Trunk, lumbar and pelvic segment rotations and coordination patterns in runners with and without a history of low back pain

By

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ABSTRACT

Low back pain (LBP) is one of the most common complaints amongst adults in the United States. It accounts for 2-3% of adult hospital visits[1]. An estimated 70- 80% of U.S citizens will experience at least one instance of low back pain. over the course of their lives [2]. 90-95% of people recover from a first a first instance. However, it is estimated that 60-75% of these will relapse. This study examines the etiology of this reoccurrence using two analysis methods: 1) segment rotations along with their ensemble average and rotational amplitude calculations and 2) Continuous Relative Phasing (CRP) and continuous relative phase variability (CRPvar). Previous studies have debated on the sensitivity of segment rotations to differentiate a population whose back pain has resolved from healthy controls and those who are currently experiencing back pain. Therefore, it is important to test the sensitivity of segment rotations. Given the similarity in our cohort of resolved and healthy controls, we hypothesized that segment rotations would be incapable of differentiating resolved LBP and healthy controls. This hypothesis was supported by the lack of significant group differences in rotational amplitudes, and the similarity of the ensemble average graphs.

More recent studies have proposed relative phasing methods that characterize the coordination segments as a method that may be more sensitive. Of these methods, CRP and its variability are one. The second hypothesis of this study was that CRP and CRPvar would find significant group differences in coordination patterns, coupled with decreased CRPvar. This hypothesis was largely supported by significant out-of-phase coordination patterns in lumbar-trunk and pelvic-lumbar flexion extension in our LBP group, and more in-phase coordination in pelvic-lumbar lateral bend. Decreases in CRPvar of pelvic-lumbar axial rotation and increases in pelvic-trunk flexion extension and lumbar-trunk axial rotation were also observed. These latter results were unexpected.

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List of Abbreviations

Low back pain	LBP
Resolved back pain	RES
Healthy controls	HC
Acute low back pain	aLBP
Chronic low back pain	cLBP
Non-specific low back pain	NSLBP
Chronic non-specific low back pain	cNSLBP
Gait Cycle	GC
Single Limb Support	SLS
Rotational Amplitudes	RA
Relative Fourier Phase	RFP
Continuous Relative Phase	CRP
Continuous Relative Phase Variability	CRPvar
Initial Contact	IC
Toe Off	TO
Terminal Swing	TS
Swing Phase	SP
7^{th} Cervical Vertebrae	C7
10^{th} Thoracic Vertebrae	T10
1^{st} Sacral Vertebrae	S1
Left Posterior Superior Iliac Spine	LPSIS
Left Anterior Superior Iliac Spine	LASIS
Right Posterior Superior Iliac Spine	RPSIS
Right Anterior Superior Iliac Spine	RASIS
Activities of Daily Life	ADL

Chapter 1 : Introduction

1.1: Motivation

Low back pain (LBP) is one of the most common complaints amongst adults in the United States and accounts for 2-3% of adult hospital visits[1]. An estimated 70- 80% of U.S citizens will experience at least one instance of LBP over the course of their lives [2]. 90-95% of people recover from a first-time bout in 4-8 weeks and return to normal activity levels. However, with a recurrence rate of 60%, the best predictor of future LBP remains a previous incident LBP[3]. This is why LBP generates approximately $90 billion in medical costs and results in a $20 billion-dollar loss in productivity annually[1]. The likelihood of developing LBP increases with age with a normal peak occurring between the ages of 55 and 64 years. However, it causes the greatest decrement in activity levels in those younger than 45 [2,4–6]. The most common type of LBP occurs without a pathophysiological reason [7]. It is approximated that 7-10% of those who suffer from NSLBP will go on to experience decrements in activity and productivity levels [8].

Due to the dynamic movement of the back, and the lumbar region's involvement in a variety of movements, it is no surprise that LBP affects activities of daily life (ADL). These include lifting, walking, and running. Various gait parameters such as cadence, stride length, rotations of and coordination patterns between the trunk and pelvis, and the effects of LBP on these parameters have been well studied in walking[9]. To the author's knowledge, however, there are few studies that characterize coordination patterns during running, and the effects of a history of LBP on these coordination patterns.

1.2: The Gait Cycle

` Description of gait cycle and phases has been ongoing since the mid-twentieth century. A gait cycle is defined as the point in which one-foot contacts the ground to the point when that same foot contacts the ground for a second time. Thus, a walking, running or sprint cycle is from

a first initial contact (IC) to a second IC of the same foot with of toe off (TO) in between [10]. There are various ways to characterize the motions that occurs between first and second IC in walking. For the purposes of this study, important points are stance and swing phases whose end points are marked by TO and IC respectively (Figure 1.1).

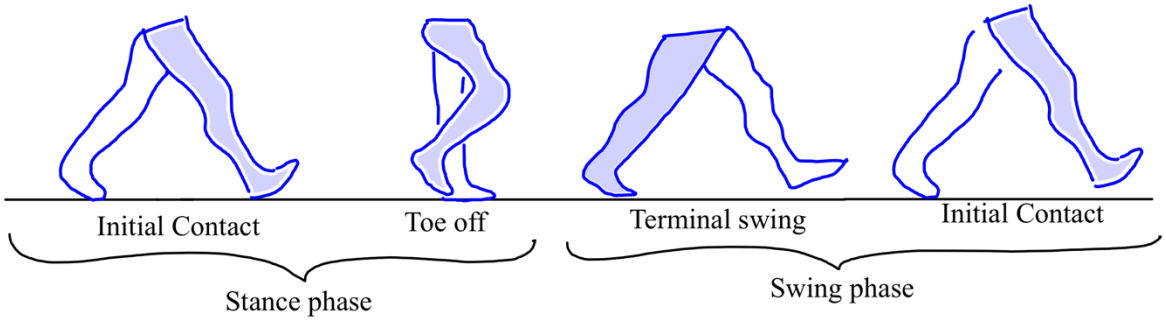


Figure 1.1: Gait Cycle
Depicts major phases of the gait cycle. For this study, the gait cycle is defined as from initial contact (IC) to IC of the same foot. Toe off (TO) marks the end of the stance phase (StP) of the gait cycle and the beginning of the swing phase (SwP). SwP ends at IC.

Walking, Running and Sprinting

Due to an extended stance phase of greater than 50% of the gait cycle, there is a period in walking before TO and at IC of the opposing leg where both feet are on the ground. This is known as the double-support phase of gait. In running and sprinting, there is no double-support phase but rather an aerial phase where neither foot has contact with the ground. In running IC occurs mostly at the heel, with 20% of runners being midfoot strikers while IC in sprinting occurs exclusively in the forefoot. Novacheck found that toe off occurs at 39% of the gait cycle in runners and 36% for sprinters with world class sprinters toeing off as early as 22% of the gait cycle [10,11].

1.3: Kinematic Parameters

Traditional gait cycle parameters focus on the effects of LBP status on changes in cadence, step length, velocity, and percentage of the gait cycle spent in stance for both left and right sides and left and right single leg support. Studies in which subjects were given the option

to choose their comfortable walking speed have shown that those with LBP choose walking speeds that are slower than their pain free counterparts [12]. For instance, Taylor and Evans evaluated 8 subjects with acute LBP (aLBP) within seven days of pain onset, and again six weeks after pain had resolved [13]. They compared these subjects to eight age, gender and height matched healthy controls. Their goal was to compare the traditional gait biomechanics parameters of aLBP subjects at onset and resolution. They first measured the subjects' comfortable walking speed and then increased it by 40% for the "fast walking" trials thus controlling walking speed. Results from Taylor and Evans are consistent with those of Khodadeh which found that subjects with aLBP increase walking speed by increasing cadence rather than by increasing step length [14,15].

Brazilay collected data on walking velocity, cadence, left and right step length, stance phase time and single limb support phase time on 60 subjects with chronic, cnsLBP as well as 24 healthy controls (HC)[9]. Subjects underwent a home-based biomechanical treatment for their LBP and were tested 3 and 6 months after treatment. In addition to a reduction in pain, Barzilay and colleagues reported increases in gait velocity and single limb support phases along with decreases in stance phase (Table 1.1). This data suggests two things. Firstly, a hallmark of LBP may be asymmetrical gait patterns especially at higher walking speeds. Secondly, that abnormal gait patterns are adopted by those with LBP in order to avoid extensive hip and spine ranges of motion. This reduces the amount of force acting on the body and shields lumbar muscles especially at higher walking speeds. This shielding mechanism can cause more harm than good. Just as foot, ankle and knee injuries can result in abnormal lower extremity musculoskeletal pathologies leading to LBP, it seems that the abnormal gait patterns that are a result of LBP can affect the lower limbs causing pain to radiate down into the lower extremities.

	cnsLBP Baseline	3 months after Tx	6 months after Tx	HC	P base 3 months	P base 6 months
Velocity (cm/s	102.6 ± 17.3	111.5 ± 17.3	113.5 ± 17.3	117.1 ± 16.9	< 0.001	< 0.001
L SLS (% GC)	38.7 ± 2.0	39.3 ± 1.9	39.5 ± 2.0	39.7 ± 1.5	<0.001	< 0.001
R SLS (%GC)	39.0 ± 1.8	39.4 ± 1.8	39.8 ± 1.7	40.0 ± 1.2	0.009	< 0.001
L stance (% GC)	61.1 ± 1.9	60.6 ± 2.1	60.3 ± 1.8	60.1 ± 1.3	0.010	< 0.001
R stance (% GC)	61.3 ± 2.1	60.8 ± 1.9	60.6 ± 2.0	60.4 ± 1.4	< 0.001	< 0.001

Table 1.1: Summarized results taken from Barzilay show that nsLBP subjects spend walk slower than HC [9]. They also spend more time in the stance phase of the gait cycle. Most interestingly, subjects with nsLBP also spend more time in the SLS phase of the gait cycle indicating an asymmetrical gait pattern. Differences in all these variables disappear after 3 months of a home-based physical therapy regimen. Suggesting that these biomechanical parameters show a non-causal correlation with back pain.

1.4: Segment Rotations & Coordination Patterns

Methods for analyzing gait and running parameter include the use of force plates and wired or wireless markers placed on bony segments. Force plates allow for the measurement of ground reaction forces in the vertical (vGRF), medial-lateral (ml-GRF) and anterior-posterior (ap-GRF) direction. While wireless markers follow the motion of individual sensors which are used in the calculation of segment rotations and coordination patterns. In these methods the spine is often divided into one or two sections designated the trunk/torso and lumbar. Segment designation is relative, however common sensor placements are between the seventh cervical (C7) and first lumbar (L1) vertebrae for torso/trunk movement and the tenth thoracic (T10) and first sacral (S1) for the lumbar region. Movement of the pelvis is tracked by sensors placed on S1, left and right posterior-superior iliac spine (LPSIS and RPSIS) and left and right anterior-superior iliac spine (LASIS and RASIS). Rotations of the spine and pelvis in two-dimensions are usually described as rotations within body planes (i.e.: sagittal, frontal and transverse). However, for this study we will commonly be using flexion/extension (sagittal plane), lateral bend (frontal plane) and axial rotation (transverse plane) to describe spine segment and pelvis rotations.

Müller analyzed rotations of the trunk and lower limb to determine the effects of LBP on running and walking on even and uneven surfaces[16]. He recruited 11 subjects with chronic non-

specific LPB (cnsLBP) (m = 5, f = 6, age = 38y ± 13.9) and 11 HC (m = 5, f= 6, age = 38.5 ± 12.1). Subjects were instructed to first walk, and then run on a 17m walkway. Subjects were allowed to select their own walking and running paces, but had to ensure that they contacted the first force plate with their right foot and the second with their left. To create the uneven surfaces, the fist force plate height was adjusted, while the second remained flush with the ground. Like Khodadadeh and others, Müller reported a decrease in preferred walking speeds. He also saw decreased pelvic rotations and trunk rotations on even and uneven surfaces. Decreases in pelvic and trunk rotations were observed in both walking and running. Thorax rotations remained largely the same between groups during running and walking on both even and uneven surfaces (

	Level Contacts							
			Walking			Running		
		Contact	Controls	cnsLBP	P	Controls	cLBP	P
transverse plane rotations	Pelvic_rot (deg)	1	32.4 (4.4)	26.9 (5.5)	0.000*	14.2 (4.0)	10.5 (3.4)	0.000*
		2	30.7 (4.3)	25.1 (5.3)	0.000*	14.6 (3.9)	12.4 (3.1)	0.002*
	Trunk_rot (deg)	1	36.7 (7.9)	32.8 (7.0)	0.306	34.5 (8.8)	27.1 (5.5)	0.000*
		2	35.4 (8.8	30.8 (5.7)	0.239	34.6 (8.3)	27.2 (5.7)	0.000*
	Uneven Contacts							
			Walking			Running		
		Contact	Controls	cnsLBP	P	Controls	cLBP	P
	Pelvic (deg)	1	33.6 (4.8)	28.0 (6.2)	0.000*	15.2 (3.8)	11.9 (3.7)	0.000*
		2	32.3 (4.9)	27.2 (5.5)	0.004*	15.6 (4.3)	13.1 (3.6)	0.008*
	Trunk_rot (deg)	1	36.4 (8.4)	33.5 (5.0)	0.794	35.6 (7.8)	28.8 (5.3)	0.000*
		2	36.7 (7.4)	32.3 (5.0)	0.188	35.9 (7.6)	27.6 (4.7)	0.000*

Table 1.2).

Table 1.2: Truncated results from Müller study [16]
Mean (standard deviation) of RA for 11 subjects with cnsLBP and 11 matched HCs walking and running on level and uneven force plate contacts. 1: indicates first force plate contact which was elevated 10cm for uneven trials, 2: indicates second force plate contact. Results are of rotational amplitudes for each segment in the transverse plane. Results show decreased pelvic and trunk rotations on both even and uneven surfaces in patient population during walking and running. While thorax rotations remained largely the same between groups in walking and running.

Like Müller, Vogt analyzed the segment rotations of 34 subjects with chronic LBP (cLBP) (m: n = 21, age = 36y± 1.7; f: n = 13, age = 32.1y ± 3.4) and 22 HCs (m: n = 16, age =

34.8y ± 5.2; f= n 6, age = 29.4y ± 1.3)[17]. Subjects with cLBP had been symptomatic for at least half the days in the past twelve months, and pain had not radiated passed the gluteal fold. Other exclusion criteria included spinal or lower extremity surgery, and joint abnormalities. All subjects walked at a consistent speed of 4.5 kph (1.25 m/s). Vogt reported no differences in absolute angular movements ($p > 0.5$). However, they did find significant differences in coefficients of variation (average stride-to-stride variability) in upper spine flexion/extension (HC: 9.69 ± 1.03, cLBP: 26.93 ± 5.21; $p < 0.001$), lateral bend (HC: 9.41 ± 1.46; cLBP: 14.87 ± 4.12; $p < 0.001$). This increase in variability is indicative of increased coupling between segments [18].

When comparing the Vogt and Müller papers we see one of the biggest drawbacks with segment rotations: they are inconsistent. Müller reported significant decreases in rotational amplitudes while Vogt did not report similar findings [16,17]. Therefore, we can conclude that segment rotations alone are not enough to properly differentiate patient and HC populations. Vogt's study delves deeper by pairing segment rations with coupling and variability. This helps to parse out the results from segment rotations alone. This is one of the reasons that in recent years there has been a shift from segment rotations to coupling and coordination. These methodologies are advantageous because they confirm findings from segment rotation studies in some cases and show promise for gaining insight as to why LBP is a persistent problem.

Lamoth's 2006 study comparing trunk coordination and muscle activation in cnsLBP used rotational amplitudes (RA) and Relative Fourier Phase (RFP) (n = 22; m = 9, f=13, age = 38y, range = 21 – 52) and HC (n = 17, m 9, f = 8, age 31y. range = 20-46)[18]. Subjects with cnsLBP had no disability due to their back pain, and their back pain had an average duration of 1.2 years, with a range of 3.5 months to 3 years. Subjects had a prescribed walking velocity that ranged from 1.4kph to 7.0 kph in 0.8kph increments. RA were defined as the absolute difference between maximum and minimum rotations. In RFP 0° indicates a relatively in-phase

coordination pattern, while 180° indicates a completely anti-phase or out-of-phase coordination pattern [18]. Like Vogt, Lamoth found no differences in RA between groups [18]. While Vogt found higher variability in all planes, Lamoth reported this finding only in the thoracic frontal plane rotations at velocities greater than 3.8 kph. While in the transverse plane she reported a higher degree of coupling between the thorax and pelvis and lumbar and pelvis [18]. Results from RFP analysis found that transverse plane thorax-pelvis and lumbar-pelvic relative phase was smaller for patient group than it was for HC. Thorax-pelvis coordination patterns in the transverse plane were characterized as in-phase but moved towards an out-of-phase patterning as walking velocity increased. This phenomenon was present in the patient population but less pronounced. While were no differences in relative phasing (RP) in the frontal plane, RP standard deviations were greater in the patient population than in HCs. This keeps with the highly variable/tight coupling observations seen in Vogt's study [18].

The pelvis-trunk coordination patterns in the transverse plane are the most commonly studied in LBP. This because the pelvis and trunk "book-end" the low back, lending to the belief that coordination patterns between these segments may lend insight to the effects of this pathology [17]. Results from Vogt's study revealed no significant difference in rotational amplitudes of trunk and pelvis rotations between groups. Vogt attributed this lack of significant difference to the velocity of the treadmill. However, there are many studies that have identified subjects' comfortable walking speed and use a certain percentage above and below as "fast" walking trials and "slow" walking trials respectively or a wide variety of velocities that have reported similar results to Vogt's [6,15,17,19–21]. Studies mentioned above and others with notable walking and running parameter analysis methodologies are outlined in Table 1.3.

1.5: From Walking to Running

During walking and running, the pelvis rotates about the frontal and transverse planes in notable ways. In walking the pelvis elevates in the frontal plane during the SwP in order to clear

the swing leg (Figure 1.1). Due to the lack of a double support phase in running, this elevation of the pelvis is decreased relative to walking. The pelvis rotates around the stance leg in the transverse plane during swing phase to increase stride length. The pelvis frontal and transverse rotations relative to the trunk and lumbar are of interest due to the pelvis' tilt in the frontal plane, and axial rotation about the transverse plane during swing phase respectively.

Bruijn believed that the axial rotation of the pelvis was used as a method for conserving angular momentum as walking velocity increased [22]. He tested nine healthy male subjects (age = 22.6y ± 3.2) walking on a treadmill at speeds starting at 2.0 kph (0.55 m/s) and increased to 5.2 kph (1.44 m/s) in increments of 0.4 kph (0.11 m/s). After completing RFP to analyze the coordination patterns of the thorax, pelvis and legs he concluded that the contribution of the pelvis and thorax to overall angular momentum is quite low. In fact, the legs and arms contribute close to 90% of the angular momentum generated during walking and increases as speed increases. This is due in large part to the maintenance of out-of-phase coordination patterns between the thorax and legs at all speeds and the transition from an in-phase pelvic-leg pattern to an out of phase coordination pattern at higher walking velocities [22].

Bruijn's conclusions seem to be supported by Seay who reported increased sagittal, but decreased transverse and frontal plane pelvic-trunk rotations in LBP and resolved (RES) groups during walking [23]. Seay collected data on three groups of 14 subjects: a control group (CTR: n = 14, age = 29.9y ± 8.5) who had never experienced LBP, a RES group (RES; n = 15, age 32.6y ± 9.4) who had recovered from an instance LBP lasting less than 6 weeks but had been running pain free for at least 6 months, and subjects with LBP (n = 14, age = 35.7y ± 10.9) who had been affected for at least 4 months. Seay tested both treadmill walking and running, and divided his walking trials into three speeds of 0.8 m/s, 1.3 m/s and 1.8 m/s and his running trials were 2.3 m/s, 3.3 m/s and 3.8 m/s. Seay's results are in line with others such as Lamoth who saw

decreased coordination in all planes between groups during walking. Therefore, it is possible that this is a strategy employed by this particular population [22,24].

Selles recruited six LBP (m = 2, f=4, avg age = 30y, age range = 16-45y) and six HC (m = 2, f = 4, avg age = 30y, range 16-45) for their study [25]. The patient population for this study was quite unique: they had experienced back pain for at least a year and had not been pain free for at least a year. All subjects showed various structural disorders that Selles described as "mild". These included some leg length discrepancies that lead to mild scoliosis, pain at sacro-iliacal level, and spondylolysis. Overall, they decided that these structural disorders could not explain their LBP and therefore they were characterized as having nsLBP. A comfortable walking velocity was calculated for all subjects and then each subject walked at velocities starting at 0.17 to 1.5 m/s in increments of 0.22 m/s. Like many previous studies, Selles found a significant decrease in comfortable walking speed in NSLBP subjects (Averages – HC: 0.81 m/s; NSLBP: 1.06 m/s) [16,18,24,26]. They also found that as speed increased, trunk-pelvic coordination patterns transitioned from a more in-phase coordination pattern to a more out of phase coordination pattern (Figure 1.2). Four patients never made the transition from in-phase to out-of-phase coordination patterns, and three of those were unable to walk at the highest velocity. Two of the four subjects unable to make the transition from in-phase to out-of-phase coordination patterns had leg length discrepancies (subjects 3 and 4, both female). The other two were reported to have osteogenesis imperfecta and hypermobility of the lumbar spine (subject 5, female), and spondylolysis at L5-S1 and pain in both legs (subject 6, male). Selles and colleagues believe this may account for the lower comfortable walking speed in the patients when compared to controls. They concluded that subjects with nsLBP were reducing relative rotations between segments in order to reduce LBP [21].

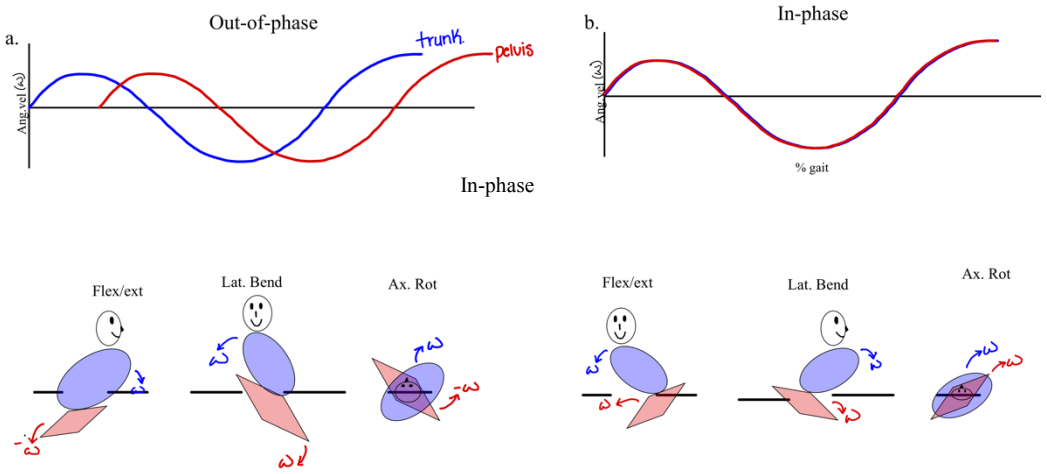


Figure 1.2a-b: Example angular velocity (ω) and corresponding trunk and pelvis rotations. a) Depicts an out of phase pattern of trunk (blue) and pelvic (red) coordination. Images below show what these coordination patterns would look like in flexion/extension (sagittal plane), lateral bend (frontal plane) and axial rotation (transverse plane). B) Depicts the same for in-phase coordination patterns

Details about CRP reveal pros and cons to using it. CRP describes how two predominantly sinusoidal oscillators move relative to one another by taking the difference of the position-velocity phase planes [27]. This allows one to track what is occurring throughout an entire stride unlike discrete measures and gives an overall picture of the relationship between two segments. However, the methods for calculating the position-velocity phase planes reveals a major drawback. Patterns of trunk, lumbar and pelvic oscillation are not perfect sinusoidal oscillators. This sinusoidal oscillator assumption significantly alters the shape of the graphs as by Hamill and Haddad, possibly removing information of interest [6,28].

Even with these drawbacks, CRP still seems to give good information that allows for the differentiation of diseased, previously diseased and now and healthy populations in both walking and running [6,19,23,29]. Examples of these studies in running are Seay and Li. Li collected data on 20 HC (m = 7, f = 13, age = 22.4y ± 3). Subjects were relatively active, exercising on average 6 hours per week. The upper thorax was defined as being between C7 and T12. Li found no linear pattern of change in trunk-pelvic RFP in the transverse plane as running velocity increased [29].

This stands in contrast to running where we see tendencies transitions from more in-phase to more out-of-phase coordination patterns as walking velocity increases[15,25,30]. Meanwhile, Seay reported decreased transverse plane rotations in both LBP and RES group when compared to HCs (HC vs LBP: $p = 0.021$; HC vs RES: $p = 0.025$; RES vs LBP: $p = 0.996$) [6]. Seay's walking trials found significant differences between groups in frontal plane motions in walking (HC vs LBP: $p = 0.029$; HC vs RES: $p = 0.851$; RES v LBP: $p = 0.064$) but no difference during running (all: $p > 0.05$) [6]. However, there were clinically significant effect sizes when comparing HCs to RES group (ES = 0.55). These results align with expectations. During walking pelvic tilt (frontal plane rotation) is increased to clear the swing limb. This strategy disappears in running due to the presence of a double float phase that replaces the double stance phase in walking. His results overall support the previous findings of an in-phase to out-of-phase transition in coordination pattern as walking speed increases [18,21,24]. While Li's suggest that there is no such transition during running in the transverse plane. Studies by Li and Seay show the dangers of extrapolating walking trials to running. Due to fundamental differences between running and walking, assuming that the same patterns that appeared in walking will also occur in running is inadvisable.

Seay also used CRP variability (CRPvar) to compare HC, LBP and RES groups for both running and walking. They found that subjects with LBP had significantly less variability in the transverse plane during running (HC vs LBP: $p = 0.022$, others: $p < 0.05$). However, clinically significant effect sizes were only found between HC and LBP groups (ES = 1.11), and HC and RES groups (ES = 0.68). These variability results suggest that the RES group represents a transition group between HC and LBP [6].

More in-phase coordination patterns seen in affected populations have become even more apparent important to characterize as research has begun to conclude that a healthy system needs a certain amount of variability to allow for proper function. Too much rigidity can lead to the

inability to adjust to perturbations while too much variability can place forces and moments on structures not meant to withstand them. Therefore, some researchers have come to understand decreases or increases in variability as indications of underlying pathologies [2,31].

The resolved population is of particular interest and important to study because the best predictor of future LBP is still a past incident of LBP. Seay found that the RES group were a transition group between LBP and HC [6]. For instance, like the LBP group the RES group displayed latent transitions from in-phase to out-of-phase trunk-pelvic coordination. Taylor also found increases in pelvic axial rotation amplitude when looking at his subjects after pain had resolved [13]. This suggests that splinting methods that were used by those with LBP still exist to some extent in the RES group. This compensation method may explain why the RES group is more likely to relapse than HCs.

