.95 $\pm$ 13.39	31.08 $\pm$ 8.65
<i>Ztrunk-Zplevis</i>					
CRP $\Theta$	Lift	HBP	16.37 $\pm$ 8.75	14.46 $\pm$ 6.00	16.15 $\pm$ 8.90
		NBP	13.55 $\pm$ 3.24	16.35 $\pm$ 6.39	23.49 $\pm$ 12.19* <sup>#</sup>
Lower		HBP	12.82 $\pm$ 5.70	11.05 $\pm$ 3.47	13.76 $\pm$ 6.46 <sup>#</sup>
		NBP	11.64 $\pm$ 3.50	12.78 $\pm$ 2.99	16.61 $\pm$ 8.74
CRPvar	Lift	HBP	31.38 $\pm$ 20.04	26.96 $\pm$ 12.60	30.69 $\pm$ 17.04
		NBP	22.57 $\pm$ 4.54	29.57 $\pm$ 11.74	39.69 $\pm$ 25.16
Lower		HBP	24.72 $\pm$ 14.22	21.28 $\pm$ 7.29	26.71 $\pm$ 13.45
		NBP	20.96 $\pm$ 5.84	23.60 $\pm$ 6.38	31.57 $\pm$ 17.26
<b>Left side</b>					
<i>Xtrunk-Xpelvis</i>					
CRP $\Theta$	Lift	HBP	38.29 $\pm$ 32.38	28.12 $\pm$ 14.73	38.83 $\pm$ 34.68
		NBP	21.69 $\pm$ 6.25	19.16 $\pm$ 7.08	18.18 $\pm$ 5.62
Lower		HBP	33.73 $\pm$ 28.45	30.13 $\pm$ 15.78	38.72 $\pm$ 40.55
		NBP	20.99 $\pm$ 9.11	19.94 $\pm$ 8.98	19.14 $\pm$ 5.52
CRPvar	Lift	HBP	53.64 $\pm$ 38.82	45.02 $\pm$ 29.76	51.23 $\pm$ 39.07
		NBP	27.41 $\pm$ 6.81	24.33 $\pm$ 7.74	24.76 $\pm$ 3.75
Lower		HBP	47.25 $\pm$ 25.75	48.09 $\pm$ 24.70	45.84 $\pm$ 26.38
		NBP	29.95 $\pm$ 9.29	30.57 $\pm$ 13.33	31.84 $\pm$ 12.45
<i>Ztrunk-Zpelvis</i>					
CRP $\Theta$	Lift	HBP	11.30 $\pm$ 3.62	15.01 $\pm$ 8.67	16.72 $\pm$ 13.58
		NBP	13.95 $\pm$ 6.16	22.09 $\pm$ 15.36	23.77 $\pm$ 23.48
Lower		HBP	9.98 $\pm$ 2.40	11.97 $\pm$ 4.73*	13.18 $\pm$ 5.31*
		NBP	12.81 $\pm$ 3.65	17.77 $\pm$ 7.30	17.26 $\pm$ 9.56
CRPvar	Lift	HBP	19.19 $\pm$ 6.93	24.54 $\pm$ 16.38*	23.56 $\pm$ 12.53*
		NBP	19.56 $\pm$ 8.24	35.43 $\pm$ 26.98	34.94 $\pm$ 25.58
Lower		HBP	18.51 $\pm$ 4.95	20.28 $\pm$ 6.97*	20.69 $\pm$ 5.31*
		NBP	19.94 $\pm$ 3.94	31.39 $\pm$ 21.26	31.14 $\pm$ 18.97

\* $p \leq 0.05$ , compared with Min 1; <sup>#</sup> $p \leq 0.05$ , compared with Min 5.

] Group values averaged (main effect for time).

Abbreviations: CRP = continuous relative phase; HBP = a history of low back pain; NBP = a group with no history of low back pain.

and CRPvar while lowering from the left. *Post hoc*s revealed that CRP $\Theta$  values were greater (more anti-phase) in the beginning than at the middle or at the end of the bout (both  $p \leq 0.02$ ), and CRPvar was significantly less at the beginning than at the other two time points (both  $p \leq 0.05$ ). All left side ES  $\leq 0.5$ , suggesting differences may be approaching clinical significance.