1.6: Implications for Runners

Results from studies comparing walking patterns in those with LBP and the few running trials have major implications for studies whose aim it is to compare healthy, resolved and LBP in runners. Since running and walking are very different locomotive patterns we cannot extrapolate what was seen in walking studies to runners [32]. While the elimination of the double-support phase during walking reduces lateral bend rotations (frontal plane), increased axial rotations (transverse plane) in running indicates that there are other areas and other rotational planes in which LBP may have a significant impact [23]. The shifting of these rotations to other planes highlights the importance of looking at rotations in all planes, not just those in which we believe the greatest rotations may exist [13,23]. To the author's knowledge only Taylor's study evaluates the effects of a history of LBP on running, while Seay's does the same in running. Results from Seay's studies suggest that this population represents a transition group, showcasing the far-reaching effects of LBP even after symptoms have resolved [33]. There is evidence to suggest that some forms of LBP do not show changes in traditional biomechanical

parameters. Huang and Bruijan collected data on subjects' ability to adjust step length, stride frequency, trunk and pelvic rotational amplitudes and RFP in 12 healthy and 12 LBP subjects between the ages of 20 and 45 years with lumbar disc herniation confirmed by CT scan [34]. Their LBP could not have pain that radiated beyond the knee. Subjects were asked to walk on a treadmill at 1.0, 2.5, 4.0 and 5.5 km/h (0.278, 0.694, 1.111, 1.528 m/s) with normal steps, small steps and large steps. All subjects were able to walk in all conditions and were able to adjust step length as required. Huang and Bruijn did not show any significant differences between healthy and patient populations when looking at stride length and stride frequency. However, they did find significant differences in pelvis rotational amplitude and RFP which included group by speed interactions particularly of the thorax-lumbar ($p < 0.01$) and thorax-pelvis ($p < 0.01$). Huang and Bruijan's results also show the importance of including the lumbar region in analysis which were not done in studies by Taylor and Seay [2,6,13]. While the only parameter missing from this study is coordination pattern variability; this confirms that traditional biomechanical parameters may not be sensitive enough to differentiate between patient and control populations, but rotational amplitudes and coordination patterns may be [34].

1.6: Specific Aims

The purpose of this study is to characterize normal trunk, lumbar, and pelvic rotation patterns as well as coordination between these segments in runners with and without a history of low back pain in all three planes (sagittal, frontal and transverse). Three methods will be used to do this. Firstly, individual segment rotations along with their rotational amplitude counterparts will be analyzed to see if differences arise between these populations. We hypothesize that no statistically significant differences will be found between groups using rotational amplitudes. Secondly, coordination patterns between the trunk-lumbar, trunk-pelvis and lumbar-pelvis will be calculated using a modified continuous relative phase methodology. In-phase and out of phase coordination patterns between these populations will be characterized. For this study we

hypothesize that subjects with LBP will show different coordination patterns from HCs in all planes in all segments. Lastly, CRP variability (CRPvar) will also be calculated. We hypothesize that CRP and CRPvar will show the greatest difference between control and patient populations. Therefore, the specific aims are as follows:

- SA1: Characterize rotations in the sagittal, frontal and transverse planes of the trunk, lumbar and pelvis of runners with and without a history of LBP.
- SA2: Characterize trunk-lumbar, trunk-pelvic and lumbar-pelvic coordination patterns using continuous relative phase protocol in same population.
- SA3: Calculate the CRP variability between populations to see if any differences between those with a history of LBP and control subjects arise.

1.7: Summary

In order to understand how LBP affects biomechanical parameters during running, it is important to look at coordination patterns in the trunk, lumbar and pelvic regions. This study will build on previous studies that have looked at similar parameters in walking. The evaluation of running instead of walking and the addition of the lumbar region in this analysis will increase the body of knowledge that exists on LBP and characterize its effects further. Looking at a population whose back pain has resolved will lend insight to the long-term effects. This will move the field away from characterizing the effects of LBP (slower walking velocity, increased stance and SLS phases) to identifying risk factors that may lead to the development of LBP. This is especially pertinent when we keep in mind that previous have suggested that the resolved population represents a transition group between controls and LBP. Since the best predictor of a future incidence LBP is a previous one it suggests that patients adapt in ways that continue to affect their walking and possibly running strategies even when LBP has resolved.

Paper	Pop.	Run/Walk	Results, Conclusions & Implications
Barzilay (2015)	HC & cnSLBP	Walk	- Inc in step length, cadence, single limb support - Dec. stance phase - No difference after 6 months of treatment - Traditional gait parameters do not explain the high recurrence of LBP even after physical therapy
Crosbie (1997)	HCs	Walk	- Out-of-phase coordination in pelvic-thorax & lumbar-pelvis frontal plane - As walking velocity inc movement towards out-of-phase coordination
Wu (2014)	HC	Walk	- Dec thorax RP with artificially stiffened spine - Rigid thorax-pelvis patterning with braced spine - These patterns are similar to what we see in subjects with LBP, therefore dec may be due to splinting in LBP populations.
Huang (2011)	HCs & LBP	Walk	- Reduced thorax-pelvis accompanied by larger steps - Explains why those with LBP tend to inc walking v by increasing step length instead cadence
Lamoth (2002)	HC & nsLBP	Walk	- No significant difference between nsLBP and HC in ROM - As walking velocity inc pelvic-thorax rotations tend towards out-of-phase - nsLBP show a delayed transition
Lamoth (2006)	HC & cnsLBP	Walk	- With inc walking velocity movement towards out-of-phase pattern was less pronounced in cnsLBP subjects
Vogt (2001)	HC & cnsLBP	Walk	- Dec comfortable walking speed in cnSLBP - No group differences between groups in RA - Dec mean thoracic-pelvic RP in cnsLBP subjects - RA are not sensitive enough to differentiate cnsLBP subjects from HCs - Relative phasing may be
Selles (2001)	HC & cnsLBP	Walk	- No difference between groups in |angular movement| - Inc stride-to-stride variability in cnsLBP - Inc variability is indicative of different adaptations in the cnsLBP group
Taylor (2003)	HC & nsLBP	Walk	- 4 cnsLBP subjects unable to transition from in-phase to out-of-phase coordination patterns in thorax-pelvis - These 4 subjects showed an in increase in thorax-pelvis stability
Ebrahimi (2017)	HC, aLBP & RES	Walk	- aLBP subjects increased pelvic list and lumbar lateral flexion in order to walk faster - Keeps with previous studies that note subjects with LBP inc walking velocity by increasing cadence rather than step length
Müller (2015)	HC & cLBP	Walk	- Reported dec in CRP variability in cLBP subjects - Dec CRP variability indicates a more guarded gait pattern in LBP
Schache (2002)	HC & cLBP	Walk & run	- cLBP subjects showed dec pelvis but unchanged thorax rotations during walking and running
Li (2018)	HC	Walk	- No linear changes in phase patterns as running velocity increases
Seay (2011)	HC, LBP & RES	Walk & run	- Dec variability in axial rotation during running in LBP subjects

Table 1.3: Summary of literature review of studies which evaluate the effects of LBP. All studies evaluated the effects of LBP on walking. This was on both traditional gait parameters (Barzilay). One study (Crosbie) characterized HC motion using CRP. One study (Wu) used RP to characterize the effects of a brace on thorax-pelvis motion. Of the 14 studies, two evaluated the effects of walking and running, and three evaluated how resolved groups faired when compared to HCs and LBP subjects. None of the studies involving a resolved group included the lumbar region in their analyses.

Chapter 2 : Comparison of trunk, lumbar and pelvic, segment rotations and rotational amplitudes in runners with and without a history of low back pain

2.1: Introduction

Low back pain (LBP) is a common complaint among adults in the United States with 70-80% of the population experiencing at least one instance[1]. While 90% will recover in 2-8-weeks and return to normal activity levels it is estimated that 60-75% will relapse[35]. Among runners, LBP accounts for 3.4% of complaints while hip/pelvic pain accounts for 10.9%[3]. Due to the dynamic activity of the spine, LBP affects activities of daily life (ADL) which include but are not limited to: walking, running, and lifting. Various gait studies have evaluated the effects of LBP on traditional gait parameters such as stride length and cadence, as well as individual segment rotations and rotational amplitudes during walking and a few during running[9,16–18,36]. However, results from segment rotations and rotational amplitudes are often contradictory with some like Vogt reporting no differences in rotational amplitudes between healthy controls (HCs) and those with chronic non-specific low back pain (cnsLBP) during walking[17] . While Müller reported decreased pelvic and trunk rotations in a those with chronic LBP (cLBP) when compared to HCs also during walking[37].

The purpose of this study was to investigate *in vivo* the effect of a history of low back pain on segment rotations and rotational amplitudes of the trunk, lumbar, and pelvis segments during running in all planes. Segment rotations are those that characterize the individual motions of the spine in all three rotational directions (i.e.: lateral bend, flexion/extension and axial rotation), while rotational amplitudes are defined as the absolute value of the difference between maximum and minimum segment rotations. There are many analysis methods available for describing spinal motion during various activities, segment rotations and rotational amplitudes

were selected for two reasons. Firstly, there is some debate as to whether traditional kinematic methods are sensitive enough to differentiate control populations from those who have a pathological history. Secondly, results from RA analysis are varied and ultimately inconclusive. Using these methods will lend insight into their ability to detect differences between controls and patients with a history of LBP. This is important for two reasons. Firstly, maladaptive techniques may continue even after pain has subsided potentially increasing the probability that LBP will return [6,15,34]. Secondly, those with a history of LBP seem to represent as a transition group between those LBP is active and HCs. By looking at this resolved population, researchers may better be able to understand the maladaptive techniques that put back pain sufferers at a risk of relapse [23].

2.2: Methods

2.2.1: Participants

Twenty subjects were contacted for testing, two were excluded because of current LBP while one did not respond for testing. Therefore, 17 subjects were tested; 10 healthy controls (HC: 3 Male; 7 Female) and 7 subjects with a history of LBP (LBP: 3 Male; 4 Female). HC had an average age of 29 years old (± 4 years) while LBP subjects had an average age of 28 years (± 6 years). All subjects were physically healthy and ran an average of 20km a week. LBP subjects were defined as those who had been diagnosed or self-reported an incident of LBP in the past year, but none in the past 3 months. Subjects with spondylolisthesis no greater than degree one as reported by the subject were eligible. Upon contact the subjects' eligibility was determined by a health questionnaire as well as the Physical Activity and Readiness Questionnaire (PAR-Q). Any subjects that indicated they had current pain or responded "yes" to any question on PAR-Q were excluded. Additional exclusion criteria included a history of low back or lower extremity surgery, neurological impairment, physical therapy within the past three months to treat LBP, currently pregnant, or any structural back deformity such as scoliosis or spondylolisthesis of

degree greater than one. In accordance with university policy, all subjects consented to testing by signing a form that was approved by the University of Kansas Medical Center (KUMC) institutional review board (IRB). Demographic information as well as BMI are recorded in Table 2.1 and Table 2.2

Subject #.	Gender	Age (y)	Height (m)	Weight (kg)	BMI	Speed (kph)
1	M	32	1.70	72.64	25.08	8.9
2	F	22	1.62	52.21	19.76	11.1
3	M	33	1.77	88.53	28.00	15.1
4	F	29	1.70	49.94	17.24	11.7
5	F	24	1.77	59.02	18.67	9.2
6	M	32	1.88	77.18	21.85	10.6
7	M	28	1.77	69.46	21.97	12.1
Average		29	1.75	67.00	21.80	11.0
Median		29	1.78	69.46	21.85	11.0
Std		4	0.08	14.01	2.74	2

Table 2.1: Gender, age, height, weight and comfortable running velocity in kph for subjects with a history of LBP. These subjects had either been diagnosed or self-reported incidence of LBP in the past year, but had been pain free for the past 3 months and had not undergone physical therapy to treat it. Subjects with current back pain, history of low back or lower extremity surgery, were pregnant or had spondylolisthesis degree greater than one were excluded. Otherwise, these subjects were physically healthy and ran an at least 20 km/wk.

Subject #.	Gender	Age (y)	Height (m)	Weight (kg)	BMI	Speed (kph)
1	F	25	1.57	54.48	21.97	10.6
2	F	23	1.65	63.56	23.32	11.7
3	M	24	1.75	78.08	25.42	11.4
4	M	24	1.85	82.17	23.90	10.9
5	M	25	1.70	70.37	24.30	10.6
6	F	40	1.65	61.29	22.49	7.6
7	F	29	1.65	56.75	20.82	8.2
8	F	39	1.70	59.92	20.69	12.7
9	F	24	1.70	63.56	21.95	9.3
10	F	29	1.68	59.02	20.69	9.3
Average		28	1.69	64.92	22.50	10.0
Median		25	1.70	62.43	22.23	11
Std		6	0.07	8.68	1.56	2

Table 2.2: Gender, age, height, weight and comfortable running velocity in kph for HC subjects. These subjects self-reported no incident of LBP within the past three years. Like subjects with LBP, these subjects also ran at least 20 km/wk

2.2.2: Experimental Set-up

Hip internal and external rotation were measured using a large goniometer. Kinematic data was collected at 60Hz using reflective markers (Motion Analysis, Santa Rosa, CA, USA). Marker placement is shown in Figure 2.1 Subjects performed 10 range of motion tasks: flexion, extension, left and right lateral bend, left and right axial rotation, right lateral bend followed by right axial rotation, left lateral bend followed by left axial rotation, right lateral bend followed by left axial rotation, and left lateral bend followed by right axial rotation. Subjects then ran on a WOODWAY treadmill for a 2-5 minute warm up. After the warm up period, the speed of the treadmill was increased until the subjects indicated that it was close to their normal running pace. This speed was then recorded. Subjects then ran for an additional 3-5 minutes. At a randomly selected point during these 3-5 minutes, one minute of data was collected.

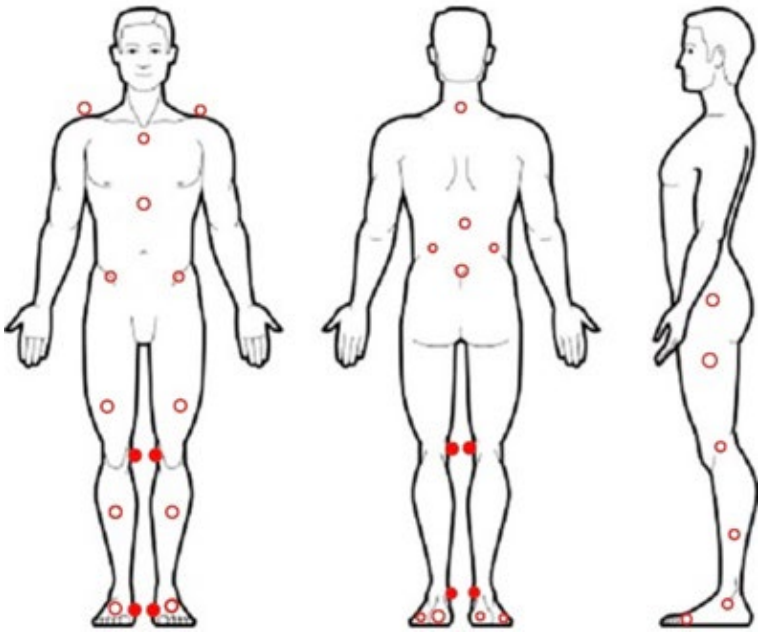


Figure 2.1: Reflective marker placement
Left and Right acromioclavicular joint (AC), clavicle, sternum (xyphoid process), LASIS, RASIS, mid-anterior thigh, upper-lateral thigh, medial and lateral knee, upper-anterior shin, lower-lateral shin, ankle, calcaneus, posterior aspect of 4th metatarsal, 2nd metatarsal, and medial malleolus. Shaded markers represent markers which were not present on some subjects.

2.4: Data Analysis

In order to track motion of the trunk, lumbar and pelvis segment, vectors were created and their rotation about a global axis was tracked. Figure 2.2 shows the vectors and the building of the trunk, lumbar and pelvis axes. For example, the trunk axes were built by first drawing vectors from C7 to T10 ($\vec{j}$), then from the Clav to T10 ($\vec{k}$). The cross product of these two vectors produced ($\vec{j} \times \vec{k} = \vec{l}$). The inverse of $\vec{l}$ corresponded rotations about the z-axis or axial rotation. Rotations about the y-axis or flexion/extension or were defined as the inverse of $\vec{l}$. Lastly, rotations about the x-axis or lateral bend, were defined as$\overrightarrow{-l} \times \vec{j}$. Axes for the lumbar and pelvic regions are shown in Figure 2.2 and were formed in the same manner as the trunk axes. Lumbar motion was tracked as the difference between the lumbar and pelvis axes. Rotations of the trunk and lumbar in the frontal plane (about the x-axis) are defined as lateral bend, and pelvic medial-lateral tilt. Rotations in the sagittal plane (about the y-axis) were defined as trunk flexion and extension, lumbar kyphosis and lordosis, and pelvic anterior-posterior tilt. Lastly, rotation in the transverse plane (about the z-axis) is defined as trunk, lumbar and pelvic axial rotation. In the figures for simplicity rotations are denoted as flexion/extension (flex/ext), lateral bend (lat bend) and axial rotation (ax rot) for all three segments. After motion of the trunk, lumbar and pelvis was tracked, a gait cycle was identified as minima to minima of the left heel data. Data was then reduced to 100 data points to represent a full gait cycle.

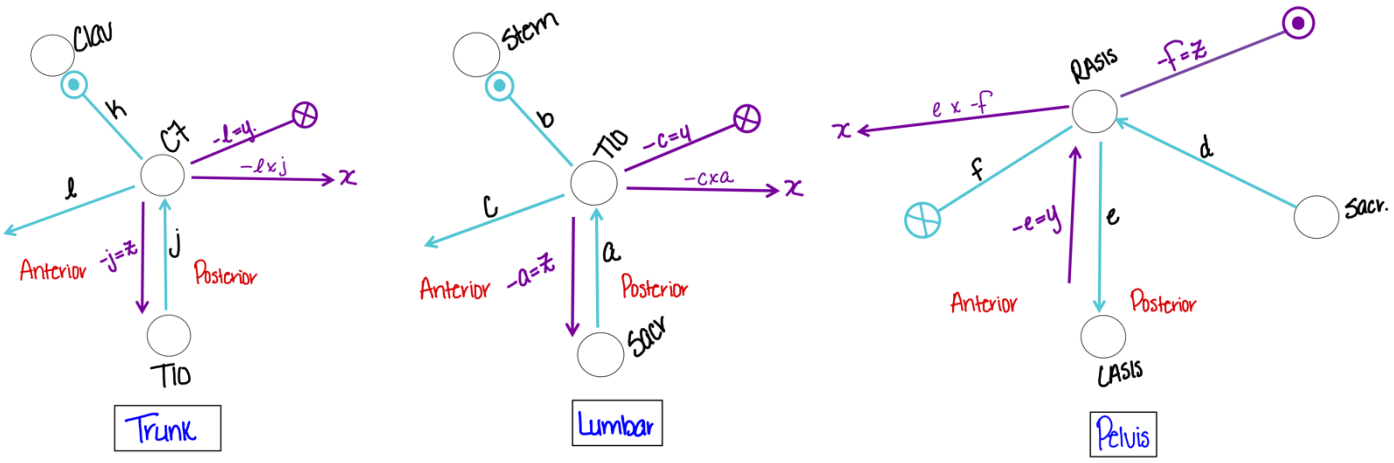


Figure 2.2: Trunk, lumbar and pelvic vectors and axes
Cerv, Cervical; C7, 7th Cervical vertebrae; T10, 10th Thoracic vertebrae; Stern, Sternum; Sacr, Sacrum; RASIS, right anterior superior iliac spine; LASIS, left anterior superior iliac spine. Sacral marker is calculated as the midpoint between the left posterior superior iliac spine and right posterior iliac spine. Trunk and lumbar and pelvic rotations are tracked as rotations about x (lateral bend; frontal plane), y (flexion/extension; sagittal plane) and z (axial rotation; transverse plane).

Ensemble averages were calculated by first calculating means and standard deviations for each segment rotation across groups. Shaded regions of the ensemble graphs were obtained by taking the average and either subtracting or adding the standard deviation. Rotational amplitudes were calculated as the absolute value difference of the maximum and minimum peaks. Calculation of rotational amplitudes were calculated.

These calculations were carried out for the two strides of the data collection. Group averages and standard deviations for trunk, lumbar and pelvis rotations in the frontal, sagittal and transverse planes were calculated and as well. Multi-variate ANOVA (MANOVA) was carried out with multiple responses as a factor of group (HC vs. LBP).

$$\text{rotational amplitudes} = |max_{rot} - min_{rot}| \quad \text{Equation 2.1}$$

2.4: Results

Ensemble averages at every time step were taken. Figure 2.3a-c represent lateral bend (frontal plane rotation, Figure 2.3a), flexion/extension (sagittal plane rotation, Figure 2.3b) and

axial rotation (transverse plane rotation, Figure 2.3c for HC. Figure 2.3a-c depicts the same for subjects with LBP. Ensemble averages were taken over two-strides which is why the x-axis maximum is 200%.

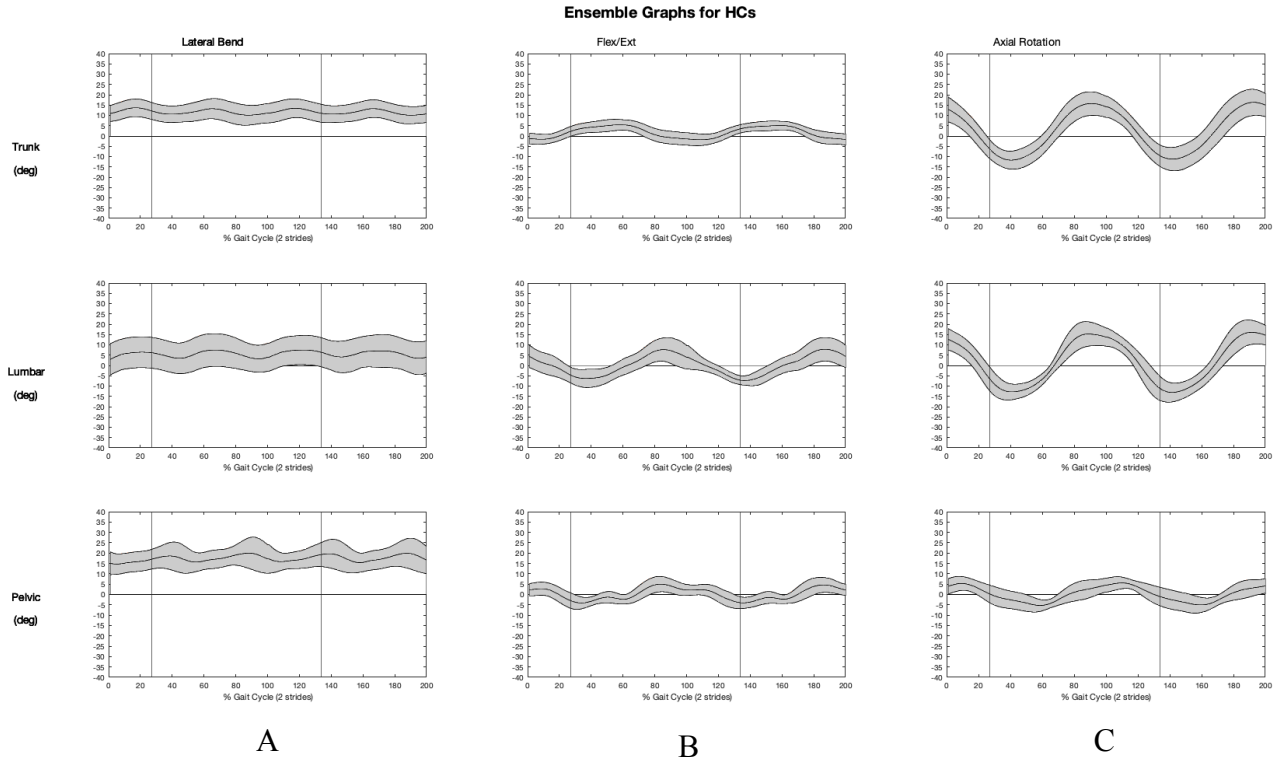
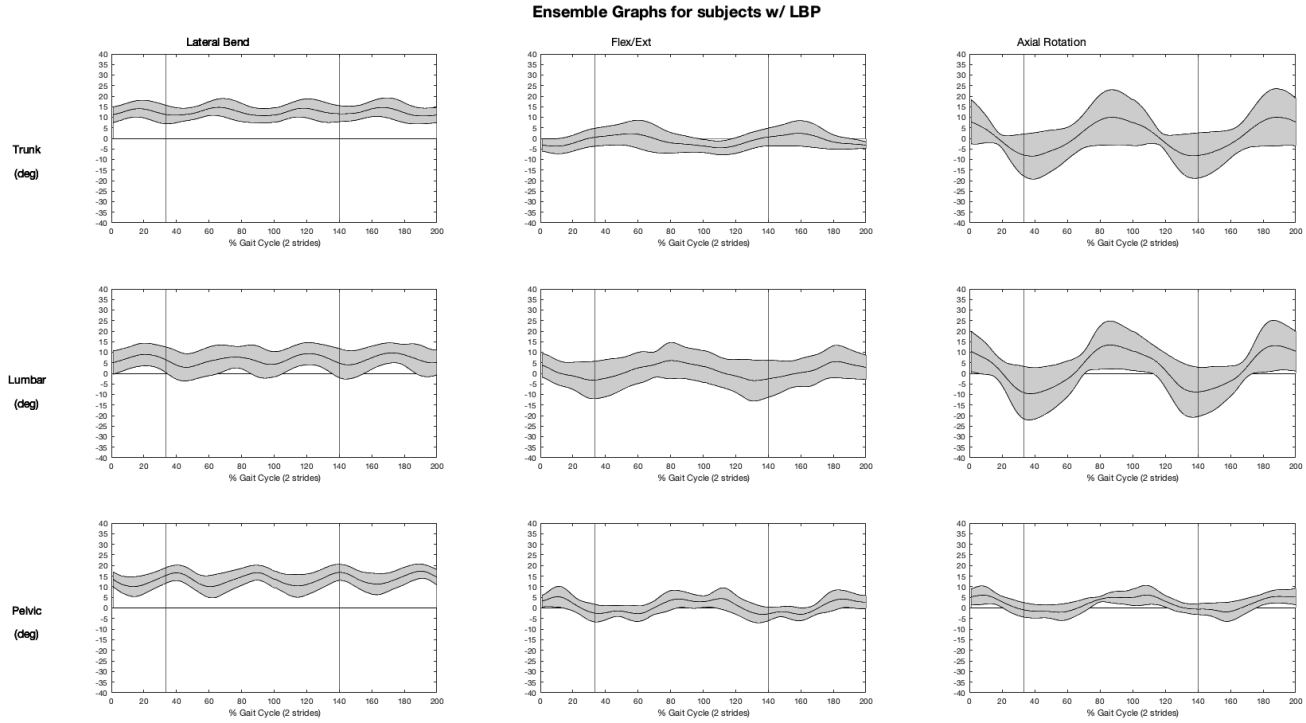


Figure 2.3a-c: Ensemble graphs for HCs for 2 gait cycles
Ensemble average graphs for gait cycles for a) lateral bend, b) flexion/extension and c) axial rotation of the trunk, lumbar and pelvis. Solid lines represent group average across two strides and shaded region one standard deviation Solid vertical line at approx. 80% shows average timing of left first and second heel strike. Differences in the shapes of the graphs, some patterning and amount of variation can be seen when comparing groups. This is particularly apparent when comparing lumbar lateral bend where HCs seem to have a wider variation than subjects with LBP. The LBP population seems to run on average more rotated to the right than HCs.



A B C

Figure 2.4a-c: Ensemble graphs for subjects with LBP for 2 gait cycles
Ensemble graphs for a single for two left heel strike cycles for a) lateral bend, b) flexion/extension and c) axial rotation of the trunk, lumbar and pelvis. Solid vertical lines indicate average timing of left first and second heel strike. Differences in the shapes of the graphs, some patterning and amount of variation can be seen when comparing groups. This is particularly apparent when comparing lumbar lateral bend where HCs seem to have a wider variation than subjects with LBP. The LBP population seems to run on average more to the right than HCs.

Ensemble averages and their corresponding graphs allow researchers to characterize more broadly the motion of specific groups they wish to compare. In the graphs depicted above, positive values indicate flexion, or lateral and axial rotation to the right. Visual inspection shows that the ranges for each group is approximately the same. Differences in the shapes of the graphs, some patterning and amount of variation can be seen when comparing groups. This is particularly apparent when comparing lumbar lateral bend where HCs seem to have a winder variation than subjects with LBP. The population with LBP seems to run on average more laterally bend to the right (+ve) than HCs.

Visual inspection of ensemble graphs showed little to no differences in range of motion. This was confirmed by rotational amplitude calculations. Results are shown in Table 2.3. Results of MANOVA and Cohen's effect sie calculations are shown in the same table. Pelvic lateral

bend and flexion/extension (frontal plane rotation) showed significant differences between groups ($p < 0.05$). However, Cohen's effect sizes showed only small effects ($ES < 0.5$).

RA Stats		Trunk			Lumbar			Pelvic		
		Lat Bend	Flex/Ext	Ax Rot	Lat Bend	Flex/Ext	Ax Rot	Lat Bend	Flex /Ext	Ax Rot
HC	Average	5.58	8.27	28.36	6.88	16.68	30.06	7.56	10.21	12.33
	Median	4.95	8.09	27.40	6.53	16.85	29.16	7.39	9.36	11.30
	Std	2.70	2.67	7.21	2.29	5.84	8.67	2.66	4.19	3.54
LBP	Average	5.80	8.73	27.22	7.55	14.55	29.87	8.88	11.91	11.40
	Median	5.90	7.56	26.27	7.14	16.01	23.16	8.80	11.54	10.54
	Std	1.70	3.47	9.91	2.62	5.39	11.96	2.44	3.41	3.59
	p-values	0.67	0.49	0.45	0.22	0.1	0.93	$p < 0.05$*	$p < 0.05$*	0.24
	Cohen's ES	0.07	0.13	0.11	0.23	0.30	0.02	0.42	0.35	0.21

Table 2.3. Results of MANOVA and Cohen's effect size calculations are shown in the same table. Pelvic lateral bend rotation showed a significant difference between groups ($p < 0.05$). However, Cohen's effect sizes showed no only small effects ($ES < 0.5$). Coincidentally, this effect size was for pelvic frontal plane rotations as well.

RA Stats		Trunk			Lumbar			Pelvic		
		Lat Bend	Flex/Ext	Ax Rot	Lat Bend	Flex/Ext	Ax Rot	Lat Bend	Flex /Ext	Ax Rot
HC	Average	5.58	8.27	28.36	6.88	16.68	30.06	7.56	10.21	12.33
	Median	4.95	8.09	27.40	6.53	16.85	29.16	7.39	9.36	11.30
	Std	2.70	2.67	7.21	2.29	5.84	8.67	2.66	4.19	3.54
LBP	Average	5.80	8.73	27.22	7.55	14.55	29.87	8.88	11.91	11.40
	Median	5.90	7.56	26.27	7.14	16.01	23.16	8.80	11.54	10.54
	Std	1.70	3.47	9.91	2.62	5.39	11.96	2.44	3.41	3.59
	p-values	0.67	0.49	0.45	0.22	0.1	0.93	$p < 0.05$*	$p < 0.05$*	0.24
	Cohen's ES	0.07	0.13	0.11	0.23	0.30	0.02	0.42	0.35	0.21

Table 2.3: MANOVA rotational amplitudes results of trunk, lumbar and pelvis for HCs and subjects with LBP in all planes. This table confirms no difference in range of motion between HCs and patient population. Pelvic lateral bend and flexion/extension showed significant differences between groups ($p < 0.05$), however effect sizes were still reported as small (< 0.2). Effect size were characterized as trivial (< 0.2), small (0.2 - 0.5), moderate (0.5 - 0.8) and large (> 0.8). None of the effect sizes calculated were greater than 0.5, therefore they were either small or trivial.

2.5: Discussion

First and foremost, there is a great deal of variation within a group. Some subjects have a higher degree of oscillation than others particularly when looking at lateral bend. This is reflected by the large shaded areas in the ensemble graphs. Whether this variation is due to high individual or group standard deviations is difficult to elucidate from these ensemble graphs.

Viewing all the subject data is helpful for seeing some differences that exist between groups. For instance, all HC subjects seem to follow a similar timing pattern in flexion/extension and axial rotation for all segments. This is not true for subjects with a history of LBP. Especially in lumbar and pelvic flexion/extension, and all segment axial rotations. This timing difference disappears when rotational are calculated. However, visual inspection of overall rotations shows that there seems to be at least one subject with LBP whose timing is deviated from the rest.

As shown in Figure 2.5 and Figure 2.6, the only segment rotation that shows a significant difference between groups is pelvic rotations in the frontal plane. However, this difference is small and likely has no clinical significance. It is however, odd that this difference would be significant at all. As stated in the introduction, pelvic frontal plane rotations are of interest in walking due to the existence of a double stance phase in walking. This requires the pelvis to laterally tilt to clear the swing limb. In running, this double stance phase is replaced by a double float phase. This eliminates the need for the pelvic lateral tilt. We would therefore expect a natural reduction in pelvic lateral tilt as one moves from walking to running.

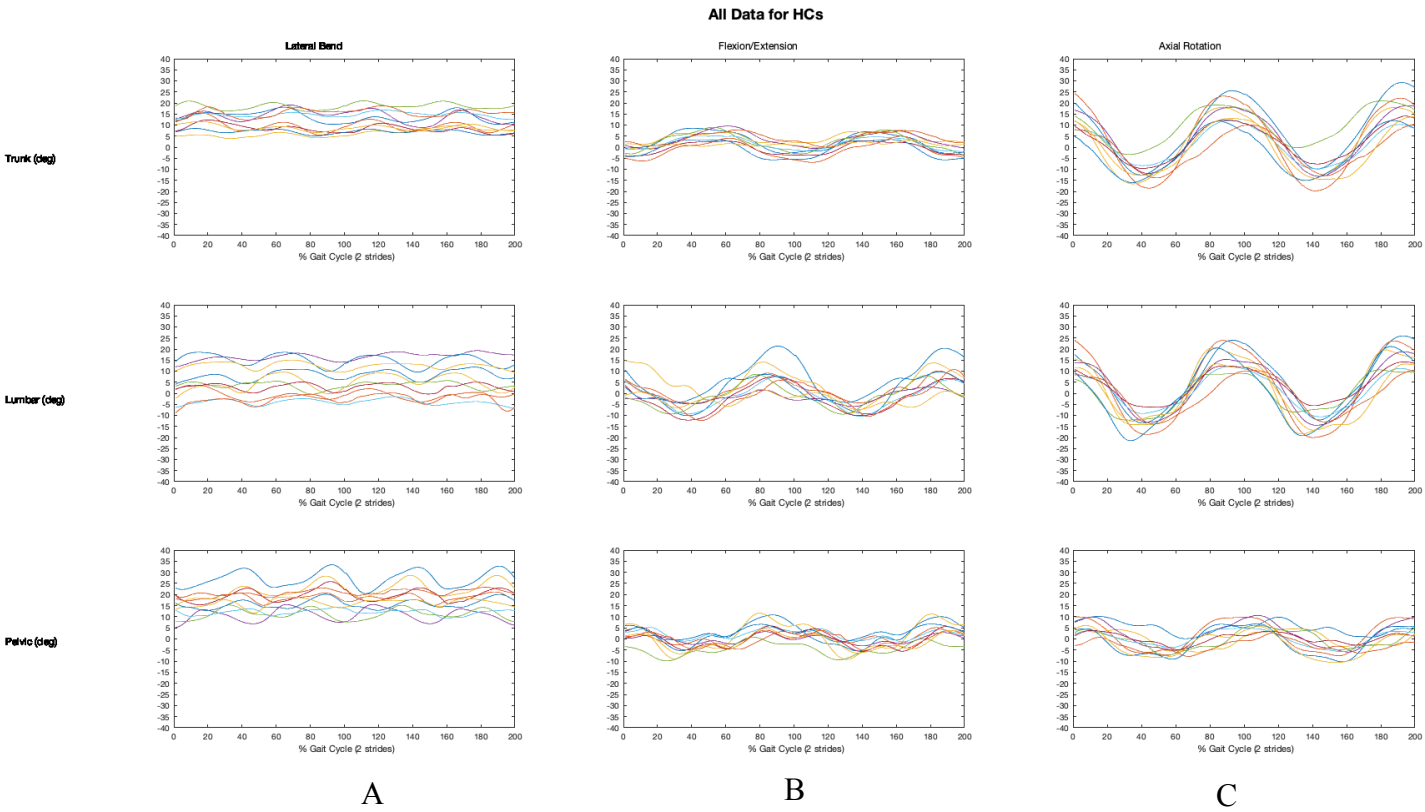


Figure 2.5: Two stride trunk, lumbar and pelvis rotations for all 10 HC subjects in all planes.
Unlike ensemble average graphs these graphs show the sources of variation. In lateral bend we some overall variation particularly in lumbar region due to running posture (generally more rotated to the right). A few of the runners seem to maintain a more neutral posture and oscillate equally right and left. We also see the same in the pelvic segment much less variation is seen in flexion/extension and axial rotation between subjects

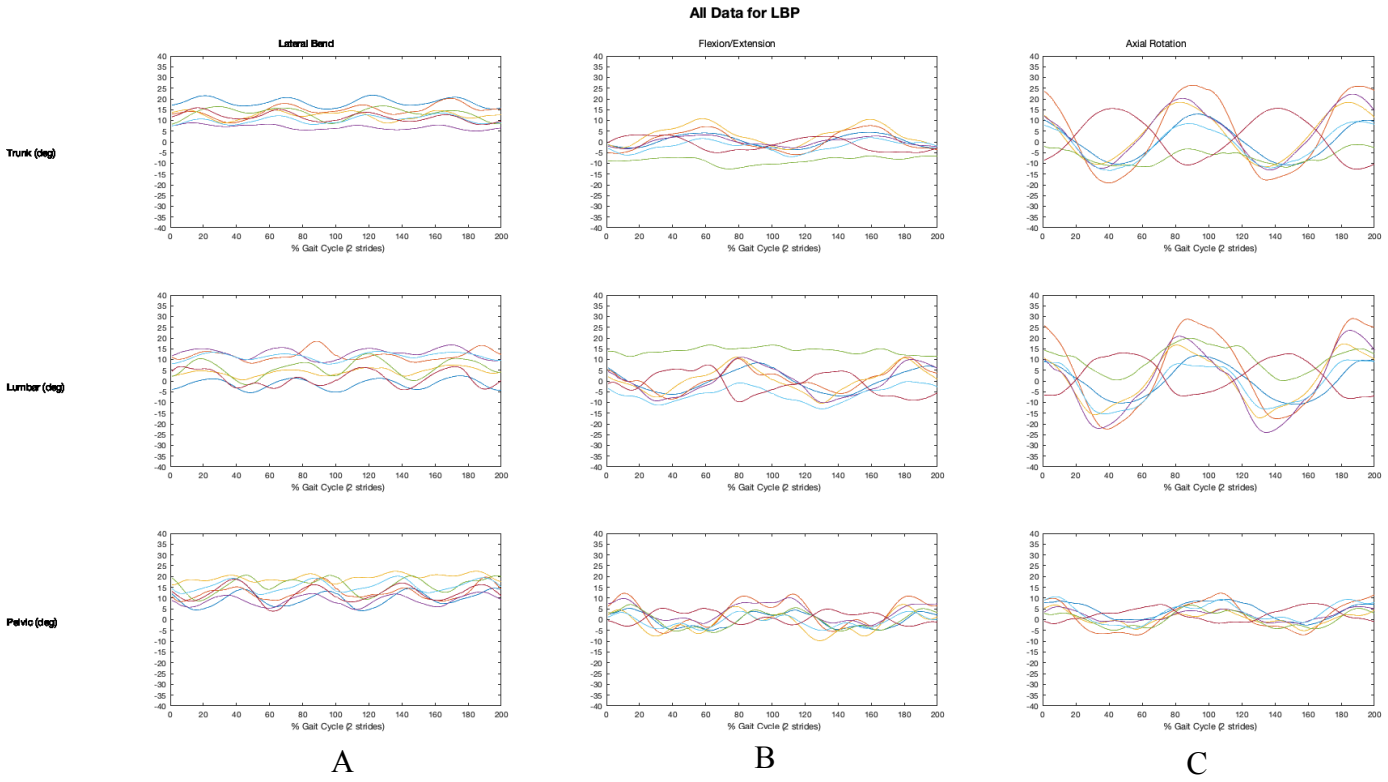


Figure 2.6: Two stride trunk, lumbar and pelvis rotations for all 7 subjects with a history of LBP in all planes Here we also see the sources of variation in this population. It seems subjects with LBP run more rotated to the right (+ve) when compared to HC. There also seems to be less variation in the pelvic region in lateral bend as well. In flexion/extension we see some timing differences between subjects that were not present in HCs. These timing differences become more apparent in axial rotation.

2.6: Discussion

Ensemble averages are a common methodology used to depict the group averages and standard deviations of spinal segment rotations. This study combined ensemble averages and rotational amplitudes in order to determine whether these methods are capable of differentiating groups with and without a history of LBP. Some interesting group similarities and differences are seen in these graphs. For instance, both groups show larger variations in lateral bend rotations than in any other direction. Within these lateral bend rotations, lumbar rotations have the largest amount of variation at approximately 15° for LBP subjects and 10° for HCs. Differences were most apparent for trunk and lumbar axial rotation. LBP subjects showed greater trunk (HC: 10°, LBP: 25°) and lumbar (HCs: 10°, LBP: 30°).

The ensemble averages combined with two stride overlays (Figure 2.5 and Figure 2.6) show why ensemble averages are inadvisable. With ensemble graphs it is difficult to determine whether variations are due to individual rotations or overall group differences. Figure 2.5 and Figure 2.6 show that there are three main origins of larger variations common to both groups, and variation differences between groups. Looking specifically at lateral bend rotations, we see that the large standard deviations seen in ensemble graphs seen in both groups are due to individual subject variability. In lumbar lateral bend, some subjects seem to remain neutral and bend laterally to the left and right in equal measure. While other subjects seem to prefer oscillating with a preference to the right side (+ve) or to the left (-ve). Group differences in axial rotations seem to come from timing differences. There is at least one subject with LBP who maintains a phasing pattern that is out of phase from his colleagues. While there are differences in minima and maxima in axial rotations, all subjects follow a similar overall rotation patterns. When these results are translated into ensemble averages, they result in large standard deviations and differences in ensemble average graph shapes. Due to the small sample size in this study, a subject who employs a different strategy from the rest of the group affects the ensemble average calculations. Therefore, in studies with small sample sizes, ensemble averages and graphs should be used with discretion, and combined with other statistical analysis methods that are not as impacted by small sample sizes.

RA calculated using Equation 2.1: calculation for rotational amplitudes showed little differences between groups. Results of MANOVA with multiple responses shown in

RA Stats		Trunk			Lumbar			Pelvic		
		Lat Bend	Flex/Ext	Ax Rot	Lat Bend	Flex/Ext	Ax Rot	Lat Bend	Flex /Ext	Ax Rot
HC	Average	5.58	8.27	28.36	6.88	16.68	30.06	7.56	10.21	12.33
	Median	4.95	8.09	27.40	6.53	16.85	29.16	7.39	9.36	11.30
	Std	2.70	2.67	7.21	2.29	5.84	8.67	2.66	4.19	3.54
LBP	Average	5.80	8.73	27.22	7.55	14.55	29.87	8.88	11.91	11.40
	Median	5.90	7.56	26.27	7.14	16.01	23.16	8.80	11.54	10.54
	Std	1.70	3.47	9.91	2.62	5.39	11.96	2.44	3.41	3.59
	p-values	0.67	0.49	0.45	0.22	0.1	0.93	$p < 0.05$*	$p < 0.05$*	0.24
	Cohen's ES	0.07	0.13	0.11	0.23	0.30	0.02	0.42	0.35	0.21

Table 2.3 show no statistically significant differences between groups except in pelvic lateral bend rotations. However, when effect sizes were also calculated, all were either trivial (< 0.2) or small (0.2 - 0.5). Like ensemble averages, the source of these differences is unclear. In both groups, there are subjects who have larger amplitudes than others. However, these rotations show a preference for direction of oscillation which may nor may be independent of LBP status.

Due to the ensemble average dependence on sample size and rotational amplitudes dependence on oscillation direction preference, these methods report show no differences between groups. However, mostly insignificant differences between groups does not indicate that no differences between these groups exists. Overall subject segment rotations show that subjects with a history of LBP may have different phasing patterns than those typically seen in HCs. These differences would not be evident in ensemble averages or rotational amplitudes calculations but they may still lend insight into how subjects with a history of LBP differ from HCs. These overall phasing differences indicate that coordination patterns between segments may be of interest. Especially because these phasing differences do not appear in all segment rotations. They are most obvious in lumbar and pelvic flexion/extension and axial rotations, but do not appear in lateral bend rotations.

There are three advantages to coordination patterns that make them more preferable to ensemble averages and rotational amplitudes. Firstly, coordination patterns are not a susceptible to group phasing differences as ensemble averages. As we have explored in this paper, in small populations, phasing differences within groups affect ensemble average calculations, in ways that do not affect coordination patterns. Secondly, unlike rotational amplitudes coordination patterns are not as impacted by left or right leanings. In calculating coordination patterns, rotations are normalized to all fall above 0. Therefore, relative rotations are the sole focus. Lastly, there is evidence to suggest that this method may be sensitive enough of differentiate a population with a history of LBP, HCs, and LBP subjects currently in pain. Therefore, future

work in this area should involve the calculation of coordination patterns between segment rotations.

2.7: Conclusions

Ensemble graphs remain a method that is commonly used to depict how the average of a particular group changes over a cycle. This study was the first to evaluate the usefulness of this method as well as RA to differentiate between runners with and without a history of LBP. When evaluating a pattern that remains similar across subjects it may be useful. This is shown in the accuracy of lateral bend ensemble graphs when compared to the individual rotations in Figure 2.6. However, the large variability and the inability to identify the origin of this variability makes ensemble graphs inadvisable when differentiating runners with and without a history of LBP.

When patterns differ within a group, ensemble graphs do no capture these phasing differences with accuracy. This is particularly evident in flexion/extension and axial rotation. Unlike lateral bend, where subjects show similar timing, flexion/extension and axial rotation shows that different groups may actually exhibit timing differences. These phase shifts can greatly affect ensemble average graphs. In ensemble average graphs with small sample sizes, this appears as larger variations in one group compared to another. In ensemble averages with larger sample sizes, these phasing differences are no longer apparent because they can be drowned in the group averages. Therefore, in small and large sample sizes and with groups who are relatively similar, ensemble averages and graphs should be used with caution and paired with other statistical analysis methods such as ANOVA and effect size calculations.

Rotational amplitudes give a different perspective on group differences. We would expect subjects with LBP to reduce oscillation amplitudes as a splinting mechanism. Results show that this may not be the case. Overall rotational amplitudes remained consistent between groups. Significant differences between LBP and HCs in pelvic lateral bend may be due to the one

subject whose rotations seem to be disproportionately tilted to the left or right, while all other subjects seem to oscillate to both sides in equal amounts. This same subject seems to run with a left lateral bend in their lumbar region as well. A significant p-value or effect size of clinical significance may have been mitigated by the phase differences present in the group with LBP.

Results from rotational amplitudes, ensemble graphs and overall data tells us two important things about these groups. Firstly, major differences between groups may not always occur where we expect. Previous research has documented the splinting methods that are used by those experiencing various sorts of joint pain. LBP clearly presents differently from knee, hip or ankle pain. While rotational amplitudes may have shown no differences, it does not mean that no differences are not present. Especially when one considers the incidence of relapse [35]. Secondly, the major differences between these groups may be in the phasing of the oscillations rather in the magnitude of the rotations. This is particularly evident when looking at the overall data. Even though we had fewer subjects with a history of LBP, none of our HCs showed a different phasing pattern. Lastly, these phasing patterns can easily get lost when ensemble averages are taken. Overall data hints at the possibility that the phasing differences may be a good method to differentiate subjects with a history of LBP from those without.

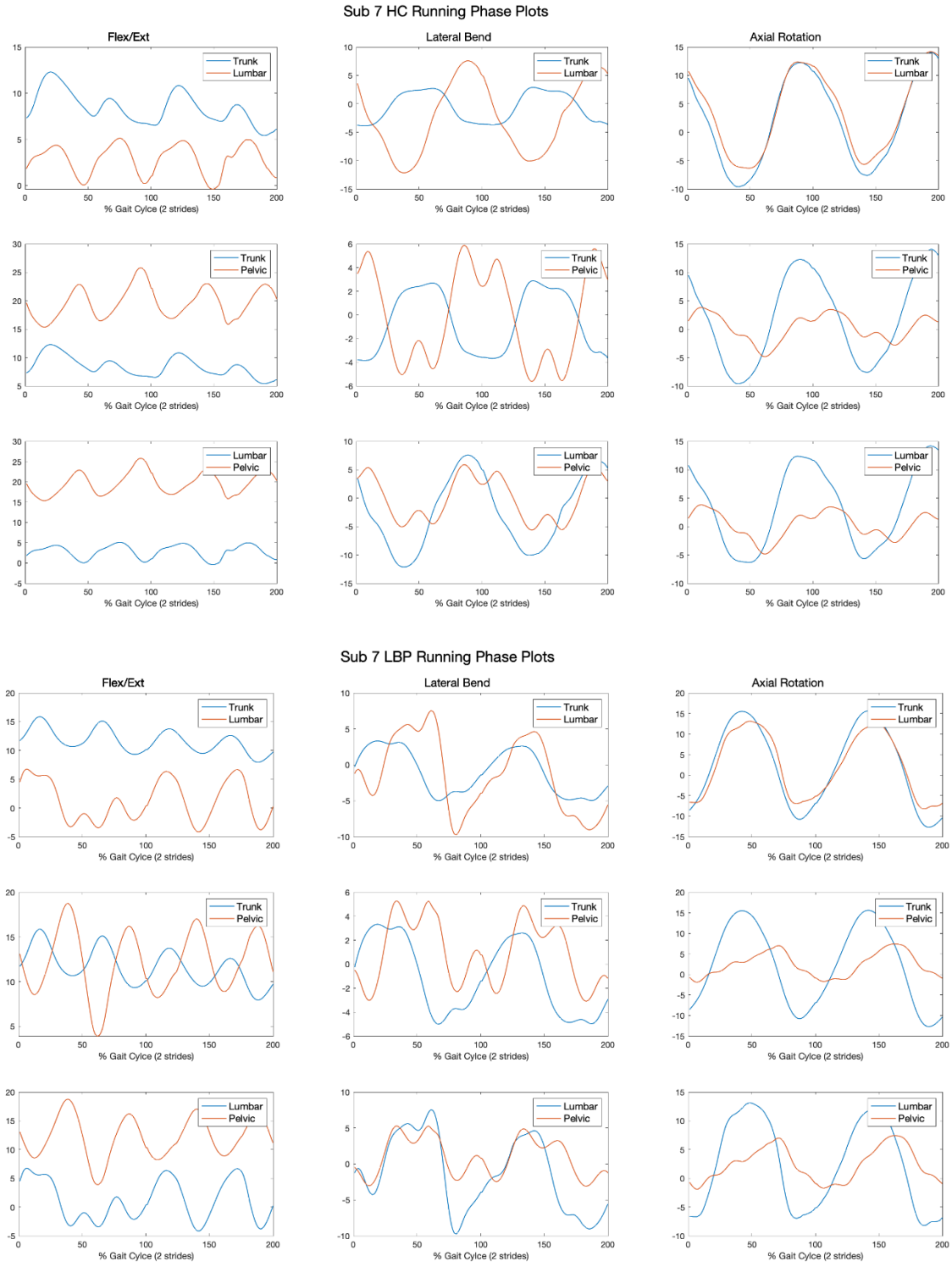


Figure 2.7: Rotation overlays for HC and LBP subject 7.
These rotation graphs show some of the phase shifts between segments. Therefore, relative phasing analysis may be the best approach for differentiating HCs from patients with a history of LBP

Figure 2.7 shows examples of HC subject 7 and subject 7 with LBP phasing plots. From these graphs we see more significant out-of-phase patterning in the subject with LBP in trunk-pelvis coordination in flexion/extension. Similar patterns are also seen in the transverse plane, but with HC now showing a greater out-of-phase patterning than the subject with LBP. Most of the data shows an out-of-phase patterning to various degrees. Therefore, it would be advisable to look for overall group differences in segment relative phasing in all planes, and see whether any significant differences between groups appear.

Chapter 3 : Trunk-lumbar, trunk-pelvic and lumbar-pelvic coordination Patterns in runners with and without low back pain

3.1: Introduction

Segment rotations and its rotational amplitudes counterpart proved to be incapable of capturing the differences between groups. While it is a dynamic approach that takes into consideration both temporal and spatial elements, simply looking at the overall and averaged rotations of trunk, lumbar and pelvic segments is insufficient. To address this and other problems that arise from non-dynamic analysis methods, relative phasing of segments have come to the forefront. In this study the method used to analyze the relative timing will be Continuous Relative Phasing (CRP) and its variability (CRPvar). Both of these methodologies choose to focus on the coordination patterns between segments rather than individual rotations. This addresses the first problem with segment rotations by choosing not to ignore the segments above and below those of interest. Secondly, it allows for the inclusion of variability in new ways.

In recent years there has been a change in the understanding of the role of variability and stability in biological systems. Stability is defined as resistance to change. Initially, variability was viewed as noise. However, as researchers have begun to investigate the role of variability further, they have found that it may hold the key to truly understanding the nuances of various pathologies. For instance, Goldberger and colleagues have investigated variability in cardiac function. They found that it is far more irregular and variable than was previously thought. In fact, those at a high risk of sudden death syndrome had more regular heart rates. The prevailing hypothesis is that this regularity increases stability reflecting a decrease adaptability [27].

Variability has also made its way into the field of musculoskeletal biomechanics. A study by Wagenaar and van Emmerik showed that a lack of variability, characterized as the inability to transition from in-phase to an out-of-phase or anti-phase coordination pattern is associated with hyper stability [38]. A hallmark of this stability is very little or no variability. A highly stable

system becomes resistant change. In gait, this is seen as an inability to transition from an in-phase coordination pattern to an out-of-phase one particularly as walking velocity increases. The current logic provided by van Sadeghi, Hamil, van Emmerik, and Seay is that highly stable systems, being resistant to perturbations by nature lack the flexibility to allow for adaptations to motion to occur [6,27,31,39].

3.1.1: Why Joint Coordination Patterns?