There were no further significant interactions or main effects in any plane for CRP $\Theta$  or CRPvar for either component phase.

### 3.2. Bend and twist comparisons

Analysis of trunk anterior lean and axial rotation (Xtrunk–Ztrunk) revealed a main effect for time in CRPvar while lowering from the right ( $p = 0.009$ ), with CRPvar at Min 9 significantly greater than at Min 5 and Min 1 ( $p \leq 0.012$ ) (ES  $\leq 0.7$ ). When lowering from the left, there was a main effect for time, with *post hoc* analyses revealing that CRP $\Theta$  was more anti-phase at Min 1 than at Min 9 ( $p = 0.03$ ). CRPvar was also significantly less at the beginning of the bout than in the middle or at the end (both  $p \leq 0.04$ , ES  $< 0.4$ ) (Table 2).

Analysis of pelvis sagittal and trunk rotation (Xpelvis–Ztrunk) revealed a group time interaction for CRP $\Theta$  ( $p = 0.03$ ) and CRPvar ( $p = 0.04$ ) during the lifting phase from the right (Table 2). For CRP $\Theta$  *post hoc* analysis revealed that, within the HBP group, Min 5 was greater than Min 9 ( $p = 0.010$ ). *Post hoc*s showed that CRPvar was greater for Min 1 and Min 9 than Min 5 within the HBP group ( $p \leq 0.04$ ). All significant relationships had clinically meaningful ES ranging from 0.5 to 0.7. There were no significant relationships between group and time when lifting to the left or lowering from the left side.

Analysis of trunk forward lean relative to pelvis axial rotation (Xtrunk–Zpelvis) revealed group time interactions for CRPvar during the lifting phase ( $p = 0.006$ ). *Post hoc* analysis revealed that, within the HBP group, CRPvar was lower at Min 1 and Min 5 than Min 9 ( $p = 0.004$ ). Additionally, during the lifting phase, CRPvar for the HBP group was significantly greater than the NBP group at Min 9 ( $p = 0.008$ ). All significant relationships in the Xtrunk–Zpelvis coupling while lifting to or lowering from the right-hand side had ES ranging from 0.8 to 1.3, indicating large practical differences. While lifting to the left side, CRP $\Theta$  was more anti-phase during Min 1 than Min 5 and Min 9 ( $p \leq 0.04$ , ES = 0.4) (Table 2).

There were no further significant interactions or main effects in any plane for CRP $\Theta$  or CRPvar for either component phase.

## 4. Discussion

The purpose of this study was to examine differences in pelvis–trunk coordination and coordination variability during a repetitive box lifting and lowering task between individuals with and without HBP. We hypothesized that individuals with HBP would demonstrate more in-phase coordination mechanics than those without, and that differences would be exacerbated over time. The majority of our main effect significant results were time-related (time-related hypotheses supported), where coordination or variability changed relative to the

beginning of the lifting bout, regardless of group. There were no main effects for group, likely because both groups were highly functional; however, analysis of significant group  $\times$  time interactions revealed that there were group-related adaptations (Table 2). Analysis of sagittal–axial (bend and twist) coordination revealed the HBP group coordination was more in-phase at the end of the lifting phase, with no such differences for the NBP group (Table 2).

### 4.1. Comparison to kinematic analysis

Results of transverse plane are consistent with transverse plane range of motion (ROM) and angular velocity results from the same cohort.<sup>25</sup> Briefly, there was no difference in pelvis and trunk segmental ROM between groups at the beginning of the bout; however, at the end of the bout, the NBP ROM decreased, while the HBP ROM remained constant throughout the bout. Ultimately this was interpreted as less constrained lifting mechanics over the entire lifting bout for the group who had never experienced LBP; the NBP group maintained the assigned lift/lower pace by utilizing their arms.<sup>25</sup>

The results of the current study compliment the kinematic findings. The more consistent kinematics observed in the HBP group were considered protective, somewhat analogous to the guarded gait which is typical of individuals who are experiencing LBP.<sup>33</sup> Results from the current study revealed significant differences in transverse plane coordination and variability during the lowering phase, and no group differences. Regardless of which phase of the lifting cycle was examined, the HBP group coordination mechanics became more in-phase (i.e., decreasing CRP) toward the end of the bout. This is also consistent with a “guarding” strategy, which may be residual from the injury. However, the coordination variability generally increased for this group as time went on as well, which is consistent with more adaptable mechanics over time that one would expect from a healthy system. Therefore, while overall mechanics became more in-phase over time, the system was still able to adapt over the course of the bout.