Within biomechanics there has been a need for new analysis methods that lend further insight into populations with current low back pain (LBP), a history of LBP and healthy controls (HCs). Previous studies have shown that segment rotations and rotational amplitudes cannot differentiate these populations well [18]. As a result, two analysis methodologies have come to the forefront. The first characterizes variability within healthy and diseased populations. In these studies stride-length variability is often the variable of choice [9]. Results are often conflicting with some reporting higher standard deviations, others lower and others no statistically significant differences [9,40]. It is important to note, that in subjects who underwent physical therapy to treat their LBP overall increases in stride-length standard deviations were reported [9]. This increase in stride-length variability, interpreted as a return to normal gait patterns, suggests that this method may be descriptive of LBP. This means we cannot draw inferences on the origins of LBP from such results.

The second methodology involves the characterization of coordination patterns between spinal segments. Unlike segment rotations and rotational amplitudes which struggle to find differences between affected, previously affected and HCs, coordination patterns have found statistically significant differences between these groups [6,18,19,23]. In contrast to stride-length variability, these differences continue to appear in those whose back pain has resolved. This indicates that coordination patterns may help us identify maladaptive patterns in those with a history of LBP that increase their likelihood of developing LBP later.

3.1.2: LBP in Runners

Runners are at a high risk of developing LBP. Roncarati and McMullen in 1988 devised a study to profile low back pain in the general population [41]. They used a two phased approach consisting of a questionnaire, and a physical examination that included full body symmetrigraph. Altogether they collected 105 assessment variables that were then divided into three categories: general health, anatomical considerations, and athletic considerations. Subjects were also divided into two categories: those with a differential diagnosis of LBP determined by a board-certified orthopedic surgeon and those without LBP. Roncarati considered eleven categories of LBP. Category 1 consisted of those whose back pain was determined to be due to "self-induced trauma". This included lumbar strain or sprain, subluxed facet joint in the lumbar spine, spondylosis, or herniated disc. Category 2 consisted of those whose LBP was due to "mechanical causes". This included poor muscle tone, chronic posture strain and unstable vertebrae. Both of these categories were included in the LBP group. Among other things, Roncarati and McMullen found that those with LBP had increased their running frequency at least 10% within the past year and that LBP onset occurred on average 7.56 weeks after this increase. The LBP group also exhibited decreases in range of motion of the lumbosacral and gastrocnemius musculature, hip extensors, internal and external rotators, and a decrease in trunk flexion. While there were multiple variables that differentiated those with LBP from those without, this study still failed to find differences in trunk, lumbar and pelvic range of motion [41].

These findings by Roncarati and McMullen have a few possible implications for coordination patterns that may be exhibited in an LBP population. For instance, the decrease in range of motion in the lumbosacral musculature in conjunction with the decrease in trunk flexion could appear as decrease in coordination in the trunk and lumbar or trunk and pelvic segments. Decreases in range of motion could have implications for the coordination between the trunk and

pelvis and lumbar and pelvis. Most likely more in-phase coordination pattern will be seen. Overall the findings suggest in-phase coordination patterns may be the most common among the subjects with LBP. While flexion and extension of the trunk-lumbar coordination pattern and all of the trunk-pelvis rotations may be affected.

3.1.3: Changing Tactics: Functional Variability

The purpose of this chapter is to explore one continuous method that compares coordination between segments for analyzing gait in runners as well as its variability component (CRP and CRP variability). To the author's knowledge, Taylor's study was the only one examining LBP vs. HC coordination in walking, and Seay doing the same in running [13,23,33,42]. While both of these studies studied coordination in all planes, neither of these studies included the lumbar spine as a segment of interest. Therefore, to the author's knowledge this is the first study to use CRP and CRP variability to characterize the coordination in the trunk, lumbar and pelvis segments in a population with a history of LBP.

CRP includes both spatial and temporal parameters that provide ways to characterize motion while considering neighboring segments. Thus, allowing for a more holistic approach to analyzing the gait cycle. While continuous methods do allow for the analysis of whole movements, some continuous methods may still be unable to capture differences in pathology. This was illustrated in Chapter 2 where continuous analysis of the trunk, lumbar and pelvis rotations were unable to help in differentiating a HC population, from one with a history of LBP. This study adds to the body of literature that shows the insensitivity and inconsistency of traditional biomechanical analysis methods.

3.2: Methods

3.2.1: Participants

Twenty subjects were contacted for testing, two were excluded because of current LBP while one did not respond for testing. Therefore, 17 subjects were tested; 10 healthy controls

(HC: 3 Male; 7 Female) and 7 subjects with a history of LBP (LBP: 3 Male; 4 Female). HC had an average age of 29 years old (± 4 years) while LBP subjects had an average age of 28 years (± 6 years). All subjects were physically healthy and ran an average of 20km a week. LBP subjects were defined as those who had been diagnosed or self-reported an incident of LBP in the past year, but none in the past 3 months. Subjects with spondylolisthesis no greater than degree one as reported by the subject were eligible. Upon contact the subjects' eligibility was determined by a health questionnaire as well as the Physical Activity and Readiness Questionnaire (PAR-Q). Any subjects that indicated they had current pain or responded "yes" to any question on PAR-Q were excluded. Additional exclusion criteria included a history of low back or lower extremity surgery, neurological impairment, physical therapy within the past three months to treat LBP, currently pregnant, or any structural back deformity such as scoliosis or spondylolisthesis of degree greater than one. In accordance with university policy, all subjects consented to testing by signing a form that was approved by the University of Kansas Medical Center (KUMC) institutional review board (IRB). Demographic information as well as BMI are recorded in Table 3.1 and Table 3.2

Subject #.	Gender	Age (y)	Height (m)	Weight (kg)	BMI	Speed (kph)
1	M	32	1.70	72.64	25.08	8.9
2	F	22	1.62	52.21	19.76	11.1
3	M	33	1.77	88.53	28.00	15.1
4	F	29	1.70	49.94	17.24	11.7
5	F	24	1.77	59.02	18.67	9.2
6	M	32	1.88	77.18	21.85	10.6
7	M	28	1.77	69.46	21.97	12.1
Average		29	1.75	67.00	21.80	11.0
Median		29	1.78	69.46	21.85	11.0
Std		4	0.08	14.01	2.74	2

Table 3.1 Gender, age, height, weight and comfortable running velocity in kph for subjects with a history of LBP. These subjects had either been diagnosed or self-reported incidence of LBP in the past year, but had been pain free for the past 3 months and had not undergone physical therapy to treat it. Subjects with current back pain, history of low back or lower extremity surgery, were pregnant or had spondylolisthesis degree greater than one were excluded. Otherwise, these subjects were physically healthy and ran an at least 20 km/wk.

Subject #.	Gender	Age (y)	Height (m)	Weight (kg)	BMI	Speed (kph)
1	F	25	1.57	54.48	21.97	10.6
2	F	23	1.65	63.56	23.32	11.7
3	M	24	1.75	78.08	25.42	11.4
4	M	24	1.85	82.17	23.90	10.9
5	M	25	1.70	70.37	24.30	10.6
6	F	40	1.65	61.29	22.49	7.6
7	F	29	1.65	56.75	20.82	8.2
8	F	39	1.70	59.92	20.69	12.7
9	F	24	1.70	63.56	21.95	9.3
10	F	29	1.68	59.02	20.69	9.3
Average		28	1.69	64.92	22.50	10.0
Median		25	1.70	62.43	22.23	11
Std		6	0.07	8.68	1.56	2

Table 3.2 Gender, age, height, weight and comfortable running velocity in kph for HC subjects. These subjects self-reported no incident of LBP within the past three years. Like subjects with LBP, these subjects also ran at least 20 km/wk

3.2.2: Experimental Set-up

Hip internal and external rotation were measured using a large goniometer. Kinematic data was collected at 60Hz using reflective markers (Motion Analysis, Santa Rosa, CA, USA). Marker placement is shown in Figure 3.1 Subjects performed 10 range of motion tasks: flexion, extension, left and right lateral bend, left and right axial rotation, right lateral bend followed by right axial rotation, left lateral bend followed by left axial rotation, right lateral bend followed by left axial rotation, and left lateral bend followed by right axial rotation. Subjects then ran on a WOODWAY treadmill for a 2-5 minute warm up. After the warm up period, the speed of the treadmill was increased until the subjects indicated that it was close to their normal running pace. This speed was then recorded. Subjects then ran for an additional 3-5 minutes. At a randomly selected point during these 3-5 minutes, one minute of data was collected.

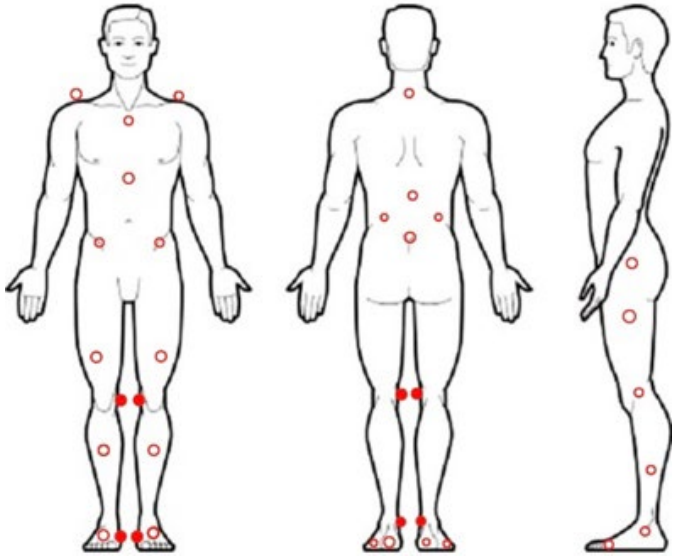


Figure 3.1: Reflective marker placement
Left and Right acromioclavicular joint (AC), clavicle, sternum (xyphoid process), LASIS, RASIS, mid-anterior thigh, upper-lateral thigh, medial and lateral knee, upper-anterior shin, lower-lateral shin, ankle, calcaneus, posterior aspect of 4th metatarsal, 2nd metatarsal, and medial malleolus. Shaded markers represent markers which were not present on some subjects.

3.3: Data Analysis

In order to track motion of the trunk, lumbar and pelvis segment, vectors were created and their rotation about a global axis was tracked. Figure 2.2 shows the vectors and the building of the trunk, lumbar and pelvis axes. For example, the trunk axes were built by first drawing vectors from C7 to T10 ($\vec{j}$), then from the Clav to T10 ($\vec{k}$). The cross product of these two vectors produced ($\vec{j} \times \vec{k} = \vec{l}$). The inverse of $\vec{l}$ corresponded rotations about the z-axis or axial rotation. Rotations about the y-axis or flexion/extension or were defined as the inverse of $\vec{l}$. Lastly, rotations about the x-axis or lateral bend, were defined as $\overrightarrow{-l} \times \vec{j}$. Axes for the lumbar and pelvic regions are shown in Figure 3.2 and were formed in the same manner as the trunk axes. Lumbar motion was tracked as the difference between the lumbar and pelvis axes. Rotations of the trunk and lumbar in the frontal plane (about the x-axis) are defined as lateral bend, and pelvic medial-lateral tilt. Rotations in the sagittal plane (about the y-axis) were defined

as trunk flexion and extension, lumbar kyphosis and lordosis, and pelvic anterior-posterior tilt. Lastly, rotation in the transverse plane (about the z-axis) is defined as trunk, lumbar and pelvic axial rotation. In the figures for simplicity rotations are denoted as flexion/extension (flex/ext), lateral bend (lat bend) and axial rotation (ax rot) for all three segments. After motion of the trunk, lumbar and pelvis was tracked, a gait cycle was identified as minima to minima of the left heel data. Data was then reduced to 100 data points to represent a full gait cycle.

between the left posterior superior iliac spine and right posterior iliac spine. Trunk and lumbar and pelvic rotations are tracked as rotations about x (lateral bend; frontal plane), y (flexion/extension; sagittal plane) and z (axial rotation; transverse plane).

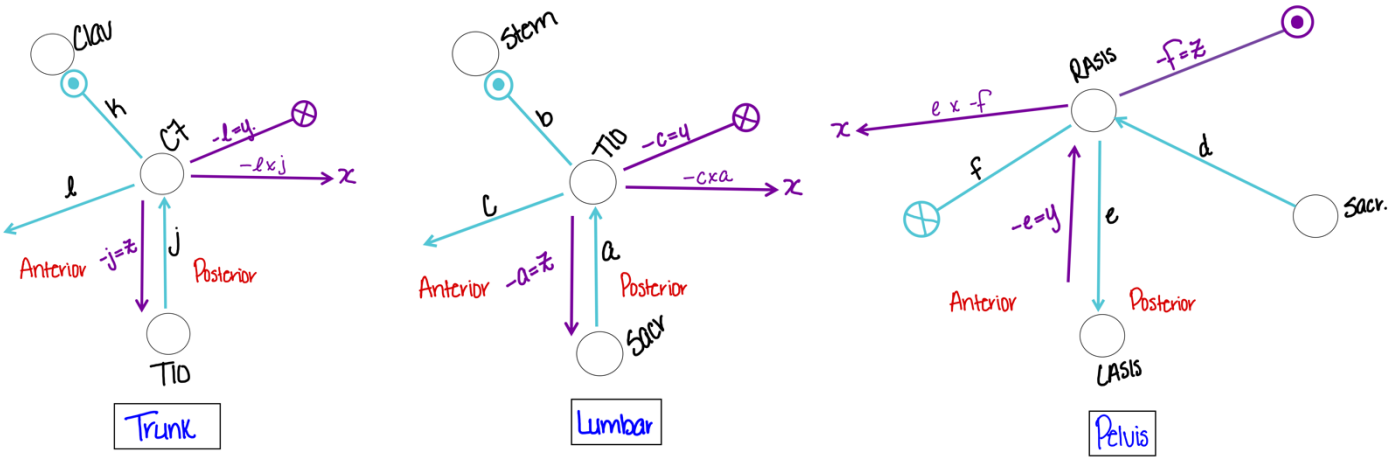


Figure 3.2: Trunk, lumbar and pelvic segment vectors and axes
Cerv, Cervical; C7, 7th Cervical vertebrae; T10, 10th Thoracic vertebrae; Stern, Sternum; Sacr, Sacrum; RASIS, right anterior superior iliac spine; LASIS, left anterior superior iliac spine. Sacral marker is calculated as the midpoint

This CRP methodology is based on Joseph Hamill's 1999 paper and Joseph Seay's 2008 dissertation [20,27]. First, we begin with the creation of phase diagrams that are graphs of the segment angle vs. angular velocity in what Hamill refers to as the 'phase-plane'. Segment angular velocity was obtained by using the forward difference method. Linear regression of the angular position data four points was obtained and the slope taken as the velocity. Afterwards, angular position and angular velocity were normalized to a unit circle using Equation 3.1 and Equation 3.2

Angular position (horizontal/x-axis) was calculated:

$$\theta_i = \frac{2*[\theta_i - \min(\theta_i)}{\max(\theta_i) - \min(\theta_i)}$$ Equation 3.1

Angular velocity (vertical/y-axis) was calculated:

$$\omega_i = \frac{\omega_i}{\max\{\max(\omega_i), \max(-\omega_i)\}}$$ Equation 3.2

An example of the phase-plane diagram is shown in

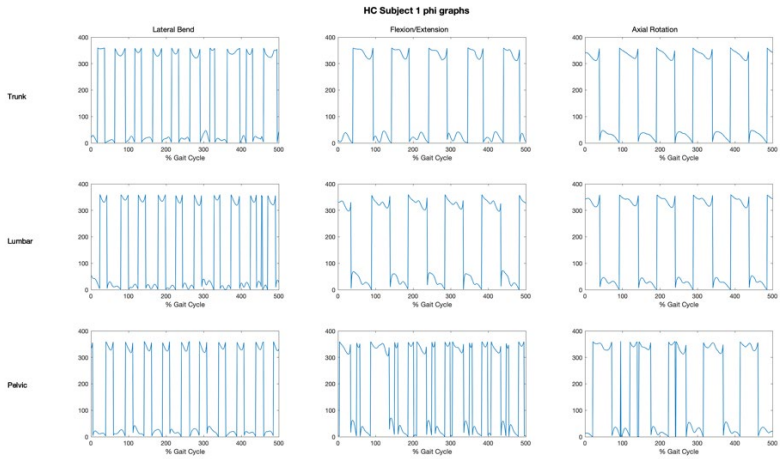


Figure 3.2. Figure 3.1 shows the four quadrant arctangent calculations. The first and second quadrants required no adjustments. The third and fourth quadrants were both adjusted by adding 360. This ensured that none of the oscillations dropped below 0. Once the phase angle (φ) was calculated, pelvis-trunk CRP was calculated according to Equation 3.3.

When we calculate the CRP, we see the importance of correcting the third and fourth quadrant by adding 360. This not only allows us to determine direction of the rotation but the coordination as well. A CRP of 0° indicates in-phase coupling between the segments. As CRP increases, towards ±180 indicates a moving towards anti-phase coordination patterns whereas 180° would indicate complete anti-phase coordination.

$$CRP_{T-P} = \varphi_{pelvis} - \varphi_{trunk}$$ Equation 3.3

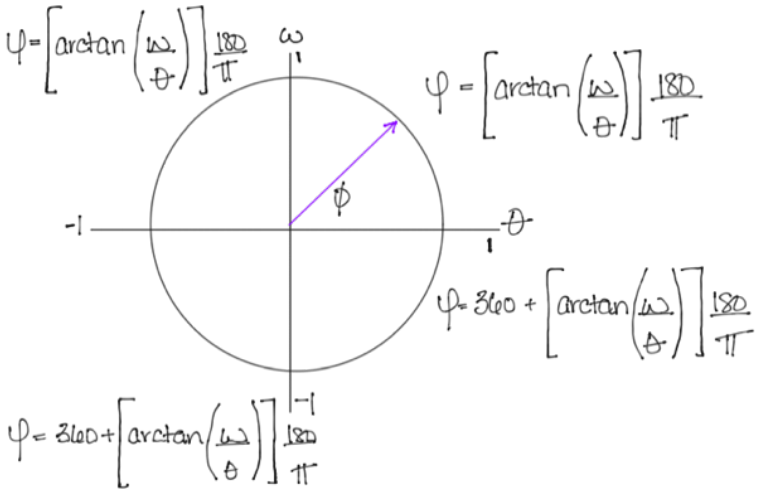


Figure 3.3: Four quadrant corrections for phase (phi) calculations.
This unit circle depicts the phase corrections that were made for each quadrant. For ϕ between ω =1 and θ =1 or -1 φ needed no correction. For θ between ω = -1 and θ = -1 or 1 φ = +360.

Subtraction of the phase rotations showed some jumps of 270° or greater where the phase diagrams did not quite match. Therefore, corrections were made for point jumps of ± 270° were by adding or subtracting 360°. Other areas where multiple points were shifted, an overall correction to bring those sections up or down was also applied. Phase rotations were taken over a series of the first 5 strides in the data collection period. After these corrections, distal segments were subtracted from proximal segments as explained above to calculate CRP. Examples of phase diagram prior to corrections and CRP 5 stride overlays for a HC subject 1 can be seen in .

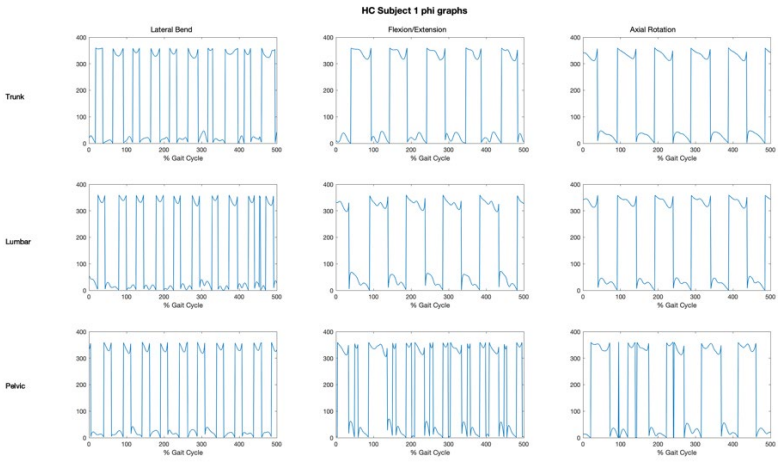


Figure 3.4: Phase (φ) diagrams of 5 strides for HC subject 1

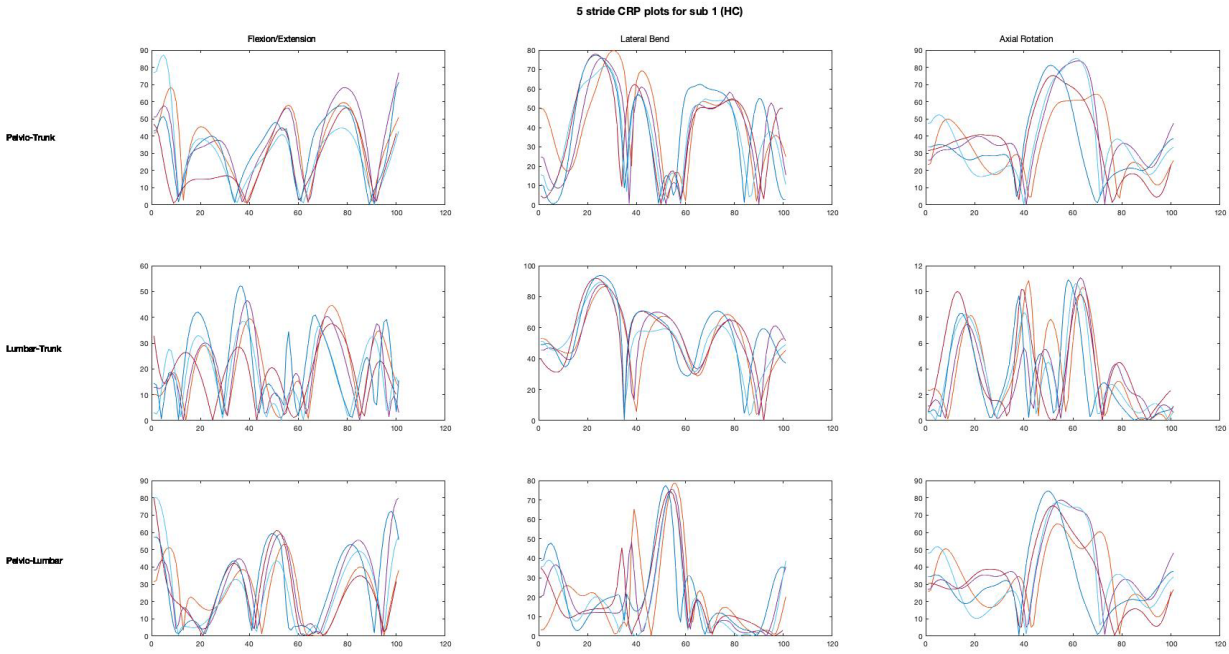


Figure 3.5: CRP diagrams for trunk-pelvic, lumbar-trunk and lumbar-pelvic coordination in all planes for HC1 Figure depicts phasing between pelvic-trunk, lumbar-pelvic and pelvic-lumbar in flexion/extension (sagittal plane), lateral bend (frontal plane) and axial rotation (transverse plane). CRP > 60° indicates a phase in the segments and a tendency towards out-of-phase coordination.

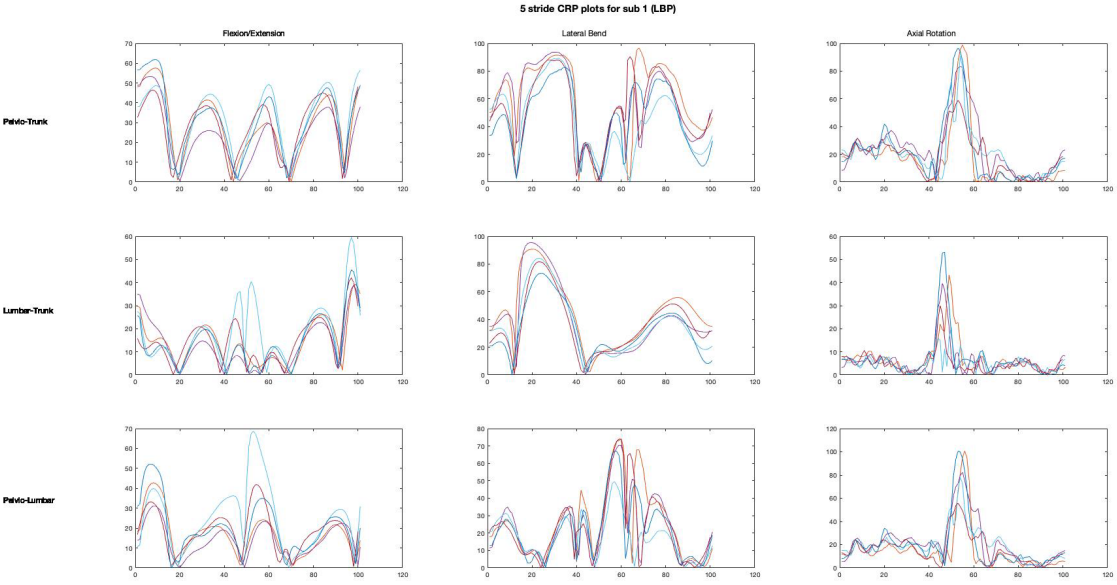


Figure 3.6: CRP diagrams for trunk-pelvic, lumbar-trunk and pelvic-lumbar coordination in all planes for subject 1 with LBP. Figure depicts phasing between pelvic-trunk, lumbar-pelvic and pelvic-lumbar in flexion/extension (sagittal plane), lateral bend (frontal plane) and axial rotation (transverse plane). CRP > 60° indicates a phase in the segments and a tendency towards more out-of-phase coordination.

3.2.1: Statistical Analysis

Statistics for CRP and CRP variability were as follows. CRP mean and standard deviations were calculated. A single average for 5 strides per subject was calculated and a MANOVA with multiple responses were carried out using these averages. P-values and Cohen's effect size calculations are reported in.