### 4.2. Single-plane couplings

Main effects for time occurred during the single-plane analyses (Xtrunk–Xpelvis, Ztrunk–Zpelvis; Table 1). Where differences occurred during the lowering phase, pelvis–trunk CRP $\Theta$  was more anti-phase at the end of the bout, suggesting that the pelvis and trunk were controlled more as separate segments as time progressed during the bout, and were less constrained to work as a pair. This likely developed with practice and as familiarity increased with the task. That there were no main effects for group suggests that the mechanics of both groups evolved similarly over the duration of the lifting bout.

### 4.3. Sagittal–axial coupling

While there were no main effects for group, sagittal–axial (bend and twist) couplings revealed coordination differences for the HBP group over time during *post hoc* analyses of group  $\times$  time interactions (Table 2). Specifically, the HBP group coordination became more in-phase at the end of the

Table 2  
Sagittal–axial (bend and twist) coordination (CRP $\theta$ ) and coordination variability (CRPvar) results.

Bend and twist coordination			Min 1	Min 5	Min 9
<b>Right side</b>					
<i>Xtrunk-Zpelvis</i>					
CRP $\theta$	Lift	HBP	145.44 $\pm$ 8.26	139.86 $\pm$ 10.38	138.58 $\pm$ 11.43
		NBP	142.57 $\pm$ 9.12	142.14 $\pm$ 8.84	144.91 $\pm$ 8.58
	Lower	HBP	138.39 $\pm$ 8.22	135.59 $\pm$ 7.32	134.47 $\pm$ 8.54
		NBP	136.49 $\pm$ 8.27	133.25 $\pm$ 10.55	135.48 $\pm$ 11.94
CRPvar	Lift	HBP	26.42 $\pm$ 7.71	29.43 $\pm$ 9.04	{ 36.52 $\pm$ 9.28* <sup>#</sup>
		NBP	28.07 $\pm$ 10.67	26.27 $\pm$ 7.28	{ 25.62 $\pm$ 7.23
	Lower	HBP	26.64 $\pm$ 5.70	33.51 $\pm$ 8.53	33.58 $\pm$ 8.31
		NBP	28.90 $\pm$ 5.03	26.64 $\pm$ 4.51	29.51 $\pm$ 9.80
<i>Xpelvis-Ztrunk</i>					
CRP $\theta$	Lift	HBP	126.45 $\pm$ 23.90	131.76 $\pm$ 10.15	121.01 $\pm$ 19.15 <sup>#</sup>
		NBP	127.89 $\pm$ 6.11	131.78 $\pm$ 5.63	132.62 $\pm$ 8.87
	Lower	HBP	123.23 $\pm$ 13.30	123.55 $\pm$ 10.85	120.27 $\pm$ 20.19
		NBP	125.89 $\pm$ 8.31	123.56 $\pm$ 8.43	126.58 $\pm$ 10.13
CRPvar	Lift	HBP	48.60 $\pm$ 13.31	41.62 $\pm$ 16.80*	50.62 $\pm$ 13.49 <sup>#</sup>
		NBP	45.74 $\pm$ 7.95	42.52 $\pm$ 8.78	41.24 $\pm$ 9.58
	Lower	HBP	52.27 $\pm$ 16.13	48.22 $\pm$ 11.21	47.57 $\pm$ 6.62
		NBP	46.62 $\pm$ 9.24	48.51 $\pm$ 10.70	46.98 $\pm$ 10.22
<i>Xtrunk-Ztrunk</i>					
CRP $\theta$	Lift	HBP	144.80 $\pm$ 8.78	139.86 $\pm$ 10.38	138.64 $\pm$ 11.19
		NBP	142.97 $\pm$ 7.63	141.13 $\pm$ 8.87	142.55 $\pm$ 9.44
	Lower	HBP	138.18 $\pm$ 7.68	135.59 $\pm$ 7.32	134.25 $\pm$ 8.38
		NBP	136.17 $\pm$ 8.36	131.95 $\pm$ 10.85	133.36 $\pm$ 9.87
CRPvar	Lift	HBP	28.14 $\pm$ 7.45	29.43 $\pm$ 9.04	34.44 $\pm$ 8.67
		NBP	28.42 $\pm$ 10.48	31.39 $\pm$ 11.50	30.37 $\pm$ 10.20
	Lower	HBP	27.26 $\pm$ 4.19	33.51 $\pm$ 8.53	32.55 $\pm$ 7.24* <sup>#</sup>
		NBP	28.39 $\pm$ 4.78	30.22 $\pm$ 6.36	32.84 $\pm$ 10.25
<b>Left side</b>					
<i>Xtrunk-Zpelvis</i>					
CRP $\theta$	Lift	HBP	145.79 $\pm$ 8.96	141.93 $\pm$ 12.48*	140.52 $\pm$ 11.06*
		NBP	146.79 $\pm$ 7.53	135.98 $\pm$ 16.47	136.83 $\pm$ 25.00
	Lower	HBP	135.28 $\pm$ 10.40	136.07 $\pm$ 10.67	130.93 $\pm$ 13.70
		NBP	132.36 $\pm$ 11.11	127.14 $\pm$ 7.65	126.18 $\pm$ 13.87
CRPvar	Lift	HBP	40.44 $\pm$ 14.94	42.23 $\pm$ 14.66	38.57 $\pm$ 11.39
		NBP	32.30 $\pm$ 7.98	51.66 $\pm$ 28.06	42.46 $\pm$ 20.38
	Lower	HBP	43.50 $\pm$ 29.62	39.75 $\pm$ 7.25	37.95 $\pm$ 12.22
		NBP	34.57 $\pm$ 6.22	45.42 $\pm$ 14.53	46.59 $\pm$ 21.97
<i>Xpelvis-Ztrunk</i>					
CRP $\theta$	Lift	HBP	117.92 $\pm$ 29.25	127.85 $\pm$ 14.94	120.01 $\pm$ 23.52
		NBP	130.18 $\pm$ 7.76	128.74 $\pm$ 7.57	129.83 $\pm$ 9.53
	Lower	HBP	119.68 $\pm$ 23.40	125.14 $\pm$ 11.07	114.44 $\pm$ 22.22
		NBP	124.02 $\pm$ 8.99	122.57 $\pm$ 9.13	124.04 $\pm$ 10.33
CRPvar	Lift	HBP	63.05 $\pm$ 32.50	56.98 $\pm$ 22.93	56.56 $\pm$ 26.56
		NBP	40.69 $\pm$ 9.43	51.90 $\pm$ 22.99	53.78 $\pm$ 21.90
	Lower	HBP	61.33 $\pm$ 26.56	55.62 $\pm$ 16.21	53.92 $\pm$ 20.66
		NBP	41.84 $\pm$ 10.19	53.50 $\pm$ 23.74	53.80 $\pm$ 18.08
<i>Xtrunk-Ztrunk</i>					
CRP $\theta$	Lift	HBP	144.22 $\pm$ 6.16	141.05 $\pm$ 8.32	141.24 $\pm$ 10.54
		NBP	144.04 $\pm$ 5.23	141.02 $\pm$ 8.78	143.40 $\pm$ 9.59
	Lower	HBP	139.27 $\pm$ 7.22	136.35 $\pm$ 8.48	135.59 $\pm$ 10.91*
		NBP	133.47 $\pm$ 6.45	131.49 $\pm$ 7.17	131.55 $\pm$ 8.69
CRPvar	Lift	HBP	27.05 $\pm$ 7.26	29.43 $\pm$ 8.04	31.09 $\pm$ 7.67
		NBP	22.73 $\pm$ 4.55	27.72 $\pm$ 8.69	26.94 $\pm$ 5.72
	Lower	HBP	26.93 $\pm$ 5.56	31.71 $\pm$ 6.29*	30.64 $\pm$ 9.00*
		NBP	28.39 $\pm$ 4.78	30.22 $\pm$ 6.36	32.84 $\pm$ 10.25

\* $p \leq 0.05$ , compared with Min 1; <sup>#</sup> $p \leq 0.05$ , compared with Min 5.