CRPvar was calculated as the average stride-to-stride standard deviation of the first 5 strides of data collection. As with CRP one average for 5 strides was calculated and a multiple response MANOVA carried out. P-values are reported in Table 3.4 below. Effect sizes were calculated as:

$$d = \frac{M_{HC} - M_{LBP}}{SD_{pooled}} \qquad \text{Equation 3.4}$$

CRP		Pelvic-Trunk			Lumbar-Trunk			Pelvic-Lumbar		
		Lat. Bend	Flex/Ext	Ax. Rot	Lat Bend	Flex/Ext	Ax. Rot	Lat. Bend	Flex/Ext	Ax. Rot
HC	Avg.	26.94	36.47	24.73	18.62	36.61	6.14	20.77	17.64	25.22
	Med.	27.30	36.65	22.58	18.37	36.15	5.81	21.31	17.33	23.15
	Std	11.03	5.64	12.39	5.30	8.24	2.27	10.50	4.30	10.35
LBP	Avg.	35.52	42.00	23.52	23.82	28.50	9.08	18.35	21.81	21.41
	Med.	35.19	43.75	23.11	19.11	31.33	9.06	16.90	21.61	21.55
	Std	10.89	8.70	9.19	10.76	9.10	3.59	5.08	4.41	6.37
	p-values	0.09	0.11	0.83	0.15	< 0.05	< 0.05	0.57	<0.05	0.39
	Effect Sizes	−0.88**	−0.84**	0.11	−0.75*	1.00**	−1.16**	0.28	−1.14**	0.43

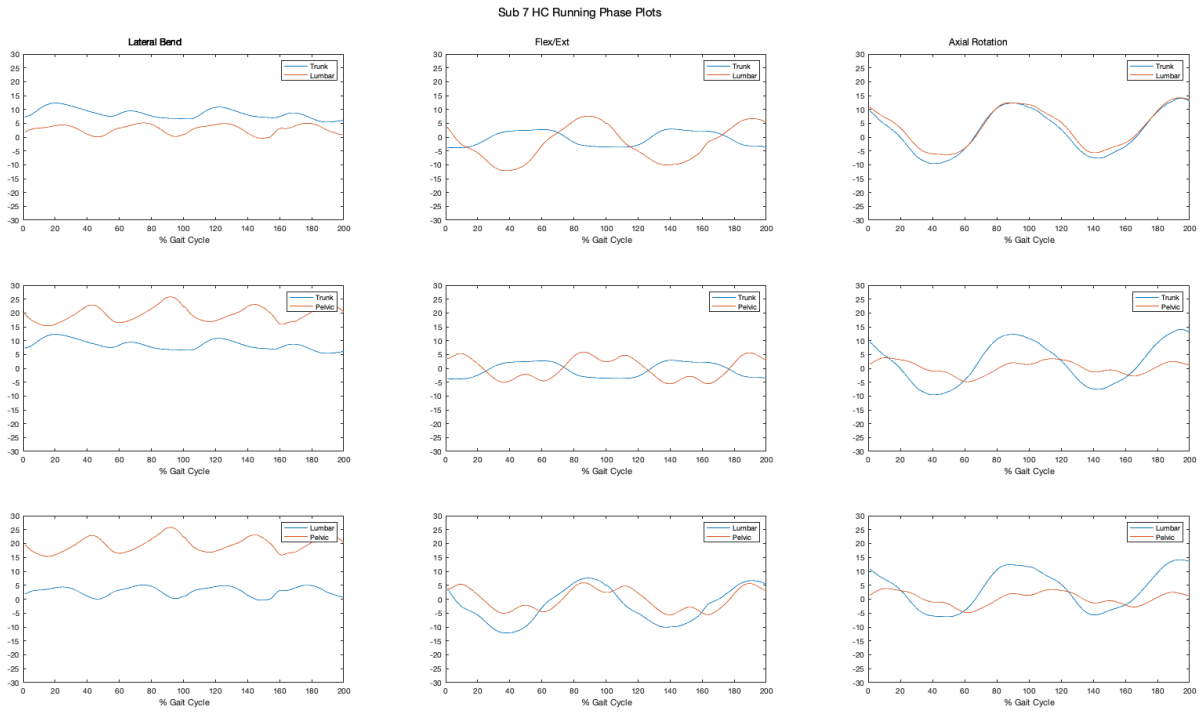
Table 3.3: CRP MANOVA results with multiple responses p-values and Cohen's effect sizes
Results show significant group differences in lumbar-trunk flexion/extension and axial rotation and pelvic-lumbar flexion/extension ($p \leq 0.05$). Near significance was found in pelvic-trunk lateral bend ($p = 0.09$). Effect sizes were calculated using Cohen's method in Equation 3.3, negative effect sizes indicated mean of HCs was smaller than those of LBP subjects. Large effect sizes were seen in pelvic-trunk lateral bend, flexion/extension, lumbar-trunk flexion/extension and axial rotation, and pelvic lumbar flexion/extension ($|ES| \geq 0.8$**). Moderate effect sizes were seen in lumbar-trunk lateral bend. All other effect sizes were either trivial ($|ES| \leq 0.2$) or small ($0.2 < |ES| < 0.5$).

CRP Var		Pelvic-Trunk			Lumbar-Trunk			Pelvic-Lumbar		
		Lat. Bend	Flex/Ext	Ax. Rot	Lat. Bend	Flex/Ext	Ax. Rot	Lat. Bend	Flex/Ext	Ax. Rot
HC	Avg. Std	16.24	22.76	17.17	12.34	23.38	6.23	13.88	15.46	17.88
	Med. Std	17.14	22.39	17.10	12.05	22.78	5.34	15.56	15.20	17.98
LBP	Avg. Std	21.83	24.53	17.51	17.52	21.24	8.50	11.71	16.92	15.65
	Med. std	10.89	8.70	9.19	10.76	9.10	3.59	5.08	4.41	6.37
	p-values	0.24	0.27	0.85	0.21	0.43	0.13	0.41	0.41	0.12
	Effect Sizes	−0.6*	−0.56*	−0.1	−0.65*	0.4	−0.78*	−0.42	0.42	0.82**

Table 3.4: CRP variability MANOVA results with multiple responses p-values
Results show no significant group differences ($p > 0.05$). Effect sizes were calculated using Cohen's method in Equation 3.3, negative effect sizes indicated mean of HCs was smaller than those of LBP subjects. Moderate effect sizes were reported for pelvic-trunk lateral bend, flexion/extension, lumbar-trunk lateral bend/axial rotation, and lumbar-trunk lateral bend and axial rotation ($0.5 \leq |ES| < 0.8$). Large effect sizes were reported for pelvic-lumbar axial rotation ($|ES \geq 0.8$**).

3.3: Discussion

Figure 3.4 and Figure 3.5 of CRP plots show that generally subjects moved from an in-phase coordination pattern (closer to 0°) to a more out-of-phase coordination pattern particularly in pelvic-trunk and lumbar-trunk flexion/extension (sagittal plane) and axial rotation (transverse plane) as well as pelvic-lumbar axial rotation. These coordination patterns were not perfectly out-of-phase because most were closer to 90° rather than 180°. This was not unexpected, examples of subject 7 in chapter 2 (Figure 2.7) showed that out-of-phase patterning would present as phase shifts of approximately 60°. This holds true for HC and LBP subject 1 (Figure 3.6Figure 3.7). These results are mostly confirmed in Table 3.3 and in accompanying figures Figure 3.8 and Figure 3.9 where we see a mixture in the phase patterning of subjects within groups. Notable features include pelvic-lumbar lateral bend where HCs have a tendency towards an out-of-phase coordination pattern when compared to subjects with LBP (HC: 60% vs. LBP: 0%).



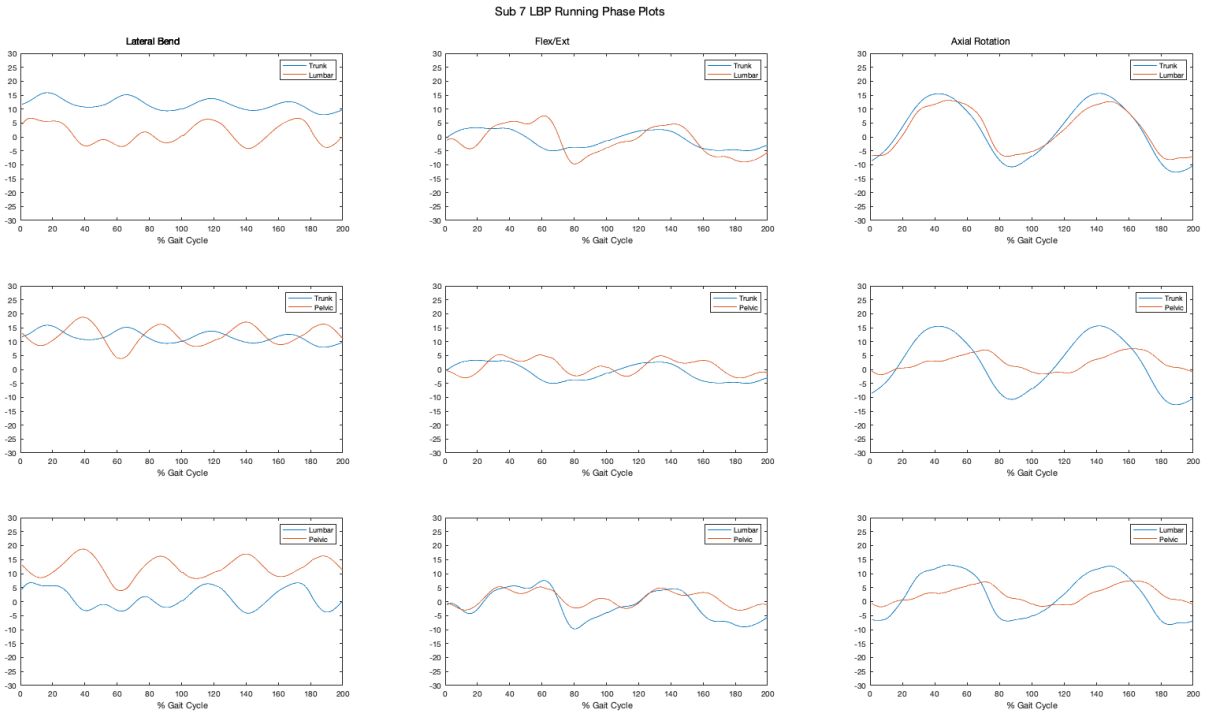


Figure 2.7: Rotation overlays for HC and LBP subject 7.
These rotation graphs show some of the phase shifts between segments. Therefore, relative phasing analysis may be the best approach for differentiating HCs from patients with a history of LBP

Max CRP		Trunk-Pelvic			Lumbar-Trunk			Pelvic-Lumbar		
Type	Subject	Lat Bend	Flex/Ext	Ax.Rot	Lat Bend	Flex/Ext	Ax.Rot	Lat Bend	Flex/Ext	Ax.Rot
HC	1	71.30	77.35	81.18	52.13	93.66	10.90	72.23	77.46	83.95
	2	51.46	61.03	78.03	38.55	82.07	35.16	29.31	52.72	98.26
	3	74.20	89.61	79.22	64.46	91.45	38.23	57.75	79.48	82.92
	4	95.71	70.19	59.42	101.55	93.80	31.14	66.65	103.81	69.77
	5	87.42	92.77	60.63	58.35	107.39	22.86	70.08	54.08	42.80
	6	69.99	66.41	44.29	44.12	67.49	13.15	81.81	64.09	39.41
	7	103.27	80.26	102.32	53.43	81.40	48.86	93.62	98.32	102.33
	8	42.59	72.94	73.83	34.12	53.37	42.49	22.34	43.11	67.33
	9	61.98	86.53	70.17	56.59	97.89	13.69	72.65	58.94	72.08
	10	32.66	74.59	27.73	48.79	61.19	33.44	31.33	45.27	47.98
	Average	69.06	77.17	67.68	55.21	82.97	28.99	59.78	67.73	70.68
	# subs > 60	70%	100%	70%	20%	90%	0%	60%	50%	70%
LBP	1	61.94	82.69	96.84	45.41	73.50	53.19	52.21	67.13	100.55
	2	75.27	75.98	83.13	45.42	64.49	14.73	48.18	65.87	89.53
	3	77.24	105.10	74.28	53.71	97.23	59.84	59.85	44.83	46.62
	4	99.25	80.34	58.26	102.98	87.29	44.63	42.77	57.71	63.17
	5	77.59	48.75	53.66	41.64	22.11	21.33	49.36	62.28	55.71
	6	58.45	80.84	45.31	59.95	89.00	20.58	25.96	55.66	38.04
	7	62.72	64.93	84.87	38.04	76.71	60.73	42.56	56.59	78.10
	Average	73.21	76.95	70.91	55.31	72.90	39.29	45.84	58.58	67.39
	# subs > 60	86%	86%	57%	14%	86%	14%	0%	43%	57%

Table 3.5: Maximum CRP of 5 strides for all subjects in all planes
Trunk-pelvic axial rotation where 70% of the HC subjects, and 57% subjects with LBP ran with a slightly more out-of-phase patterning (CRP > 60°). This same phenomenon presents in lumbar-trunk lateral bend with 90% HCs opting for a slightly more out-of-phase patterning versus 86% subjects with LBP. This pattern of maintaining an in-phase coordination pattern in the patient population is also apparent in the pelvic-lumbar rotations in all planes where more HCs seemed to run with slightly more out-of-phase patterns in lateral bend (HC: 60% vs. LBP: 0%) and axial rotation (HC: 70%, LBP: 57%). In flexion/extension on the other hand seems to go either way with about half of both groups either choosing an in-phase coordination pattern or an out-of-phase one.

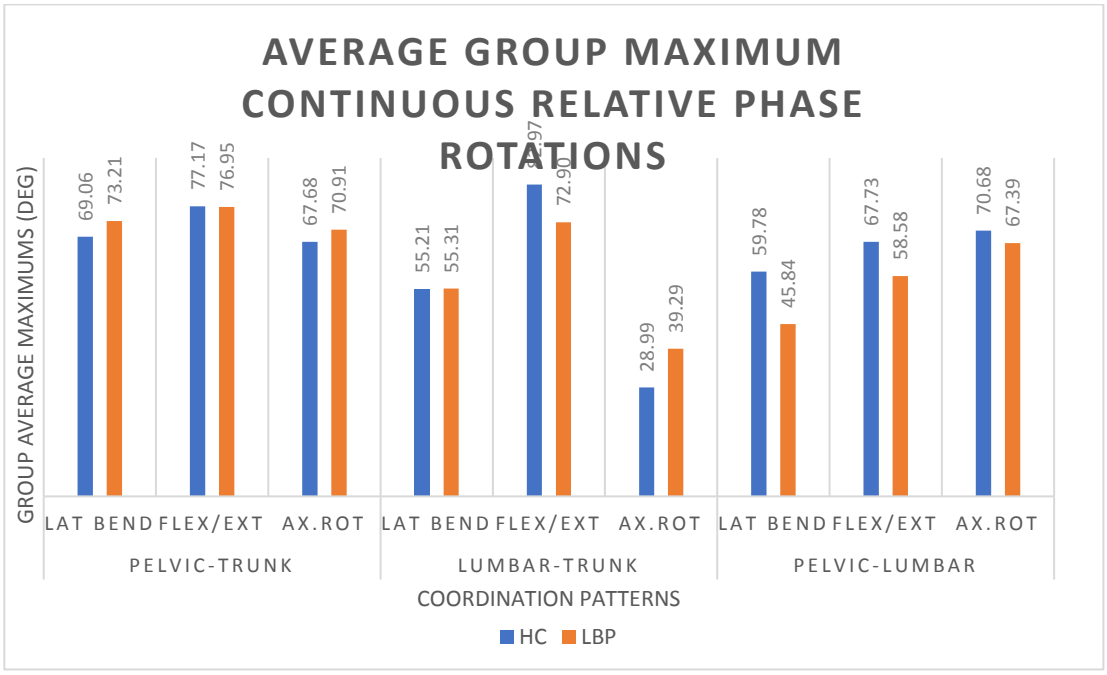


Figure 3.7 Average group maximum continuous relative phase rotations
Group average maximum rotations for CRP show that HCs run with rotations of 60°or greater on in pelvic-lumbar lateral bend and flexion/extension. Meanwhile, in these rotations, subjects with LBP tend to maintain rotations less than 60°. This shows a tendency in subjects with LBP to run with more in-phase pelvic-lumbar coordination patterns.

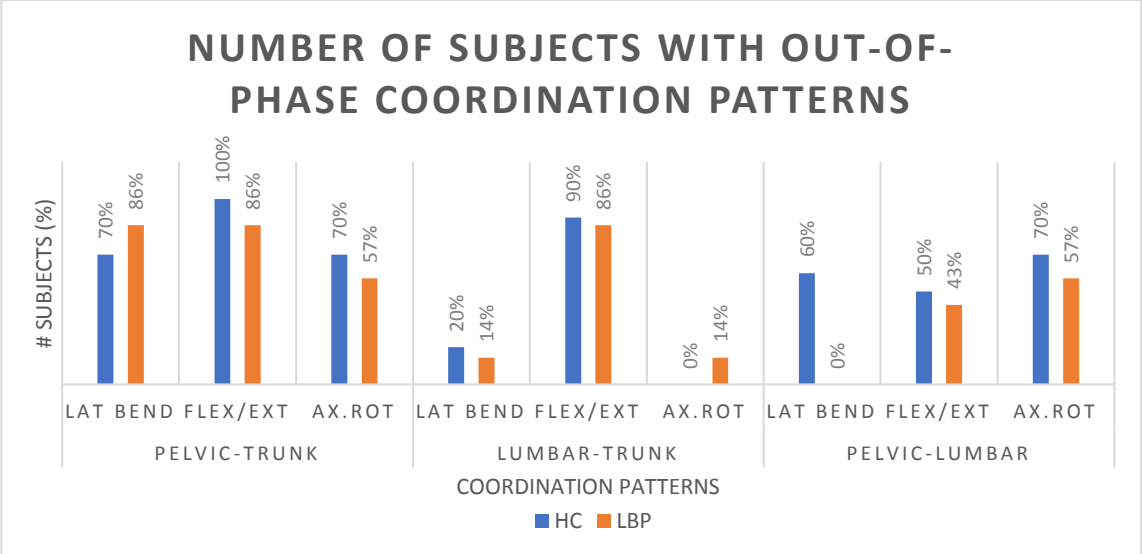


Figure 3.8 Group comparisons showing more out-of-phase coordination patterns
This chart shows the number of subjects in each group whose rotations tended towards an out-of-phase pattern (i.e.: > 60°). In pelvic-lumbar lateral bend, the majority of HCs maintain a more out-of-phase coordination pattern than subjects with LBP.

When these results are combined with MANOVA results in Table 3.5 we see that these do not correspond well with the statistical analysis. It seemed that maxima showed group differences in pelvic-lumbar lateral bend, however these results showed both insignificant group

differences ($p > 0.05$) and small effect sizes ($0.2 < ES < 0.5$). However, our max CRP results do give us a clue as to the origins of moderate and large effect sizes, but small insignificant p-values. It seems within healthy controls there are some subjects that maintain higher peak rotations than all other subjects. These rotations sometimes breaking beyond 100° in trunk-pelvic lateral bend and axial rotation, and pelvic-lumbar axial rotation. Other subjects maintain very low relative to group rotations in all planes of trunk-pelvic coordination. Dipping as low as 27° in trunk-pelvic lateral bend. In the LBP group we have more subjects whose rotation maximums above 100° than in our HCs. Our study expanded beyond those of Seay by including lumbar-trunk and lumbar-pelvic CRP and CRP variability. We only saw significant group differences in lumbar-trunk flexion/extension and pelvic-lumbar flexion extension CRP ($ES \geq 0.8$), while large ones were reported in lumbar-trunk lateral bend. ($0.5 < ES < 0.8$). Seay also found moderate effect sizes ($ES = 0.55$) between HC and subjects with LBP in trunk-pelvic lateral. However, since larger effect sizes were between lumbar-trunk in flexion/extension in this study, it is possible that Seay's exclusion of the lumbar region greatly influenced the effect sizes resulting in smaller effect sizes than what we reported. When creating the segment axes sensors which spanned the segment of interest were used (Figure 2.2). This allowed us more accurately capture movement in the individual segments.

Overall, significant group differences were seen in flexion/extension and axial rotation when looking at both MANOVA and CRP maximum results. These differences do not reside in our pelvic-trunk segments, but rather in lumbar-trunk and pelvic-lumbar coordination. Results from Table 3.3 show that in these planes and segments are where the largest difference between groups lie. In lumbar-trunk axial rotation subjects with LBP rotate on average 10° more out-of-phase than HCs (HC: 28.99° LBP: 39.29°). Max CRP results also revealed possible group differences in pelvic-lumbar lateral bend subjects with LBP rotated on average 14° more in-

phase than HCs (HC: 59.78°, LBP: 45.84). However, this trend was not confirmed in MANOVA results. Overall however, in flexion/extension in lumbar-trunk with an average of 10° in-phase (HC: 82.97°, LBP: 72.90°) and pelvic-lumbar with an average of 9° in-phase (HC: 67.73°, LBP: 58.58°). These higher averages may have been due to some subjects' higher rotations (lumbar-trunk lateral bend – HC: 107.39°; LBP: 97.23°).

As for CRP variability, we report no statistically significant differences between groups. In contrast, Seay only found statistically significant group differences in pelvic-trunk axial rotation CRP variability. Like Seay, however, we reported large effect sizes in pelvic-trunk lateral bend and flexion/extension, lumbar-trunk lateral bend and axial rotation and pelvic-lumbar axial rotation. These results also highlight the contribution of the lumbar region to group differences in CRP variability. Given the directionality of the effect size calculation, HCs run with less variability in all rotations, except pelvic-lumbar axial rotation where they have more variability than subjects with LBP. However, caution should be taken in interpreting these results as clinically significant. CRP variability is calculated as a standard deviation, and Cohen's method uses pooled standard deviation to calculate effect sizes. Therefore, the effect sizes of CRP variability are calculated as the group difference in pooled standard deviation of the CRP standard deviation (CRP variability). The circular nature of these calculations should be taken into consideration when interpreting the results.

3.4: Conclusions

CRP results from this study are well aligned previous research also documenting the effects of a history of LBP [23,33,42]. This study however, expanded to include lumbar coordination patterns. Differences in transverse planes were expected based on previous literature, especially when compared to Seay's RES group [23,42]. Seay reported that this group may present a transition group between HCs and those whose back pain is more recent [6]. These results add to the growing body of literature that views those with resolved back pain this way. This population is clinically

important to study because an incident of LBP significantly increases likelihood of developing another. Comparing those with resolved LBP to those with current LBP and HCs may help researchers discover which adaptive mechanics exist even after LBP has resolved that could lead to another instance of LBP.

Our CRP variability results did align fairly well with Seay's. The only exception is that Seay reported statistically significant group differences trunk-pelvis axial rotations ($p < 0.05$), where we saw no such differences. This may be due largely to differences in our subject populations. Like Seay, we also report moderate effect sizes in lateral bend and flexion/extension. Due to Seay's exclusion of the lumbar region, he could not determine the overall contribution of the lumbar region to these differences in variability. In this study however, we saw large and moderate effect sizes in rotations that included the lumbar segment. This suggests, that the lumbar region contributes to group differences in variability like it does in coordination patterns.

This research proves the importance of including the lumbar region in analysis of low back pain. While results align well with other studies that have been conducted in this area using this methodology, some of our significant results appeared in lumbar-trunk and pelvic-lumbar patterns. The lumbar region seems to contribute more to the phasing differences we see in populations than anticipated.

Chapter 4 : Conclusions, Limitations & Future Work

4.1: Conclusions

LBP is a costly, pervasive, recurring problem it is requires special attention. The high recurrence of LBP combined with its varied physiology and seemingly contradictory results from previous studies signals the need for new analysis methods that are better at characterizing LBP and can be used to identify factors that increase the likelihood of developing back pain.

A broad overview of current analysis methods such as gait parameters that look at walking velocity, cadence, single limb and double stance support phases, segment rotations and rotational amplitudes was given in the literature review seen in chapter 1[9,17]. This review showed that these studies do a great deal to help in characterize effects of LBP. However, they can be contradictory. This was especially true of studies that used rotational amplitudes [17,43]. When juxtaposed with the knowledge that future back pain is best predicted by previous back pain, we find that they are inadequate in helping elucidate why this is the case. In order to sufficiently understand the limitations of segment rotations and rotational amplitudes, the current study begun by looking at their accuracy their ability to differentiate two populations: those with a history of LBP and HCs.

Results from segment rotation and rotational amplitudes calculations aligned well with other studies that found that these methods were insensitive to population differences [24,34]. In this study, contribution of individual variation either added immensely to segment rotation ensemble average graphs, or were erased in the averaging process. This was particularly apparent when two stride overlays for all subjects were observed (Figure 2.5 and Figure 2.6). Lateral bend and axial rotation phase differences were lost in the ensemble graphs. While HCs showed similar phase patterning, there was an obvious difference in subjects with LBP who did not overlay in time as cleanly as HCs. Results from RA were no more conclusive.

When looking at results from RA (Table 2.3) we see the only RA with a significant group effect with small effect sizes in pelvic anterior-posterior tilt (sagittal plane rotation) ($p = 0.02$, ES = 0.42). Near significance, with small effect sizes in pelvic tilt (frontal plane rotation) ($p = 0.05$, ES = 0.35). The reasoning for this higher RA is difficult to determine. Especially when looking at

Figure 2.5 because it seems that just one subject may be contributing to this overall higher RA calculation. These results continue to support the idea that segment rotations and RA may not be sensitive enough to differentiate a population whose back pain has resolved from HCs.

Subjects with resolved LBP are of particular importance because they may be able to help parse out differences that can lead to a better understanding of why LBP is a recurring problem. While looking at this population, it is important to characterize the motion in not just adjoining segments but within the segment of interest. This is where this study was unique. Other studies either tested resolved, active LBP and HC but in two segments (trunk and pelvic) or active LBP and HC in three segments (trunk, lumbar and pelvic) [19,33,33,34]. This study addressed both resolved LBP and HC populations and looked at rotations in all three planes, in all three segments. This combined with the use of a new analysis method CRP and CRP variability sets it apart from others.

Results of our study aligned well with results from previous studies that indicated different coordination patterns were adopted by those whose back pain was resolved when compared to HCs. Moreover, moderate and large effect sizes were seen in other studies looking trunk and pelvic segments, appeared in our study but also in all coordination patterns between the trunk-lumbar and lumbar-pelvic. Again, indicating the importance of including the lumbar segment in calculations. Our study indicated that subjects rotated with more out-of-phase coordination patterns in lumbar-trunk axial rotations. A phenomenon that was confirmed by Seay

but in pelvic-trunk rotations. Our results also aligned with Seay when reporting more in-phase rotation patterns in lateral bend but again in pelvic-lumbar coordination instead of pelvic-trunk.

Overall, this study adds to the body of scientific literature that acknowledges the importance of studying a resolved population and the inclusion of the lumbar segment in relative phasing analysis methods. It also supports the movement away from traditional segment rotations for characterizing populations towards relative phasing and variability.

4.2 Limitations

The first and most obvious limitation in our study is the sample size. Seay had 36 subjects; 14 in each group. This may have contributed to the larger effect sizes that were seen in CRP and CRP variability. Additionally, CRP analysis has a major drawback that comes from the normalization method used. These normalization methods are necessary because they account for frequency differences in the signals. However, there may be information in these frequencies that we are lost due to the normalization.

4.3: Future Work

Future work in this area would include using other relative phasing methodologies and seeing how they compare to CRP. For instance, other studies have used Relative Fourier Phase [18,24,34]. They have also found differences in healthy and diseased populations, however to the author's knowledge they are yet to be used in those with a history of LBP.

Ideally a longitudinal study that tracks a cohort of subjects over time would be most beneficial. Such a study would be in a better position to investigate what adaptations occur prior to having LBP that put one at risk of developing LBP later. Due to the various causes of LBP, the cohort of subjects would need to be large enough to overcome confounding environmental factors such as occupations that require more lifting (e.g.: nurses, factory workers, etc.). These studies could also evaluate the effects of rehabilitation and rehabilitation methods on reducing recurrence of LBP. While this study and others shows the importance of focusing on motions in

all planes not just more affected ones, which exercises and rehabilitation methods these would be is still an open question.

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APPENDIX

Appendix 1: Data Collection sheet for Running Analysis Study

Trunk biomechanics in runners with and without history of low back pain

Subject number_____ Research Assistant name(s)_____

Equipment/forms needed

1. Screening form; completed; date_____
2. Consent form print/completed; date_____
    a. Assign subject number and place on consent forms
3. Demographic data collection form _____
4. PAR-Q questionnaire; date_____
5. Testing data collection form; indicate date of _____
6. Equipment needed
    a. Tight shorts and sports bra – subjects to bring with them
    b. Large goniometer
    c. Tape measure
    d. PAR-Q questionnaire (print)

Pain rating

Average back pain during past month _____

Present pain intensity (prior to start of the analysis) yes/no

if yes, subject disqualifies for the study

<u>Demographic Data</u>

Age:_____

Gender: Male, Female

Ethnicity: Hispanic or Latino, Non-Hispanic or non-Latino

Race:

- American Indian/Alaska Native,
- Asian,
- Black/African American,
- Native Hawaiian or Other Pacific Islander,
- White,
- Other

Body weight: (…….. lb) = (…….Kg) Body height: (….feet and….inch) = (……. m)

BMI (kg/m^2) =

Work status: Full time / Part time / Unemployed/homemaker

Heaviness of work load: Office (sedentary) / Light manual/ Heavy manual

Have you experienced any injury or pain in the past 2 years that may prevent you from running? Yes / no

Type of injury, how recent, and any PT:

_____

_____

_____

PAR-Q questionnaire_____

Clinical Tests:

Hip IR and ER with goniometer (prone)

IR: Right _____ Left _____
ER: Right _____ Left _____

Set up for EMG and motion analysis data collection
EMG

- Practice MVC tasks with subjects to familiarize (see instructions below)
- Wipe down skin with alcohol wipes for EMG electrode placement (see instructions for anatomical landmarks below)
- Mark skin for EMG landmarks
- Turn on the EMG electrodes of glut max and glut med prior to placing electrodes on the subject
- Place all EMG electrodes and secure with a tape
- Complete MVC test (see instructions below)

Electrode placement and test position: hold each for 3 seconds with 30 seconds rest per trial

Electro placement on body:

Channel 1 = R glut max Channel 2 = L glut max Channel 3 = R glut med
Channel 4 = L glut med Channel 5 = R erector spinae (ES) Channel 6 = L erector spinae
Channel 7 = R ext oblique (EO) Channel 8 = L ext oblique

Glut Max:

½ way between the base of the sacrum and the greater trochanter; mark the base of the sacrum and top of the greater trochanter. Measure the distance and place the electrode ½ way distance.

Glut Med:

½ way between the iliac crest and the greater trochanter; mark the top of iliac crest, measure the distance and place electrode ½ way.

Erector Spinae (ES):

3.5 cm lateral to L3 spinous process on each side; place your hands on the subject's iliac crest, which identifies the level of L4 (or between L4/L5), count SPs up to L3, mark L3 and mark 3.5 cm on each side.

Ext Oblique (EO):

(15 cm lateral to umbilicus) – anterior angle of the rib cage; mark the area with a pen

Maximum Voluntary Contraction:

Patient instructions: In this experiment, I will test your muscle force of hip and trunk

muscles, once muscle at a time. You will perform maximum muscle contraction 3 TIMES for each muscle. Remember you have to use your MAXIMUM FORCE. Do you have any questions or understand the test?

When I say go, please contract your muscle until I say stop. Commend: go, hold, hold, hold and relax

Repeat each test 3 times/muscle on each side of the body (provide 30 sec break between each contraction)

Glut Max: (standing 10 degrees of hip ext):

- Subject standing against table that is above the knee joint line. Have subject perform ~ 10 degrees of hip ext and then push leg into the table. Someone should hold the table or place a heavy chair against so it doesn't move. Patient must stand tall while performing hip ext and MVC (do not allow trunk lean forward). Can allow subject to bend their knee slightly but not 90 degrees of knee flexion.

Glut Med: (standing 20 degrees of hip abd):

- Subject standing against table that is at the level between mid-thigh and knee joint line. Have subject perform ~ 20 degrees of hip abduction and then push leg into the table. Someone should hold the table or place a heavy chair against so it doesn't move. Patient must stand tall while performing hip abd and MVC (do not allow the subject to lean to the side).

ES: (in prone position)

- Superman isometric exercise on a table in the prone position. Have the subject lift their upper body / sternum off the table while resisting maximally at mid-back for 6 seconds; repeat 3 times. Place strap/belt around the feet to stabilize feet or have someone hold down subject's feet. We are testing and recording both ES muscle data simultaneously.

EO: (in supine position)

- Subject supine, bring right shoulder toward left knee (to test R EO), resist in diagonal direction for 6 sections; repeat 3 times; test opposite side

Data collection for MVC analysis:
Subject ID: _____ Date_____
Tester_____

EMG channel: Place Check mark beside each after the 3 trials
1= R glut Max___ 2= L glut max___ 3 = R glut med___ 4 = L glut med___
5 = R ES___ 6 = L ES___ 7 = R EO___ 8 = L EO

Comments
_____
_____

_____
_____

Motion analysis

- Cover shoes with tape
- Cover reflective areas of the shorts
- Place reflective markers (see instructions for landmarks below)
- Secure markers with tape (if needed)

Marker Placements *=Bilaterally placed marker
39 total

- Heel* @ level of 2nd MTP
- 2nd MTP*
- 5th MTP*
- Lateral Ankle*
- Calcaneus (round lat aspect of heel of shoe)*
- Medial MTP*
- Medial Ankle*
- Lat Lower shank (2/3 below patella)*
- Mid shank (1/3 below patella)*
- Lateral knee*
- Medial knee*
- Lower anterior thigh (1/3 above patella)*
- Lat aspect of mid-thigh (2/3 above patella)*
- Greater Troch*
- ASIS*
- PSIS*
- Sacral Base
- Mid Clavicle
- Xiphoid
- C7 SP
- T10 SP
- Anterior AC join

Motion analysis system

- **Calibration Pose**
  - Do Right and Left Static Marker set with the Frame
    - Stand with designated foot (right side first, then flip the frame to the other side and do left side), back and to the edge of the frame. Fold arms across belly to not interfere with the markers
  - Remove Medial MTP, Ankle, and Patella markers and do Dynamic set
    - Stand in the middle of the force plate with arms across belly

- **Trunk ROM**
  - Instruct the subject to perform trunk motion (3 times each) on the force plate. Use a researcher to stabilize pelvis if needed (check off once complete) _____
    - Flexion
    - Ext
    - Right SB
    - Left SB
    - Right Rot
    - Left Rot
    - Combined motions:
      - R SB and R rot
      - R SB and L rot
      - L SB and L rot
      - L SB and R rot

Set up the treadmill

- **Running-Instructions to subject**
- Now we are going to have you run on the treadmill. Use the next two to five minutes as a warm up to get use to the treadmill and to get to your self-paced speed. Run at a normal pace that is comfortable to you, do not worry about the speed just have it feel comfortable. Let us know when you are at the self-paced speed that you want and then do not adjust the speed any. Continue running for an additional three to five minutes and we will collect data at some point during this time. During the running portion we ask that you please refrain from talking as it can interfere with data collection. We will instruct you on anything else that may need done. After we say stop you can perform a cool down period as needed.

- **Testers To Dos**
  - Instruct subject on how to use the treadmill
  - Have patient perform 5 min of warm up as s/he attempts to reach their self-select comfortable daily running speed
- **Pain intensity during running or testing** yes/no rating (0-10 scale) _____
  Are you experiencing any pain now? (ask during warmup period)

- Do not allow the subject to view running speed on the monitor
- Do not allow the subject to speak during the run
- Start data collection once the subject reaches their self-pace speed without informing the subject about data collection
- Collect data for 1 min
- Have the subject run additional 1-2 minutes and also walk for few additional minutes, if they desire

- **Pain intensity post testing** yes/no rating (0-10 scale) _____

  Are you experiencing any pain now? (ask after running)

  - Obtain subject's speed from the monitor_____

Comments related to kinematics

_____

_____

_____

_____

Post test

- Review any questions the subject may have and thank them for their participation
- Clean and put treadmill and anything else away
- Clean up markers/ re-tape
- Place subjects data sheet and all other sheets in a file for storage

Appendix 2: Screening Form

Thank you for your interest in our running study! Let me give you a little more information and ask you a few questions to see if you are qualified based on your responses. If you do not wish to answer or participate you are free to do so at any time, and we will withdraw you from the study. This will in no way affect your standings with the University of Kansas Medical Center.
We are conducting a study to understand how joint motions occur and muscle forces act on the trunk while running, and to learn if there is a difference in healthy runners and runners with low back pain. We will place a number of markers throughout your body to detect joint movements and EMG electrodes to detect muscle forces; none of this should cause any pain. Then you will perform a few simple motions of the back and muscle contraction of the trunk against a force. After that you will be asked to complete a short run on a treadmill at a self-selected pace. This will take place during one visit and will take between an hour and twenty minutes to two hours.

If you would please answer the following questions and email your responses back to me, we can determine your eligibility to participate in the study.

1. What is your age? _____ Gender: _____

2. Do you run at least 20 km (~12 miles)/week?
   Yes / no

3. Do you feel comfortable running on a treadmill?
   Yes / no

4. Can you read and understand English language?
   Yes / no

5. Do you have a structural back deformity?
   Yes / no

6. Do you have any other injuries that may prevent you from running such as recent ankle sprain, knee or hip pain?
   Yes / no

7. Have you had any surgeries?
   Yes / no_____

   _____

8. Do you have a history of low back pain or have you been diagnosed with low back pain from a health professional within the last year?
   Yes / no
   List any specific diagnosis:

9. Do you currently experience low back pain and if so, what is the pain on a 0-10 scale where 0=no pain and 10=worse pain imagined:
   Yes/no; If yes, rate your pain on 0-10 pain scale: _____
   About how long have you experienced current low back pain? _____

10. Do you experience pain during running?
    Yes / no

11. Have you had any previous physical therapy treatment for low back pain within the last 3 months?
    Yes / no

12. Do you have a neurological condition (i.e. stroke)?
    Yes / no

13. Do you have a heart condition?
    Yes / no

14. Do you have uncontrolled diabetes?
    Yes / no

15. Do you have uncontrolled high blood pressure?
    Yes / no

16. Are you currently pregnant?
    Yes / no

Thanks again for your interest in our study. After I review your responses, I will be in touch with you and we will go from there.

Appendix 3: Research Consent form

Title: Trunk biomechanics in runners with and without history of low back pain

Protocol # N/A

You are being asked to join a research study. You are being asked to take part in this study because you are considered a long distance runner who is either healthy or has low back pain. You do not have to participate in this research study. The main purpose of research is to create new knowledge for the benefit of future patients and society in general. Research studies may or may not benefit the people who participate.

Research is voluntary, and you may change your mind at any time. There will be no penalty to you if you decide not to participate, or if you start the study and decide to stop early. Either way, you can still get medical care and services at the University of Kansas Medical Center (KUMC).

This consent form explains what you have to do if you are in the study. It also describes the possible risks and benefits. Please read the form carefully and ask as many questions as you need to, before deciding about this research.

You can ask questions now or anytime during the study. The researchers will tell you if they receive any new information that might cause you to change your mind about participating.

This research study will take place at the University of Kansas Medical Center (KUMC) with Neena Sharma PT PhD and Janice Louden PT PhD as the researchers.

BACKGROUND

Running is a popular exercise for many individuals. Unfortunately, running athletes often times experience various forms of injury. Low back pain is a common injury complaint that can be caused by many different factors. Motions of the legs and feet during running have been studied before. But there has not been much research on trunk motion (for example, slight trunk bend and side to side rotation during running) and its relation to pain or injury. About 20 people will be in the study at KUMC, 10 healthy and 10 with history of low back pain.

PURPOSE

By doing this study, researchers hope to learn
1. How motions of the leg and trunk joints occur during running.
2. How muscle forces from the hips and trunk muscle occur during running.
3. if there is a difference between the joint motions or muscle forces of healthy

runners and runners with low back pain.

PROCEDURES

If you are eligible and decide to participate in this study, your participation will last approximately 2 and 1⁄2 hours. The study will take place at the Human Performance Laboratory (HPL) on the first floor of the Landon Center on Aging building, located at 3901 Rainbow Boulevard, Kansas City, KS 66160. Some data may be collected in Clinical Orthopedic Research and Rehabilitation (CORR) lab at KUMC. Your participation will involve answering few questions and filling out one questionnaire related to pain, activity level and running habits. It may take 20 minutes to answer these questions and fill out the questionnaire. We will assess motion of your hips and trunk and joint measurements of your legs and trunk. We will record your trunk and hip muscles while you run.

You will be asked to change into the proper testing clothing, and testing will begin with measurement of range of motion measurements of the trunk and legs. Proper clothing includes wearing spandex shorts and no shirts for males and shorts and sports bra for females. You will need to bring your own proper clothing for testing. The proper clothing is required to place markers and EMG electrodes. You do not have to wear these clothes and participate in this study. Standard joint markers will be placed on your ankles, knees, hips, and trunks to detect joint motions during running. Electromyography (EMG) electrodes (sticky pads) will be placed on your hip and trunk muscles to detect muscle activity. Also for EMG, you will be asked to perform a series of individual muscle contractions. This will include six seconds of maximal holds for each muscle tested. You will then perform various range of motion activities using the motion capture system. Next you will run on a treadmill at a pace you feel comfortable for about five to eight minutes. This includes a couple minutes to warm up to become comfortable with the treadmill, testing time, and cool down.

RISKS

1. Physical risk: You may experience fatigue, sweating, and breathlessness due to running on the treadmill. You may experience muscle soreness the following day due to the running. Surface EMG is a standard and safe technique to record muscle activity but it may cause skin irritation. These risks are minimal. There may be other risks of the study that are not yet known.
2. You might be embarrassed by the proper clothing necessary for the testing. Males will be wearing spandex shorts and no shirt. Females will be wearing spandex shorts and a sports bra. You may choose not to hear these clothes and not to participate in the study.

NEW FINDINGS STATEMENT

You will be told about anything new that might change your decision to be in this study. You may be asked to sign a new consent form if this occurs.

BENEFITS Individual

You will not benefit from this study.

Societal Benefits

The results from this study will help us understand the trunk motions and muscle activation pattern in runners with and without back pain. Researchers hope that the information from this study may be useful in developing potential treatment or prevention plans for runners with or at risk for low back pain.

ALTERNATIVES

Participation in this study is voluntary. Deciding not to participate will have no effect on the care or services you receive at the University of Kansas Medical Center. At any time you can choose not to be in this study.

COSTS

There is no cost for being in the study.

PAYMENT TO SUBJECTS

There is no payment for this study.

IN THE EVENT OF INJURY

If you experience harm or other problem during this study, you should immediately contact Dr. Neena Sharma at 913-588-4566. If it is after 5:00 p.m., a holiday or a weekend, you should call the emergency room.

If you have a bodily injury as a result of participating in this study, treatment will be provided for you at the usual charge. Treatment may include first aid, emergency care and follow-up care, as needed. Claims will be submitted to your health insurance policy, your government program, or other third party, but you will be billed for the costs that are not covered by the insurance. You do not give up any legal rights by signing this form.

INSTITUTIONAL DISCLAIMER STATEMENT

If you think you have been harmed as a result of participating in research at the University of Kansas Medical Center (KUMC), you should contact the Director, Human Research Protection Program, Mail Stop #1032, University of Kansas Medical Center, 3901 Rainbow Blvd., Kansas City, KS 66160. Under certain conditions, Kansas state law or the Kansas Tort Claims Act may allow for payment to persons who are injured in research at KUMC.

CONFIDENTIALITY AND PRIVACY

Your health information is protected by a federal privacy law called HIPAA. By signing this consent form, you are giving permission for KUMC to use and share your health information. If you decide not to sign the form, you cannot be in the study.

The researchers will only use and share information that is needed for the study. To do the study, they will collect health information from the study activities. You may be identified by information such as name, address, phone, date of birth, social security number, or other identifiers. Your health information will be used at KUMC by Dr. Neena Sharma, members of the research team, The University of Kansas Hospital Medical Record Department, the KUMC Research Institute and officials at KUMC who oversee research, including members of the KUMC Human Subjects Committee and other committees and offices that review and monitor research studies.

By signing this form, you are giving Dr. Neena Sharma and the research team permission to share information about you with persons or groups outside KUMC. Your information will be shared with U.S. agencies that oversee human research (if a study audit is performed). These groups or agencies may make copies of study records for audit purposes. The purpose for using and sharing your information is to make sure the study is done properly and to evaluate the safety and effectiveness of the study.

The HIPAA privacy law may not apply to everyone who receives your health information. Your information might not be protected by HIPAA if persons outside KUMC disclose it. In some cases, there may be other laws that protect your information from improper use.

Your permission to use and share your health information will not expire unless you cancel it. Any research information that is placed in your medical record will be kept indefinitely.

While you are participating in this study, you may see and copy any study information that is placed in your KUMC medical record. However, some study information is kept only by the researcher. The records kept only by the researcher may not be available to you until the end of the study.

The researchers may publish the results of the study. If they do, they will only discuss group results. Your name will not be used in any publication or presentation about the study.

QUESTIONS

Before you sign this form Dr. Neena Sharma or other members of the study team should answer all your questions. You can talk to the researchers if you have any more questions, suggestions, concerns or complaints after signing this form. If you have any questions about your rights as a research subject, or if you want to talk with someone who is not involved in the study, you may call the Human Subjects Committee at (913)

588-1240. You may also write the Human Subjects Committee at Mail Stop #1032, University of Kansas Medical Center, 3901 Rainbow Blvd., Kansas City, KS 66160.

SUBJECT RIGHTS AND WITHDRAWAL FROM THE STUDY

You may stop being in the study at any time. Your decision to stop will not prevent you from getting treatment or services at KUMC. The entire study may be discontinued for any reason without consent by the investigator conducting the study.

You have the right to cancel your permission for researchers to use your health information. If you want to cancel your permission, please write to Dr. Neena Sharma. The mailing address is Dr. Neena Sharma, University of Kansas Medical Center, 3901 Rainbow Boulevard, Mail Stop 2002, Kansas City, KS 66160. If you cancel permission to use your health information, you will be withdrawn from the study. The research team will stop collecting any additional information about you. The research team may use and share information that was gathered before they received your cancellation.

CONSENT

Dr. Neena Sharma or the research team has given you information about this research study. They have explained what will be done and how long it will take. They explained any inconvenience, discomfort or risks that may be experienced during this study.

By signing this form, you say that you freely and voluntarily consent to participate in this research study. You have read the information and had your questions answered. ***You will be given a signed copy of the consent form to keep for your records.***

_____ Print Participant's Name

_____ _____ _____
Signature of Participant Time Date

_____

_____ Print Name of Person Obtaining Consent

_____ Signature of Person Obtaining Consent

_____ Date

OPTIONAL STORAGE OF DATA FOR FUTURE USE

You are being asked to allow storage of the information collected for this study, to be used in future research in healthy or clinical populations. If you agree, we will keep the information you provided for this study in a secure database. Only authorized persons will have access to the information. The information may be kept indefinitely.

Your information might be combined with results from our other studies to learn more about low back pain. It might also be shared with other researchers who are studying similar topics. If we share your study information with other researchers, we will remove any items that directly identify you.

The explanation about uses and disclosures of your personal information in the main study also applies to the information saved for future research. Giving permission to store your study information is entirely optional. You can still be in the main study even if you decide not to provide your information for future research.

No additional risks are expected from research being conducted on your information because confidentiality will be protected. You will not directly benefit from the future research, but it may help researchers learn more about their study.

If you say yes to storing your study information and change your mind later, please contact the study team at the address listed in the main consent form. They will stop using your information at that time.

Please mark your choice "Yes" or "No" below. If you have any questions you can talk to Dr. Neena Sharma or the study team.

☐ **Yes, I agree** to allow Dr. Neena Sharma to store my study information for future research

☐ **No, I do not agree** to allow Dr. Neena Sharma to store my study information for future research

_____

_____ Print Participant's Name

_____ Signature of Participant

_____ Print Name of Person Obtaining Consent

_____ Signature of Person Obtaining Consent

_____ _____ Time Date

_____ Date

Appendix 4: Physical Activity and Readiness Questionnaire (PAR-Q)

Physical Activity Readiness
Questionnaire - PAR-Q
(revised 2002)

PAR-Q & YOU

(A Questionnaire for People Aged 15 to 69)

Regular physical activity is fun and healthy, and increasingly more people are starting to become more active every day. Being more active is very safe for most people. However, some people should check with their doctor before they start becoming much more physically active.

If you are planning to become much more physically active than you are now, start by answering the seven questions in the box below. If you are between the ages of 15 and 69, the PAR-Q will tell you if you should check with your doctor before you start. If you are over 69 years of age, and you are not used to being very active, check with your doctor.

Common sense is your best guide when you answer these questions. Please read the questions carefully and answer each one honestly: check YES or NO.

YES	NO	
☐	☐	**1. Has your doctor ever said that you have a heart condition <u>and</u> that you should only do physical activity recommended by a doctor?**
☐	☐	**2. Do you feel pain in your chest when you do physical activity?**
☐	☐	**3. In the past month, have you had chest pain when you were not doing physical activity?**
☐	☐	**4. Do you lose your balance because of dizziness or do you ever lose consciousness?**
☐	☐	**5. Do you have a bone or joint problem (for example, back, knee or hip) that could be made worse by a change in your physical activity?**
☐	☐	**6. Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition?**
☐	☐	**7. Do you know of <u>any other reason</u> why you should not do physical activity?**

If you answered

YES to one or more questions

Talk with your doctor by phone or in person BEFORE you start becoming much more physically active or BEFORE you have a fitness appraisal. Tell your doctor about the PAR-Q and which questions you answered YES.

- You may be able to do any activity you want — as long as you start slowly and build up gradually. Or, you may need to restrict your activities to those which are safe for you. Talk with your doctor about the kinds of activities you wish to participate in and follow his/her advice.
- Find out which community programs are safe and helpful for you.

NO to all questions

If you answered NO honestly to <u>all</u> PAR-Q questions, you can be reasonably sure that you can:

- start becoming much more physically active – begin slowly and build up gradually. This is the safest and easiest way to go.
- take part in a fitness appraisal – this is an excellent way to determine your basic fitness so that you can plan the best way for you to live actively. It is also highly recommended that you have your blood pressure evaluated. If your reading is over 144/94, talk with your doctor before you start becoming much more physically active.

DELAY BECOMING MUCH MORE ACTIVE:

- if you are not feeling well because of a temporary illness such as a cold or a fever – wait until you feel better; or
- if you are or may be pregnant – talk to your doctor before you start becoming more active.

PLEASE NOTE: If your health changes so that you then answer YES to any of the above questions, tell your fitness or health professional. Ask whether you should change your physical activity plan.

<u>Informed Use of the PAR-Q</u>: The Canadian Society for Exercise Physiology, Health Canada, and their agents assume no liability for persons who undertake physical activity, and if in doubt after completing this questionnaire, consult your doctor prior to physical activity.

No changes permitted. You are encouraged to photocopy the PAR-Q but only if you use the entire form.

NOTE: If the PAR-Q is being given to a person before he or she participates in a physical activity program or a fitness appraisal, this section may be used for legal or administrative purposes.

"I have read, understood and completed this questionnaire. Any questions I had were answered to my full satisfaction."

NAME _____

SIGNATURE _____ DATE _____

SIGNATURE OF PARENT _____ WITNESS _____
or GUARDIAN (for participants under the age of majority)

Note: This physical activity clearance is valid for a maximum of 12 months from the date it is completed and becomes invalid if your condition changes so that you would answer YES to any of the seven questions.

© Canadian Society for Exercise Physiology www.csep.ca/forms

Appendix 5: Research Protocol

University of Kansas Medical Center
Research Protocol Involving Human Subjects

Version date: 4/19/2015

Principal Investigator: Neena Sharma

Study Title: Trunk biomechanics in runners with and without history of low back pain

Co- Investigator(s): Janice Loudon

Purpose, Background and Significance

A. Aim and Hypotheses

The goal of this pilot project is to understand spinal kinematics in the long distance runners with and without a history of self-reported low back pain (LBP). Although LBP is not a common primary injury in runners, when it does occur it can be devastating and prevent the runner from continuing training. Additionally, there is evidence that LBP can alter functional ability and increase the risk of lower extremity injury which is common in the long distance runner. (Zazulak BT et al.; Hammill et al., 2008)

Aim 1. Examine pelvic and spinal biomechanics in healthy runners.
Hypothesis 1 – Healthy long distance runners will display a consistent kinematic pattern of the trunk during running.

Aim 2. Examine pelvic and spine biomechanics in runners with history of back pain.
Hypothesis 2 – Long distance runners with a history of low back pain will display a variety of kinematic patterns.

Aim 3. Compare pelvic and trunk kinematic patterns between long distance runners with and without history of low back pain.
Hypothesis 3 – Long distance runners with a history of low back pain will display a varied kinematic pattern of the trunk that is different than the healthy runner.

EMG data of trunk and pelvic muscles will be collected and used as secondary and exploratory outcome measures to understand/complement kinematic results and to guide future studies related to therapeutic intervention improving muscle strength or targeting motor control strategies.

Background and Significance

Running is a popular exercise modality for many individuals of all ages. Unfortunately, running athletes, especially long-distance runners, are commonly afflicted with various injuries. (Taunton et al) Although not the most common area for injury complaint, low back pain (LBP) can range from severe problems, such as disc injury, stress fractures or arthritis, to mild problems, such as muscle strains. On average, spine or pelvic injury rate is 3%-11% of total injuries in long distance runners. (Taunton et al.) Several risk factors have been suggested in the literature as causative (Ferber & Kendall, 2009, Powers, 2010). Excessive faulty pelvic motion has been suggested to contribute to lower leg pain

(Loudon & Reiman, 2012). Prospective clinical studies have linked LBP history with lower extremity injuries, and a history of lower extremity injury with LBP. Zazulak and colleagues found that a history of LBP was a significant predictor of knee injury in both female athletes and knee ligament injury in male athletes. Chronic LBP or history of LBP is usually defined as 6 months of continuous or intermittent LBP within the past 2 years. Identifying excessive or lack of trunk motion would be helpful for the physical therapist in order to focus treatment on this impairment and perhaps minimize injury.

Knowledge Gap (Aim 1) What is the typical 3-demintion (3d) trunk kinematic pattern in long distance runners while running?

Very little research has been generated on the 3d kinematics of the long distance runners. A study published in 1998 describes kinematics of the pelvis during running, but little information is given related to the number of subjects and sex of the study subjects. (Novacheck, 1998) A year later, a review was published that included the lumbar spine, but once again little detail on the subjects used for the analysis were given. (Schache et al.) We need to determine typical kinematics before we can compare to runners with LBP.

Knowledge Gap (Aim 2) Is there a varied trunk kinematic pattern that occurs in runners with a history of low back pain?

Trunk muscle function is altered in LBP sufferers. (Hammill) As a result, these individuals may not be able to produce sufficient pelvic stability to provide a stable base for lower extremity motion and control. Proximal alterations in the operation of this kinetic chain linkage may increase injury risk at more distal regions. This relationship between LBP and altered lower extremity movement control has been observed in several studies. (Haddas et al, Van Dillen) Whether this pattern continues when pain is absent needs to be determined. The other question is whether the varied trunk kinematics are a cause or result of the LBP.

Knowledge Gap (Aim 3) Is there a difference between trunk kinematics in runners with and without low back pain?

Low back pain is associated with kinematic and kinetic alterations that can increase the risk of lower extremity injury, particularly in the presence of fatigue. Patients with LBP have diminished lower extremity strength, flexibility, and range of motion, (VanDillen) as well as altered lower extremity biomechanics and neuromuscular control. (Shum) These changes may increase lower extremity injury risk. No studies to date have addressed trunk kinematics in runners with LBP.

II. Research Plan and Design

A. Study Objectives:

The long-range goal of this project is to determine effective treatment methods to optimize running performance in people with LBP and eventually prevent further episodes of LBP injuries or injuries to lower extremity joints (i.e. knee injuries) in long distance runners. The objective of this study is to understand the difference in kinematics and muscle forces activing on trunk during running between long distance runners with and without a history of LBP.