] Group values averaged (main effect for time); { group difference at specified time point.

Abbreviations: CRP = continuous relative phase; HBP = a history of low back pain; NBP = a group with no history of low back pain.

bout, suggesting at least some degree of guarding occurred within the HBP group as time progressed. These findings are consistent with Jones et al.,<sup>34</sup> who reported that individuals with HBP demonstrated increased back muscle activation patterns during postural responses to trunk perturbations. The motions utilized in our paradigm were more predictable and consistent, so the guarding may have taken place during the end of the bout as HBP individuals became more tired. One potential limitation of our study is that we did not utilize electromyography (EMG); future studies utilizing these techniques in combination with lifting mechanics would elucidate this matter.

The results of our study were coupling-dependent, which supports the concept posited by Hodges and Tucker<sup>35</sup> that the adaptations related to HBP are more complex and less uniform than initially posited. That our results were different between lifting and lowering phases supports the earlier work of Nelson et al.,<sup>36</sup> who reported kinematic differences in ROM lifting mechanics between lifting and lowering phases during a box lift which occurred in the sagittal plane only (symmetric). Nelson et al.<sup>36</sup> reported that lumbo-pelvic motion occurred more simultaneously during the lifting phase, and motions were more concurrent during the lowering phase of the cycle. While we would apply this interpretation of motions directly to our findings, in that more in-phase coordination corresponds to more simultaneous motion, and more anti-phase coordination to more concurrent motion, there were important differences between their study and the current study. In addition to the fact that our lifting paradigm was different from that of Nelson et al.<sup>36</sup> in that it was more asymmetric, involving motions in the sagittal and axial plane, Nelson et al.<sup>36</sup> required all participants to lift and lower without bending the knees, which likely exacerbated differences in their healthy cohort.

#### 4.4. Right and left side comparisons

While there were different patterns of statistical significance between the right and left sides, generally the values for CRP $\theta$  and CRPvar were similar for each coupling, and followed similar trends over time. There was a group-related adaptation during lifting to the right side, where CRPvar for HBP was significantly greater than for NBP. No such difference existed for the left side. We surmise that this larger difference in CRPvar may have occurred due to the right-hand side being the dominant side in our participant pool. Since the dominant side is associated with finer motor control than the non-dominant side, we posit that side-related preference may have manifested in CRPvar during a bilateral task. In this case, lower CRPvar may signify increased control during the task. Future studies should explore this possibility further to confirm this observation.

#### 4.5. Limitations

There were a number of limitations associated with our study. We recognize that limiting lifting frequency could have influenced coordination. Future studies could mitigate this effect by designating a specific number of lifts (for example, 125 lift/lower cycles), counting lifts and collecting data during

pre-designated lift intervals during the bout. We also acknowledge that we might have seen greater side–side differences between groups if we had documented which side had been more affected by LBP in our HBP group (generally speaking, idiopathic LBP does not tend to be symmetric). Despite these potential limitations, differences in lifting mechanics were observed using the current paradigm.

## 5. Conclusion

This study has documented changes in coordination profiles during manual materials handling paradigm over an extended bout compared to other research. Data from the current study offer a preliminary view of coordination profiles during 10 min of lifting an 11-kg box with handles at 12 lift/lower cycles per minute between individuals with and without HBP. Results indicated that coordination (CRP $\theta$ ) and coordination variability (CRPvar) were sensitive enough measures to detect differences between these two highly functional groups. More in-phase coordination in the HBP group may represent a coordination pattern analogous to “guarded gait” which has been observed in other studies. While ES suggested limited practical differences in the single-plane couplings, the sagittal axial couplings in general had larger practical differences, which may lend insight as to why these individuals are at increased risk for re-injury. Our results also demonstrated the benefit of using both single-plane and multi-plane analysis for characterizing coordination profiles during an asymmetric (i.e., out-of-plane) lift.

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## Authors' contributions

JFS and TCR conceived the study, and participated in its design and coordination; SGS executed the study and reduction of video data; JFS, SGS, and TP processed the video data and conducted coordination calculations; JFS performed the statistical analysis and drafted the initial manuscript. All authors have read, contributed to, and approved the final version of the manuscript, and agree with the order of presentation of the authors.

## Competing interests

None of the authors declare competing financial interests.

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