The first specific aim is to identify the typical 3d (3-dimension) trunk kinematic pattern in long distance runners while running.

The second specific aim is to determine if there is a varied trunk kinematic pattern in runners with a history of LBP.

The third specific aim is to determine if there a difference between trunk kinematics in runners with and without low back pain.

B. Study Type and Design: This study is a cross-sectional non-interventional study.

To accomplish Aim 1,2,3, it is necessary to measure 3d trunk kinematics during running on a treadmill. Reflective markers will be placed on legs and trunks at specific anatomical landmarks to measure ankle, knee, hip, pelvic and trunk motion. As secondary measures we will collect clinical outcomes and muscle recording of the following muscles: Gluteus medius and maximus, erector spinae and external oblique- bilaterally. EMG recording will be collected for hip and trunk muscles with surface EMG.

C. Sample size, statistical methods, and power calculation:

Since it is a pilot study, we will collect data on 20 subjects (10 healthy and 10 with LBP) and then conduct a power analysis to determine the sample size for future studies of large scale.

D. Subject Criteria (See Vulnerable Populations appendix, if applicable)

Inclusion criteria:

- Gender and age: females or males between the age of 20 – 40 years
- Running history: run at least 20 km (~12 miles)/week
- Comfortable running on a treadmill
- Speaks and reads English
- LBP subjects:
    - History of LBP diagnosis (by a health care professional and/or reported by the subject). Subjects with Spondylolisthesis of grade I are eligible, as reported by the subject
    - LBP injury defined as LBP that caused an alternation in the runner's training schedule, as reported by the subject
- Healthy subjects:
    - Matched group with age (± 2 years), gender and training/week (± 4 km) history

Exclusion Criteria:

- Presence of current LBP > 2 on 0-10 pain scale (where 0=no pain and 10=worse pain imagined) at rest or during daily activities
- Presence of LBP during running
- History of back or LE surgery
- Neurological impairment
- Previous treatment of physical therapy for low back pain (within past 3 months)
- Current pregnancy
- Structural back deformity i.e. scoliosis or diagnosis of >grade I spondylolisthesis
- "yes" on PAR-Q questionnaire

Withdrawal/Termination criteria: If the subject cannot complete data collection he/she will be terminated from the study. Subjects can voluntarily withdraw before completion of collection. Subjects who cannot be reached for scheduling of data collection will be withdrawn from the study.

E. Specific methods and techniques used throughout the study:

1. Study Procedures:
   - Treadmill Running Trials (Performed at the Human Performance Laboratory; HPL): Subjects will run at self-selected pace on the WOODWAY treadmill while kinematics (Raptor-E Digital cameras, Motion Analysis Inc., Santa Rosa, CA) of movement and EMG of muscles are collected. Subjects will run for approximately five-8 minutes. Half-way through the run, kinematic and EMG data will be collected for approximately one minute.

F. Risk/benefit assessment:

1. Physical risk: Subjects may experience fatigue, sweating, and breathlessness due to running on the treadmill. Subjects may experience muscle soreness the following day due to the running. Surface EMG is a standard and safe technique to record muscle activity but it may cause muscle soreness or skin irritation. These risks are minimal.
2. Psychological risk: None
3. Social risk: None
4. Economic risk: None
5. Benefit of participating in the study: The results from this study will help us understand the trunk biomechanics and muscle activation pattern in runners with and without back pain.

F. Location where study will be performed: All testing will be performed at the Human Performance Laboratory (HPL) on the first floor of the Landon Center on Aging building, located at 3901 Rainbow Boulevard, Kansas City, KS 66160. Protected health information will be stored in a locked file cabinet in the Human Performance Lab (HPL) and Clinical Research and Rehabilitation (CORR) lab that is accessible only by study personnel. All data related to study measures will be collected by study personnel and stored on secure servers within the HPL at the Landon Center on Aging and CORR lab on the KUMC campus. All data will be encoded by a study-specified patient number

while the patient's identifying information will be locked and stored in a separate location within the CORR lab.

G. Collaboration (with another institution, if applicable): Dr. Janice Loudon, Associate Professor from Rockhurst University, Kansas City, MO will be collaborating on this project.

H. Personnel who will conduct the study, including:

1. Present during study procedure(s) and their proximity during the study:

   Primary Investigator: Neena Sharma

   Co-investigator: Janice Loudon

   Research Associates; Jessie Huisinga, PhD; Adam Bruetsch

   Research Assistants: Anne Schwartz; Nathan Vogel; Jordan Umscheid; Caleb Laird; Avery Clifton; Kathryn Brown; Abby Larson; Kaylah Williamson (students)

   Determining eligibility:

   a. Obtaining informed consent: Neena Sharma, Anne Schwartz; Nathan Vogel; Jordan Umscheid; Caleb Laird; Avery Clifton; Kathryn Brown; Abby Larson; Kaylah Williamson
   b. Providing on-going information to the study sponsor and the IRB: Neena Sharma
   c. Maintaining participant's research records: Neena Sharma; Jessie Huisinga; Adam Bruetsch
   d. Completing physical examination: Neena Sharma, Janice Loudon, Anne Schwartz; Nathan Vogel; Jordan Umscheid; Caleb Laird; Avery Clifton; Kathryn Brown; Abby Larson; Kaylah Williamson
   e. Taking vital signs, height, weight: Neena Sharma, Janice Loudon, Anne Schwartz; Nathan Vogel; Jordan Umscheid; Caleb Laird; Avery Clifton; Kathryn Brown; Abby Larson; Kaylah Williamson
   f. Drawing / collecting laboratory specimens: N/A
   g. Performing / conducting tests, procedures, interventions, questionnaires: Neena Sharma, Janice Loudon, Jessie Huisinga, Adam Bruetsch, Anne Schwartz; Nathan Vogel; Jordan Umscheid;

Caleb Laird; Avery Clifton; Kathryn Brown; Abby Larson; Kaylah Williamson

h. Completing study data forms: Neena Sharma, Janice Loudon, Jessie Huisinga, Adam Bruetsch, Anne Schwartz; Nathan Vogel; Jordan Umscheid; Caleb Laird; Avery Clifton; Kathryn Brown; Abby Larson; Kaylah Williamson
i. Managing study database: Neena Sharma, Jussie Huisinga, Adam Bruetsch

J. Assessment of Subject Safety and Development of a Data and Safety Monitoring Plan - This study proposal had no more than minimal risk.

III. Subject Participation

A. Recruitment: Study participants will be recruited through social media (posting of IRB approved flyer on Facebook and Craigslist), advertisement at KUMC, local fitness centers, and local specialty running stores.

B. Screening Interview/Questionnaire: Study personnel will conduct the screening interview and will ask questions outlined in the attached document titled “Subject recruitment questions”.

C. Informed consent process and timing of obtaining of consent: For potential runner subjects with and without LBP, the determination of subjects’ eligibility into the study will be completed. Subjects will be asked to verbally provide authorization to allow the research team to determine their eligibility for this study (See attached screening form). After determining subject’s eligibility, informed consent will be obtained prior to data collection. Informed consent form will be presented by study personnel once the subject meets the study criteria and agrees to participate in the study. Subjects will have time to review the consent form and ask questions to the study personnel at this time. The participant will review the study protocol, have any questions answered and discuss the consent form with study personnel prior to signing. The consenting interview will take place in a private room at CORR lab or at a private table within the large laboratory areas at HPL. If the subject signs the consent, then they will be enrolled in the study and contacted to schedule a day/time to complete the study procedures in the CORR lab and the HPL.

If non-English speaking persons will be enrolled, state the informed consent process for enrolling the subjects, including who will conduct the consent interview, use of interpreters, translated documents, etc.: Non-English speakers will not be enrolled due to the required questionnaires being employed in the study.

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D. Alternatives to Participation: There are no alternatives to participation

E. Costs to Subjects: There will be no costs to the subjects for participation

F. How new information will be conveyed to the study subject and how it will be documented: Any new information will be conveyed to the study subject via phone calls.

G. Payment, Payment for a research-related injury: N/A

IV. Data Collection and Protection

A. Data Management and Security: Protected health information will be stored in a locked file cabinet in the Human Performance Lab (HPL) or in the CORR lab that is accessible only by study personnel. All data related to study measures (standing and walking) will be collected by study personnel and stored on secure servers within the HPL at the Landon Center on Aging or CORR lab on the KUMC campus. All data will be encoded by a study-specified patient number while the patient's identifying information will be locked and stored in a separate location within the HPL.

B. Sample / Specimen Collection: N/A

C. Tissue Banking Considerations: N/A

D. Procedures to protect subject confidentiality: All data will be de-identified.

E. Quality Assurance and Monitoring:

V. Data Analysis and Reporting

A. Statistical and Data Analysis:

Aim 1. To examine pelvic and spinal biomechanics in healthy runners
Descriptive statistics (i.e. mean, standard deviation, frequency measures) and patterns of consistency/inconsistency of kinematics across all healthy participants will be examined.

Aim 2. To examine pelvic and spine biomechanics in runners with history of back pain
Descriptive statistics (i.e. mean, standard deviation, frequency measures) and patterns of consistency/inconsistency of kinematics across all LBP participants will be examined.

Aim 3. Compare pelvic and trunk kinematic patterns between long distance runners with and without history of low back pain
Independent sample T-test of trunk kinematic will be conducted between healthy and LBP participants.

Secondary/exploratory analysis: EMG data of trunk and hip muscles will be used as secondary and exploratory outcome measures to examine muscle activation pattern during running across healthy and LBP participations.

B. Outcome:

Aim 1 – pelvic and trunk joint motions/angles will be obtained from the motion analysis system and a pattern of kinematic measures will be determined for running motion in healthy subjects. Alternatively, our results may suggest no consistent pattern across healthy subjects, which is an important finding to recognize for future cross-sectional studies of running analysis.

Aim 2 – pelvic and trunk joint motions/angles will be obtained from the motion analysis system and a pattern of kinematic measures will be determined for running motion in LBP subjects. Alternatively, our results may suggest no consistent pattern across LBP subjects, which is an important finding to recognize that pain and potentially physiological effects of pain may result in inconsistent running pattern.

Aim 3 – pelvic and trunk joint motions/angles will be obtained from the motion analysis system and a comparison of running analysis between the healthy and LBP participants will be conducted to determine if there are differences in both populations. These findings may lead to future intervention studies. It should be noted that these preliminary results will be used to further examine with studies of larger sample size in future.

C. Study results to participants: none unless requested by participant.

D. Publication Plan: Research findings will be published after data collection is complete.

VI. Bibliography / References / Literature Cited

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Taunton JE, Ryan MB, Clement DB. A retrospective case-control analysis of 2002 running injuries. *Br J Sports Med*. 2002; 36(2):95-101.

Novacheck TF. The biomechanics of running. *Gait and Posture*. 1998; 7:77-95

Schache AG, Blanch P, Rath D, Wrigley T, Bennell, K. Three-dimentional angular kinematics of the lumbar spine and pelvis during running. *Human Movement Science*. 2002; 21:273-293

Van-Dillen LR, Bloom NJ, Gombatto SP, Susco TM. Hip rotation range of motion in people with and without low back pain who participate in rotation-related sports. Phys Ther Sport 2008;9(2):72-81.

Haddas R, Sizer P, Sawyer S, et al. Effect of volitional spine stabilization and lower extremity fatigue on landing performance in a recurrent low back pain population. Presented at the 37th annual American Society of Biomechanics Meeting, Omaha, NE, September 2013.

Shum GLK, Crosbie J, Lee RYW. Effect of low back pain on the kinematics and joint coordination of the lumbar spine and hip during sit-to-stand and stand-to-sit. Spine 2005;30(17):1998-2004.

Appendix 6: R-code

```
## S. Mukui Mutunga
# Stats for Rotational Amplitudes, Continuous Relative Phase and
Continuous Relative Phase Variability
# Date created: Wednesday 13 March 2019
# Date modifed: Tuesday 26 March 2019
  # Use within subject average CRP maxima for MANOVA calculations
instead 5 stride averages
  # Use (CRPmax - CRPmin) for MANOVA calculations instead of 5 stride
averages



setwd("~/Documents/RunningAnalysis/Running - R Analysis")
## libraries -  may need to load packages if they don't install
library(ggplot2) # - install.packages("ggplot2") -- for plotting
library(readxl)  # - install.packages("readxl") -- for reading excel
sheets
library(car)
library(gridExtra) # - install.packages("gridExtra")

library(broom) # - install.packages("broom") -- for cleaning lm and
pulling out p-values
library(effsize) # - install.packages("effsize") -- for Cohen's effect
size calculations
library(gmodels) # - install.packages("gmodels") -- for confidence
interval calculations



######################################## CRP 1 Average Analysis
#####################################################################
CRPlavg_dat <- read_excel("CRP_5strides.xlsx", sheet = "CRP_lavg")
CRPlavg_dat <- within(CRPlavg_dat, {Type <- factor(Type, level =
c("1","2"), label = c("HC","LBP"))})
CRPlavg_dat <- within(CRPlavg_dat, {Sub <- factor(Sub, level =
c(1:17))})


CRPlavg.lm  <- lm(cbind(CRPlavg_dat$PTF, CRPlavg_dat$PTS,
CRPlavg_dat$PTT, CRPlavg_dat$LTF, CRPlavg_dat$LTS,
                        CRPlavg_dat$LTT, CRPlavg_dat$PLF,
CRPlavg_dat$PLS, CRPlavg_dat$PLT) ~ CRPlavg_dat$Type)
summary(CRPlavg.lm)

tidy_CRPlavg <- tidy(CRPlavg.lm) # need the "broom" package for this to
work

CRPlavg_p <- matrix(c(tidy_CRPlavg$p.value[seq(from = 2, to = 18, by =
2)]), nrow = 1, ncol = 9)
```

```
rownames(CRPlavg_p) <- c("p-values")
colnames(CRPlavg_p) <- c("PT - Lat bend", "PT - Flex/ext", "PT - Ax.
Rot","LT - Lat bend", "LT - Flex/ext",
                         "LT. Ax. Rot","PL - Lat bend", "PL - Flex/ext",
"PL -Ax. Rot")

CRPlavg_ES<- matrix(c(0), nrow = 1, ncol = 9)
for (i in 1:9)
  CRPlavg_ES[i]<- (cohen.d(CRPlavg_dat[[i]], CRPlavg_dat$Type))$estimate

CRPlavg_pES <- rbind(CRPlavg_p, CRPlavg_ES)
rownames(CRPlavg_pES) <- c("p-values", "ES")
colnames(CRPlavg_pES) <- c("PT - Lat bend", "PT - Flex/ext", "PT - Ax.
Rot","LT - Lat bend", "LT - Flex/ext",
                          "Ax. Rot - LT","PL - Lat bend", "PL - Flex/ext",
"PL -Ax. Rot")


######################################## CRPvar 1 Average Analysis
#####################################################################
CRPvarlavg_dat <- read_excel("CRP_5strides.xlsx", sheet = "CRPvar_1avg")
CRPvarlavg_dat <- within(CRPvarlavg_dat, {Type <- factor(Type, level =
c("1","2"), label = c("HC","LBP"))})


CRPvarlavg.lm  <- lm(cbind(CRPvarlavg_dat$PTF, CRPvarlavg_dat$PTS,
CRPvarlavg_dat$PTT, CRPvarlavg_dat$LTF, CRPvarlavg_dat$LTS,
                           CRPvarlavg_dat$LTT, CRPvarlavg_dat$PLF,
CRPvarlavg_dat$PLS, CRPvarlavg_dat$PLT) ~ CRPvarlavg_dat$Type)
summary(CRPvarlavg.lm)

tidy_CRPvarlavg <- tidy(CRPvarlavg.lm) # need the "broom" package for
this to work

CRPvarlavg_p <- matrix(c(tidy_CRPvarlavg$p.value[seq(from = 2, to = 18,
by =  2)]), nrow = 1, ncol = 9)
rownames(CRPvarlavg_p) <- c("p-values")
colnames(CRPvarlavg_p) <- c("PT - Lat bend", "PT - Flex/ext", "PT - Ax.
Rot","LT - Lat bend", "LT - Flex/ext",
                            "LT. Ax. Rot","PL - Lat bend", "PL - Flex/ext",
"PL -Ax. Rot")

CRPvarlavg_ES<- matrix(c(0), nrow = 1, ncol = 9)
for (i in 1:9)
  CRPvarlavg_ES[i]<- (cohen.d(CRPvarlavg_dat[[i]],
CRPvarlavg_dat$Type))$estimate

CRPvarlavg_pES <- rbind(CRPvarlavg_p, CRPvarlavg_ES)
rownames(CRPvarlavg_pES) <- c("p-values", "ES")
colnames(CRPvarlavg_pES) <- c("PT - Lat bend", "PT - Flex/ext", "PT -
Ax. Rot","LT - Lat bend", "LT - Flex/ext",
```

```
                                    "Ax. Rot - LT","PL - Lat bend", "PL -
Flex/ext", "PL -Ax. Rot"}
```

Appendix 7: MatLab Code

Appendix 7.1: Main Body Code

```
%   S. Mukui Mutunga
%   Date Created: Thursday 22 June 2017

%   Purpose: analyze treadmill running data for Dr. Neena Sharma
%   .trc files converted to .txt files for convenience

%% New in Rev52 11 December 2018
% Use right heel strike to signify stride rather than trochanter peaks.

% Removed ROM analysis.

% Note: Flexion/Extension = about y-axis
%       Lateral Bend      = about x-axis
%       Axial Rotaion     = about z -axis


%%

clear
close all
clc


path = '/Users/Kui/Documents/RunningAnalysis/RunningData/';
strides = 5;
n = 1;

set(0, 'DefaultLineLineWidth', 1)

% figspath = % location to save figures from running data
for regspan = 4

   for itype = 1
      if itype == 2
         type = 'LBP';
      else
         type = 'HC';
      end
      for isub = 1
         for itask = 11

            filename = [type num2str(isub) '_' num2str(itask),'.txt'];

            pname = ['Sub ' num2str(isub) ' ' type ' ' ];

            data = RunningImport01(path,filename);

            RASIS = data(:,1:3);
```

```
RPSIS = data(:,4:6);
LASIS = data(:,7:9);
LPSIS = data(:,10:12);
VSacr = data(:,13:15);
%           VSacr = zeros(length(LPSIS),3);
%           for i = 1:3
%               VSacr(:,i) = mean([LPSIS(:,i),RPSIS(:,i)],2);
%           end
RTROC = data(:,16:18);
LTROC = data(:,49:51);
Cerv = data(:,82:84);
Thor = data(:,85:87);
Clav = data(:,88:90);
Strn = data(:,91:93);
RSHO = data(:,94:96);
LSHO = data(:,97:99);
RHeel = data(:,40:42);
LHeel = data(:,73:75);

X = 'X';
Y = 'Y';
Z = 'Z';

rotationsequence = cat(2,Y,X,Z);  % Cardan Angle Sequence, flexion about y-axis

[lumbarM,trunkM,pelvicM] = RunningMatrix01(Clav,Strn,Cerv,Thor,VSacr,RASIS,LASIS);

initmat = [1 0 0; 0 1 0; 0 0 -1];
trunkMcorrinit = rotatecorr01(trunkM,inv(initmat));
lumbarMcorrinit = rotatecorr01(lumbarM,inv(initmat));
pelvicMcorrinit = rotatecorr01(pelvicM,inv(initmat));

[lumbarE,trunkE,pelvicE] =
TrunkRot01(lumbarMcorrinit,trunkMcorrinit,pelvicMcorrinit,rotationsequence);

%% Running - Normalizing data flexion/ext of trunk
LTROC3 = LTROC(:,3);
LHeel3 = LHeel(:,3);
%           VSacr3 = VSacr(:,3);

% calculation of segment angular velocity for Hamill CRP, 1999-
% linear regression

[trunkE_v, lumbarE_v, pelvicE_v] = Hamill_vCalc01(trunkE, lumbarE, pelvicE,regspan); % Calculation
of angular velcity from angular position according to Hamill, 1999
[ntrunkE, nlumbarE, npelvicE, nTrunkE_v, nLumbarE_v, nPelvicE_v] = Hamill_normCRP01(trunkE,
lumbarE, pelvicE,trunkE_v, lumbarE_v, pelvicE_v); % normaliation of angular position and velocity according to
Hamill, 1999

%           nTrunkE = ntrunkE - mean(ntrunkE);
%           nLumbarE = nlumbarE - mean(nlumbarE);
%           nPelvicE = npelvicE - mean(npelvicE);

nTrunkE = ntrunkE;
nLumbarE = nlumbarE;
nPelvicE = npelvicE;
```

```
%               [TrunkE, LumbarE, PelvicE] = StatCycle03(ntrunkE, nlumbarE, npelvicE, LTRO
%             [TrunkE_v, LumbarE_v, PelvicE_v] = StatCycle03(ntrunkE_v, nlumbarE_v, npelvicE_v,
LTROC3); % segment angular velocity

[SubData, pklocs] = StatCycle08(nTrunkE,nLumbarE, nPelvicE,LHeel3,strides,isub);
[SubData_v, pklocs_v] = StatCycle08(nTrunkE_v,nLumbarE_v, nPelvicE_v,LHeel3,strides,isub);

%               [SubData, pklocs] = StatCycle08(ntrunkE,nlumbarE, npelvicE,LTROC3,strides,isub);
%               [SubData_v, pklocs_v] = StatCycle08(nTrunkE_v,nLumbarE_v,
nPelvicE_v,LTROC3,strides,isub);

%% Synchrony calculations
%               pt = PelvicE - TrunkE;
%               lt = LumbarE - TrunkE;
%               pl = PelvicE - LumbarE;
%
%               [pt_Syn, lt_Syn, pl_Syn] = Synchrony01(pt, lt, pl);
%
%               Sync = [pt, lt, pl];
%               mean_Sync = nanmean(Sync);
%               Sync = Sync - mean_Sync;
%% Running Trunk rotations

%               figure()
%               subplot(2,2,1), plot(TrunkE(LTlocs(i),1),TrunkE_v(LTlocs(i+1),1))
%               title([pname ' Running Trunk Lat'])
%               ylabel ('Deg/s')
%               subplot(2,2,2), plot(TrunkE(LTlocs(i),2), TrunkE_v(LTlocs(i+1),2))
%               title ([pname ' Running Trunk Flex/Ext'])
%               ylabel ('Deg/s')
%               subplot(2,2,3), plot(TrunkE(LTlocs(i),3),TrunkE_v(LTlocs(i+1),3))
%               title([pname ' Running Trunk Ax. Rot'])
%               xlabel ('Deg')
%               ylabel ('Deg/s')


%% Running Lumbar Rotations
%               figure()
%               subplot(2,2,1), plot(LumbarE(:,1),LumbarE_v(:,1))
%               title([pname ' Running Lumbar Lateral Bend'])
%               ylabel ('Deg/s')
%               subplot(2,2,2), plot(LumbarE(:,2),LumbarE_v(:,2))
%               title ([pname ' Running Lumbar Angle'])
%               ylabel ('Deg/s')
%               subplot(2,2,3), plot(LumbarE(:,3),LumbarE_v(:,3))
%               title([pname ' Running Lumbar Ax. Rot'])
%               xlabel ('Deg')
%               ylabel ('Deg/s')

%% Running Pelvic Rotations
%               figure()
%               subplot(2,2,1), plot(PelvicE(:,1),PelvicE_v(:,1))
%               title([pname ' Running Pelvic Tilt'])
%               xlabel ('Deg')
%               ylabel ('Deg/s')
```

```
%               subplot(2,2,2), plot(PelvicE(:,2),PelvicE_v(:,2))
%               title ([pname ' Running Pelvic Obliquity'])
%               xlabel ('Deg')
%               ylabel ('Deg/s')
%               positionVector = [0.6, 0.2, 0.6, 0.2];
%               subplot('Position',positionVector)
%               subplot(2,2,3), plot(PelvicE(:,3),PelvicE_v(:,3))
%               title([pname ' Running Pelvic Ax. Rot'])
%               xlabel ('Deg')
%               ylabel ('Deg/s')

%% Running Trunk, Lumbar and Pelvic Phase Plots
%                       figure ((100*itype)+isub)
%                       for ii = 1:3
%                          subplot(3,3,ii)
%                          plot(TrunkE(:,ii))
%                          hold on
%                          plot(LumbarE(:,ii))
%                          hold off
%                          legend('Trunk','Lumbar')
%
%                          subplot(3,3,ii+3)
%                          plot(TrunkE(:,ii))
%                          hold on
%                          plot(PelvicE(:,ii))
%                          hold off
%                          legend('Trunk','Pelvic')
%
%                          subplot(3,3,ii+6)
%                          plot(LumbarE(:,ii))
%                          hold on
%                          plot(PelvicE(:,ii))
%                          hold off
%                          legend('Lumbar','Pelvic')
%
%                          axes('Position',[0 0 0.40 0.96],'Visible','off');
%                          text(0.5, 0.98,'Flex/Ext', 'FontSize', 12);
%
%                          axes('Position',[0 0 0.94 0.96],'Visible','off');
%                          text(0.5, 0.98,'Lateral Bend', 'FontSize', 12);
%
%                          axes('Position',[0 0 1.49 0.96],'Visible','off');
%                          text(0.5, 0.98,'Axial Rotation', 'FontSize', 12);
%
%                          axes('Position',[0 0 1 1],'Visible','off');
%                          text(0.40, 0.98,[pname 'Running Phase Plots'], 'FontSize', 15);
%
%                          for i = ((100*itype)+isub)
%                             h = figure(i);
%                             print(h,[figspath pname 'Running Phase Plots'],'-dpdf','-fillpage')
%                          end
%                       end

%% Running Trunk, Lumbar and Pelvic Coordination Plots
%                       figure ((1000*itype)+isub)
%                       for ii = 1:3
```

```
%                       subplot(3,3,ii)
%                       plot(TrunkE(:,ii),LumbarE(:,ii))
%                       xlabel('Trunk Angle ')
%                       ylabel('Lumbar Angle')
%
%                       subplot(3,3,ii+3)
%                       plot(TrunkE(:,ii),PelvicE(:,ii))
%                       xlabel('Trunk Angle')
%                       ylabel('Pelvic Angle')
%
%                       subplot(3,3,ii+6)
%                       plot(LumbarE(:,ii),PelvicE(:,ii))
%                       xlabel('Lumbar Angle')
%                       ylabel('Pelvic Angle')
%
%                       axes('Position',[0 0 0.40 0.96],'Visible','off');
%                       text(0.5, 0.98,'Flex/Ext', 'FontSize', 12);
%
%                       axes('Position',[0 0 0.94 0.96],'Visible','off');
%                       text(0.5, 0.98,'Lateral Bend', 'FontSize', 12);
%
%                       axes('Position',[0 0 1.49 0.96],'Visible','off');
%                       text(0.5, 0.98,'Axial Rotation', 'FontSize', 12);
%
%                       axes('Position',[0 0 1 1],'Visible','off');
%                       text(0.40, 0.98,[pname 'Running Coordination Plots'], 'FontSize', 15);
%
%                       for i = ((1000*itype)+isub)
%                          h = figure(i);
%                          print(h,[figspath pname 'Running Coordination Plots'],'-dpdf','-fillpage')
%                       end
%                   end

%% Plot of sensor positions: Sternum, T10, Sacral (animation)

%           fname = ['Subject ' num2str(isub) ' ' type ' Treadmill '];
%           i =  [0 1200 -600 600 1000 2200];
%           figure()
%           plot3(Strn(1,1),Strn(1,2),Strn(1,3),'go')
%           grid
%           hold on
%           plot3([Cerv(1,1) Thor(1,1) VSacr(1,1)],[Cerv(1,2) Thor(1,2) VSacr(1,2)],[Cerv(1,3)
Thor(1,3) VSacr(1,3)],'ro-')
%           plot3([LPSIS(1,1) RPSIS(1,1) RASIS(1,1) LASIS(1,1) LPSIS(1,1)],[LPSIS(1,2) RPSIS(1,2)
          RASIS(1,2) LASIS(1,2) LPSIS(1,2), [LPSIS(1,3) RPSIS(1,3) RASIS(1,3) LASIS(1,3)
          LPSIS(1,3)],'mo-')
%           axis(i);
%           xlabel('x position(mm)')
%           ylabel('y position(mm)')
%           zlabel('z position(mm)')
%
%           plotaxes4(fname,Clav,Strn,Cerv,Thor,VSacr,LPSIS,LASIS,RPSIS,RASIS,i,isub,itask);


%% Figure showing rotations for all subjects
%       figure(1221)
```

```
%       for ii = 1:9
%          x = (1:100);
%          subplot(3,3,ii)
%          plot(SubData(:,ii,isub))
%          hold on
%
%          % Labels
%          axes('Position',[0 0 0.40 0.96],'Visible','off');
%          text(0.5, 0.98,'Flex/Ext', 'FontSize', 12);
%
%          axes('Position',[0 0 0.94 0.96],'Visible','off');
%          text(0.5, 0.98,'Lateral Bend', 'FontSize', 12);
%
%          axes('Position',[0 0 1.49 0.96],'Visible','off');
%          text(0.5, 0.98,'Axial Rotation', 'FontSize', 12);
%
%          axes('Position',[0 0 0.05 0.82],'Visible','off');
%          text(0.5, 0.98,'Trunk', 'FontSize', 12);
%          axes('Position',[0 0 0.05 0.79],'Visible','off');
%          text(0.5, 0.98,'(deg)', 'FontSize', 12);
%
%          axes('Position',[0 0 0.05 0.52],'Visible','off');
%          text(0.5, 0.98,'Lumbar', 'FontSize', 12);
%          axes('Position',[0 0 0.05 0.49],'Visible','off');
%          text(0.5, 0.98,'(deg)', 'FontSize', 12);
%
%          axes('Position',[0 0 0.05 0.22],'Visible','off');
%          text(0.5, 0.98,'Pelvic', 'FontSize', 12);
%          axes('Position',[0 0 0.05 0.19],'Visible','off');
%          text(0.5, 0.98,'(deg)', 'FontSize', 12);
%
%          if itype == 1
%             axes('Position',[0 0 1 1],'Visible','off');
%             text(0.38, 0.98,'Control Flex/Ext Ensemble Graphs', 'FontSize', 15,'FontWeight','bold');
%          else
%             axes('Position',[0 0 1 1],'Visible','off');
%             text(0.38, 0.98,'LBP Flex/Ext Ensemble Graphs', 'FontSize', 15,'FontWeight','bold');
%          end
%       end
end
%% Hamill method for CRP Analysis


phase = atan2(SubData_v, SubData);

phi = phase;
for i = 1:size(SubData_v,1)
   for ii = 1:size(SubData_v,2)
      if  SubData_v(i,ii,isub) > 0 && SubData(i,ii,isub) > 0 % quadrant 1
         phi(i,ii,isub) = phase(i,ii,isub) * 57.3;
         %ph012i01(i,ii,isub) =0;
      elseif SubData_v(i,ii,isub) > 0 && SubData(i,ii,isub) < 0 % quadrant 2
         phi(i,ii,isub) = phase(i,ii,isub) * 57.3;
         %phi(i,ii,isub) =0;
      elseif SubData_v(i,ii,isub) <= 0 && SubData(i,ii,isub) < 0 % quadrant 3
         %phi(i,ii,isub) = (2*pi - (phase(i,ii,isub))) * 57.3;
```

```
            phi(i,ii,isub) = 360 + phase(i,ii,isub) * 57.3;
        elseif SubData_v(i,ii,isub) <= 0 && SubData(i,ii,isub) > 0 % quadrant 4
            %phi(i,ii,isub) = (2*pi - (phase(i,ii,isub))) * 57.3;
            phi(i,ii,isub) = 360 + phase(i,ii,isub) * 57.3;
        end
    end
end

%% Stop for Peak Diff Method
Trunk_phi(:,:,isub) = phi(:,1:3,isub);  %#ok<SAGROW>
Lumbar_phi(:,:,isub) = phi(:,4:6,isub); %#ok<SAGROW>
Pelvic_phi(:,:,isub) = phi(:,7:9,isub); %#ok<SAGROW>

phi2 = [Trunk_phi, Lumbar_phi, Pelvic_phi];

[phi_corr] = PeakDiff02(phi2,isub);
phi_corr2 = phi_corr;

for i = 1:size(phi_corr,2)
    a = find(~isnan(phi_corr2(:,i,isub)),1);

    if phi_corr2(a,i,isub) >= 270
        phi_corr2(:,i,isub) = phi_corr(:,i,isub) - 360;
    elseif phi_corr2(a,i,isub) <= -270
        phi_corr2(:,i,isub) = phi_corr(:,i,isub) + 360;
    end
end

[phi_corr3] = PhiGaps01(phi_corr2,isub);

PT(:,:,isub) = abs(phi_corr3(:,7:9,isub) - phi_corr3(:,1:3,isub)); %#ok<SAGROW>
LT(:,:,isub) = abs(phi_corr3(:,4:6,isub) - phi_corr3(:,1:3,isub)); %#ok<SAGROW>
PL(:,:,isub) = abs(phi_corr3(:,7:9,isub) - phi_corr3(:,4:6,isub)); %#ok<SAGROW>

if itype == 1
    CRP_HC = [PT LT PL];
    [stdCRP_HC,CRPvar_HC,CRPmax_HC] = CRPvar03(isub,CRP_HC);
    CRP_HC2 = CRP_HC;
    for i = 1:isub
        CRP_HC2(:,10,i) = i;
    end
    CRP_HC2(:,11,:) = itype;
    CRP_HC3 = permute(CRP_HC2,[1 3 2]);
    CRP_HC3 = reshape(CRP_HC3,[],size(CRP_HC2,2),1);
%       filename = 'CRPData_HC.xlsx';
%       xlswrite(filename,CRP_HC3,'sheet1');
else
    CRP_LBP = [PT LT PL];
    [stdCRP_LBP,CRPvar_LBP,CRPmax_LBP] = CRPvar03(isub,CRP_LBP);
    CRP_LBP2 = CRP_LBP;
    for i = 1:isub
        CRP_LBP2(:,10,i) = i;
    end
    CRP_LBP2(:,11,:) = itype;
    CRP_LBP3 = permute(CRP_LBP2,[1 3 2]);
    CRP_LBP3 = reshape(CRP_LBP3,[],size(CRP_LBP2,2),1);
```

```
%             filename = 'CRPData_LBP.xlsx';
%             xlswrite(filename,CRP_LBP3,'sheet1');
        end
        %% stride overlays
%           o = (1:strides).*100;
%           CRPname = [num2str(strides) ' stride CRP plots for sub ' num2str(isub) ' (' type ') ' ];
%           for i = 1:size(o,2)-1
%              for ii = 1:9
%                 if itype == 1
%                    figure(isub); subplot(3,3,ii); plot(CRP_HC(1:100,ii,isub)); hold on;
plot(CRP_HC(o(i):o(i+1),ii,isub));
%                    axes('Position',[0 0 1 1],'Visible','off');
%                    text(0.50,0.98,CRPname, 'FontSize', 15,'FontWeight','bold','HorizontalAlignment','center');
%
%                    % Labels
%                    axes('Position',[0 0 0.40 0.96],'Visible','off');
%                    text(0.5, 0.98,'Lateral Bend', 'FontSize', 12);
%
%                    axes('Position',[0 0 0.94 0.96],'Visible','off');
%                    text(0.5, 0.98,'Flexion/Extension', 'FontSize', 12);
%
%                    axes('Position',[0 0 1.49 0.96],'Visible','off');
%                    text(0.5, 0.98,'Axial Rotation', 'FontSize', 12);
%
%                    axes('Position',[0 0 0.05 0.82],'Visible','off');
%                    text(0.5, 0.98,'Pelvic-Trunk', 'FontSize', 12);
%
%                    axes('Position',[0 0 0.05 0.52],'Visible','off');
%                    text(0.5, 0.98,'Lumbar-Trunk', 'FontSize', 12);
%
%                    axes('Position',[0 0 0.05 0.22],'Visible','off');
%                    text(0.5, 0.98,'Pelvic-Lumbar', 'FontSize', 12);
%
%
%                 else
%                    figure(isub); subplot(3,3,ii); plot(CRP_LBP(1:100,ii,isub)); hold on;
plot(CRP_LBP(o(i):o(i+1),ii,isub));
%
%                    axes('Position',[0 0 1 1],'Visible','off');
%                    text(0.50,0.98,CRPname, 'FontSize', 15,'FontWeight','bold','HorizontalAlignment','center');
%
%                    % Labels
%                    axes('Position',[0 0 0.40 0.96],'Visible','off');
%                    text(0.5, 0.98,'Lateral Bend', 'FontSize', 12);
%
%                    axes('Position',[0 0 0.94 0.96],'Visible','off');
%                    text(0.5, 0.98,'Flexion Extension', 'FontSize', 12);
%
%                    axes('Position',[0 0 1.49 0.96],'Visible','off');
%                    text(0.5, 0.98,'Axial Rotation', 'FontSize', 12);
%
%                    axes('Position',[0 0 0.05 0.82],'Visible','off');
%                    text(0.5, 0.98,'Pelvic-Trunk', 'FontSize', 12);
%
%                    axes('Position',[0 0 0.05 0.52],'Visible','off');
%                    text(0.5, 0.98,'Lumbar-Trunk', 'FontSize', 12);
```

```
%
%                   axes('Position',[0 0 0.05 0.22],'Visible','off');
%                   text(0.5, 0.98,'Pelvic-Lumbar', 'FontSize', 12);
%                end
%             end
%          end
      end
   end
end
%    HC_SynAll = [];
%    LBP_SynAll = [];
%    if itype == 1
%       for n = 1:size(HC_Syn,3)
%          i = 100;
%          sub = repmat(1:isub,i,1);
%          sub = sub(:);
%          HC_SynAll = cat(1,HC_SynAll,HC_Syn(:,:,n));
%       end
%    else
%       for n = 1:size(LBP_Syn,3)
%          i = 100;
%          sub = repmat(1:isub,i,1);
%          sub = sub(:);
%          LBP_SynAll = cat(1,LBP_SynAll,LBP_Syn(:,:,n));
%       end
%    end
% end
%
% if itype == 1
%    HC_SynAll = [sub, HC_SynAll];
%    statsfile = ['HC Synchrony' '.txt'];
%    fid = fopen([statspath statsfile], 'w+');
%    for ii = 1:size(HC_SynAll,1)
%       fprintf(fid,'%.4f\t', HC_SynAll(ii,:));
%       fprintf(fid, '\n');
%    end
%    fclose(fid);
% else
%    LBP_SynAll = [sub, LBP_SynAll];
%    statsfile = ['LBP Synchrony' '.txt'];
%    fid = fopen([statspath statsfile], 'w+');
%    for ii = 1:size(LBP_SynAll,1)
%       fprintf(fid,'%.4f\t', LBP_SynAll(ii,:));
%       fprintf(fid, '\n');
%    end
%    fclose(fid);
% end
%% Full Ensemble graphs
% figure(itype)
% for ii = 1:9
%    x = (1:100);
%    subplot(3,3,ii)
%    plot(sFinal(:,ii))
%    hold on
%    plot(pFinal(:,ii))
%    h = area([sFinal(:,ii) pdiff(:,ii)]); % fill area in graph
```

```
%     plot(mSubData(:,ii), 'k')
%     %         hline = refline([0,0]);
%     %         hline.Color = 'k';
%     %         set(hline,'LineStyle',':')
%     h(1).FaceColor = [1 1 1]; % fixes part of the graph that is coloured when it's not supposed to be
%     h(2).FaceColor = [0.8 0.8 0.8];
%     xlabel('% Gait Cycle')
%
%     % Labels
%     axes('Position',[0 0 0.40 0.96],'Visible','off');
%     text(0.5, 0.98,'Flex/Ext', 'FontSize', 12);
%
%     axes('Position',[0 0 0.94 0.96],'Visible','off');
%     text(0.5, 0.98,'Lateral Bend', 'FontSize', 12);
%
%     axes('Position',[0 0 1.49 0.96],'Visible','off');
%     text(0.5, 0.98,'Axial Rotation', 'FontSize', 12);
%
%     axes('Position',[0 0 0.05 0.82],'Visible','off');
%     text(0.5, 0.98,'Trunk', 'FontSize', 12);
%     axes('Position',[0 0 0.05 0.79],'Visible','off');
%     text(0.5, 0.98,'(deg)', 'FontSize', 12);
%
%     axes('Position',[0 0 0.05 0.52],'Visible','off');
%     text(0.5, 0.98,'Lumbar', 'FontSize', 12);
%     axes('Position',[0 0 0.05 0.49],'Visible','off');
%     text(0.5, 0.98,'(deg)', 'FontSize', 12);
%
%     axes('Position',[0 0 0.05 0.22],'Visible','off');
%     text(0.5, 0.98,'Pelvic', 'FontSize', 12);
%     axes('Position',[0 0 0.05 0.19],'Visible','off');
%     text(0.5, 0.98,'(deg)', 'FontSize', 12);
%
%     if itype == 1
%        axes('Position',[0 0 1 1],'Visible','off');
%        text(0.38, 0.98,'Control Flex/Ext Ensemble Graphs', 'FontSize', 15,'FontWeight','bold');
%        figsname = 'NLB_Ensemble';
%        print('-f1',[figspath figsname],'-dpdf','-fillpage')
%     else
%        axes('Position',[0 0 1 1],'Visible','off');
%        text(0.38, 0.98,'LBP Flex/Ext Ensemble Graphs', 'FontSize', 15,'FontWeight','bold');
%        figsname = 'LBP_Ensemble';
%        print('-f2',[figspath figsname],'-dpdf','-fillpage')
%     end
% end

%% Trunk, Lumbar and Pelvic Flexion/Extension ensemble graphs
% figure(itype*10)
% subplot(3,1,1)
% plot(sFinal(:,1))
% hold on
% plot(pFinal(:,1))
% h = area([sFinal(:,1) pdiff(:,1)]); % fill area in graph
% plot(mSubData(:,1), 'k')
% %         hline = refline([0,0]);
% %         hline.Color = 'k';
```

```
% %         set(hline,'LineStyle',':')
%
% h(1).FaceColor = [1 1 1]; % fixes part of the graph that is coloured when it's not supposed to be
% h(2).FaceColor = [0.8 0.8 0.8];
%
% subplot(3,1,2)
% plot(sFinal(:,4))
% hold on
% plot(pFinal(:,4))
% h2 = area([sFinal(:,4) pdiff(:,4)]);
% plot(mSubData(:,4), 'k')
%
%
% h2(1).FaceColor = [1 1 1]; % fixes part of the graph that is coloured when it's not supposed to be
% h2(2).FaceColor = [0.8 0.8 0.8];
%
% subplot(3,1,3)
% plot(sFinal(:,7))
% hold on
% plot(pFinal(:,7))
% h3 = area([sFinal(:,7) pdiff(:,7)]);
% plot(mSubData(:,7), 'k')
%
%
% h3(1).FaceColor = [1 1 1]; % fixes part of the graph that is coloured when it's not supposed to be
% h3(2).FaceColor = [0.8 0.8 0.8];
% xlabel('% Gait Cycle')
%
% axes('Position',[0 0 0.83 0.96],'Visible','off');
% text(0.5, 0.98,'Trunk Flexion/Extension', 'FontSize', 12);
% axes('Position',[0 0 0.05 0.85],'Visible','off');
% text(0.5, 0.98,'Trunk', 'FontSize', 12);
% axes('Position',[0 0 0.05 0.81],'Visible','off');
% text(0.5, 0.98,'(deg)', 'FontSize', 12);
%
% axes('Position',[0 0 0.83 0.66],'Visible','off');
% text(0.5, 0.98,'Lumbar Kyphosis/Lordosis', 'FontSize', 12);
% axes('Position',[0 0 0.05 0.55],'Visible','off');
% text(0.5, 0.98,'Lumbar', 'FontSize', 12);
% axes('Position',[0 0 0.05 0.51],'Visible','off');
% text(0.5, 0.98,'(deg)', 'FontSize', 12);
%
%
% axes('Position',[0 0 0.83 0.35],'Visible','off');
% text(0.5, 0.98,'Pelvic Anterior/Posterior Tilt', 'FontSize', 12);
% axes('Position',[0 0 0.05 0.24],'Visible','off');
% text(0.5, 0.98,'Pelvic', 'FontSize', 12);
% axes('Position',[0 0 0.05 0.20],'Visible','off');
% text(0.5, 0.98,'(deg)', 'FontSize', 12);
%
% %         Figure labels & saving graphs
% if itype == 1
%     axes('Position',[0 0 1 1],'Visible','off');
%     text(0.38, 0.98,'Control Flex/Ext Ensemble Graphs', 'FontSize', 15,'FontWeight','bold');
%     figsname = 'NLB_Flex_PEnsemble';
%     print('-f30',[figspath figsname],'-dpdf','-fillpage')
```

```
% else
%     axes('Position',[0 0 1 1],'Visible','off');
%     text(0.38, 0.98,'LBP Flex/Ext Ensemble Graphs', 'FontSize', 15,'FontWeight','bold');
%     figsname = 'LBP_Flex_Ensemble';
%     print('-f40',[figspath figsname],'-dpdf','-fillpage')
% end

%% Trunk, Lumbar and Pelvic Lateral Bend ensemble graphs
% figure(itype*100)
% subplot(3,1,1)
% plot(sFinal(:,2))
% hold on
% plot(pFinal(:,2))
% h = area([sFinal(:,2) pdiff(:,2)]); % fill area in graph
% plot(mSubData(:,2), 'k')
% %         hline = refline([0,0]);
% %         hline.Color = 'k';
% %         set(hline,'LineStyle',':')
%
% h(1).FaceColor = [1 1 1]; % fixes part of the graph that is coloured when it's not supposed to be
% h(2).FaceColor = [0.8 0.8 0.8];
%
% subplot(3,1,2)
% plot(sFinal(:,5))
% hold on
% plot(pFinal(:,5))
% h2 = area([sFinal(:,5) pdiff(:,5)]);
% plot(mSubData(:,5), 'k')
%
%
% h2(1).FaceColor = [1 1 1]; % fixes part of the graph that is coloured when it's not supposed to be
% h2(2).FaceColor = [0.8 0.8 0.8];
%
% subplot(3,1,3)
% plot(sFinal(:,7))
% hold on
% plot(pFinal(:,7))
% h3 = area([sFinal(:,7) pdiff(:,7)]);
% plot(mSubData(:,7), 'k')
%
%
% h3(1).FaceColor = [1 1 1]; % fixes part of the graph that is coloured when it's not supposed to be
% h3(2).FaceColor = [0.8 0.8 0.8];
% xlabel('% Gait Cycle')
%
% axes('Position',[0 0 0.83 0.96],'Visible','off');
% text(0.5, 0.98,'Trunk Lateral Bend', 'FontSize', 12);
% axes('Position',[0 0 0.05 0.85],'Visible','off');
% text(0.5, 0.98,'Trunk', 'FontSize', 12);
% axes('Position',[0 0 0.05 0.81],'Visible','off');
% text(0.5, 0.98,'(deg)', 'FontSize', 12);
%
% axes('Position',[0 0 0.83 0.66],'Visible','off');
% text(0.5, 0.98,'Lumbar Lateral Bend', 'FontSize', 12);
% axes('Position',[0 0 0.05 0.55],'Visible','off');
% text(0.5, 0.98,'Lumbar', 'FontSize', 12);
```

```
% axes('Position',[0 0 0.05 0.51],'Visible','off');
% text(0.5, 0.98,'(deg)', 'FontSize', 12);
%
%
% axes('Position',[0 0 0.83 0.35],'Visible','off');
% text(0.5, 0.98,'Pelvic Tilt', 'FontSize', 12);
% axes('Position',[0 0 0.05 0.24],'Visible','off');
% text(0.5, 0.98,'Pelvic', 'FontSize', 12);
% axes('Position',[0 0 0.05 0.20],'Visible','off');
% text(0.5, 0.98,'(deg)', 'FontSize', 12);
%
%
% %         Figure labels & saving graphs
% if itype == 1
%     axes('Position',[0 0 1 1],'Visible','off');
%     text(0.30, 0.98,'Control Lat Bend Ensemble Graphs', 'FontSize', 15,'FontWeight','bold');
%     figsname = 'NLBP_Lat_Ensemble';
%     print('-f100',[figspath figsname],'-dpdf','-fillpage')
% else
%     axes('Position',[0 0 1 1],'Visible','off');
%     text(0.30, 0.98,'LBP Lat Bend Ensemble Graphs', 'FontSize', 15,'FontWeight','bold');
%     figsname = 'LBP_Lat_Ensemble';
%     print('-f200',[figspath figsname],'-dpdf','-fillpage')
% end

%% Trunk, Lumbar and Pelvic Axial Rotation ensemble graphs

% figure(itype*1000)
% subplot(3,1,1)
% plot(sFinal(:,3))
% hold on
% plot(pFinal(:,3))
% h = area([sFinal(:,3) pdiff(:,3)]); % fill area in graph
% plot(mSubData(:,3), 'k')
% %         hline = refline([0,0]);
% %         hline.Color = 'k';
% %         set(hline,'LineStyle',':')
%
% h(1).FaceColor = [1 1 1]; % fixes part of the graph that is coloured when it's not supposed to be
% h(2).FaceColor = [0.8 0.8 0.8];
%
% subplot(3,1,2)
% plot(sFinal(:,6))
% hold on
% plot(pFinal(:,6))
% h2 = area([sFinal(:,6) pdiff(:,6)]);
% plot(mSubData(:,6), 'k')
%
%
% h2(1).FaceColor = [1 1 1]; % fixes part of the graph that is coloured when it's not supposed to be
% h2(2).FaceColor = [0.8 0.8 0.8];
%
% subplot(3,1,3)
% plot(sFinal(:,9))
% hold on
% plot(pFinal(:,9))
```

```
% h3 = area([sFinal(:,9) pdiff(:,9)]);
% plot(mSubData(:,9), 'k')
%
%
% h3(1).FaceColor = [1 1 1]; % fixes part of the graph that is coloured when it's not supposed to be
% h3(2).FaceColor = [0.8 0.8 0.8];
% xlabel('% Gait Cycle')
%
% axes('Position',[0 0 0.83 0.96],'Visible','off');
% text(0.5, 0.98,'Trunk Axial Rotation', 'FontSize', 12);
%
% axes('Position',[0 0 0.83 0.66],'Visible','off');
% text(0.5, 0.98,'Lumbar Axial Rotation', 'FontSize', 12);
%
% axes('Position',[0 0 0.83 0.35],'Visible','off');
% text(0.5, 0.98,'Pelvic Axial Rotation', 'FontSize', 12);
%
%       % Figure labels & saving graphs
%       if itype == 1
%           axes('Position',[0 0 1 1],'Visible','off');
%           text(0.38, 0.98,'NLBP Ensemble Graphs', 'FontSize', 15,'FontWeight','bold');
%           figsname = 'NLBPEnsemble';
%           print('-f10',[figspath figsname],'-dpdf','-fillpage')
%       else
%           axes('Position',[0 0 1 1],'Visible','off');
%           text(0.38, 0.98,'LBP Ensemble Graphs', 'FontSize', 15,'FontWeight','bold');
%           figsname = 'LBPEnsemble';
%           print('-f20',[figspath figsname],'-dpdf','-fillpage')
%       end
%   end
% end
```

Appendix 7.2: Peak Difference Method

```
function [phi_corr] = PeakDiff02(phi2,isub)
%PEAKDIFF02 Summary of this function goes here
%   Detailed explanation goes here

phi_corr = phi2;

% for positive jumps
for isub = 1:isub
   for i = 1:size(phi2,2) % columns of phi data (TFE, TLB, TAx, LFE, LLB, LAx, PFE, PLB, PAx)

      phi_diff(:,i,isub) = diff(phi_corr(:,i,isub));
      %find the difference in phi_corr

      %     [gpks,glocs] = findpeaks(phi_diff(:,i,isub),'minPeakHeight',340); % find the peaks of the differences >
340
      glocs = find(phi_diff(:,i,isub) >= 270);
      %     glocs2 = find(phi_negdiff(:,i,isub) >= 300);


      for j = 1:size(glocs,1)
         if j <= size(glocs,1)-1
            phi_corr(glocs(j)+1:glocs(j+1),i,isub) = (phi_corr(glocs(j)+1:glocs(j+1),i,isub)) - (j*360);
         else
            phi_corr(glocs(j)+1:end,i,isub) = (phi_corr(glocs(j)+1:end,i,isub)) - (j(end)*360);

         end
      end

      %        for j = 1:size(glocs2,1)
      %           if j <= size(glocs2,1)-1
      %              phi_corr(glocs2(j)+1:glocs2(j+1),i,isub) = (phi_corr(glocs2(j)+1:glocs2(j+1),i,isub)) - (j*360);
      %           else
      %              phi_corr(glocs2(j)+1:end,i,isub) = (phi_corr(glocs2(j)+1:end,i,isub)) - (j(end)*360);
      %           end
      %        end

      clear glocs
   end


   % for negative jumps
   for i = 1:size(phi2,2) % columns of phi data (TFE, TLB, TAx, LFE, LLB, LAx, PFE, PLB, PAx)

      phi_diff2(:,i,isub) = diff(phi_corr(:,i,isub)); %find the difference in phi_corr

      %     [gpks,glocs] = findpeaks(phi_diff(:,i,isub),'minPeakHeight',340); % find the peaks of the differences >
340
      glocs2 = find(phi_diff2(:,i,isub) <=-  270) ;


      for j = 1:size(glocs2,1)
         if j <= size(glocs2,1)-1
            phi_corr(glocs2(j)+1:glocs2(j+1),i,isub) = (phi_corr(glocs2(j)+1:glocs2(j+1),i,isub)) + (j*360);
```

```
            else
                phi_corr(glocs2(j)+1:end,i,isub) = (phi_corr(glocs2(j)+1:end,i,isub)) + (j(end)*360);

            end
        end

        clear glocs2
    end
end
```

Appendix 7.3: Phi Gaps

```
% S. Mukui Mutunga
% Date Created: sometime in November 2018

% Puprose: fix remaining gaps and jumps that were not fixed by
% PeakDiffMethod

function [phi_corr3] = PhiGaps01(phi_corr2,isub)
phi_corr3 = phi_corr2;

for isub = 1:isub
   [rgaps,cgaps] = find(phi_corr3(:,:,isub) >= 270);
   for i = 1:size(rgaps,1)
      phi_corr3(rgaps(i),cgaps(i),isub) = phi_corr3(rgaps(i),cgaps(i),isub) - 360;
   end

   [rngaps,cngaps] = find(phi_corr3(:,:,isub) <= -270);
   for ii = 1:size(rngaps,1)
      phi_corr3(rngaps(ii),cngaps(ii),isub) = phi_corr3(rngaps(ii),cngaps(ii),isub) + 360;
   end

end

end
```