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EFFECTS OF BACKPACK TYPE ON KINEMATICS OF THE LOWER BACK DURING WALKING AND JOGGING

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THESIS

A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Science in Biomedical Engineering the
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ABSTRACT OF THESIS

EFFECTS OF BACKPACK TYPE ON KINEMATICS OF THE LOWER BACK DURING WALKING AND JOGGING

Heavy backpacks have been suggested to have a pathogenic role in experience of low back pain among children. We have conducted a repeated-measure study to investigate the backpack-induced changes in lumbo-pelvic coordination of forty gender-balanced college age students when they walked and jogged on a treadmill with two different types of backpacks: normal and ergonomically modified. The backpack-induced changes in lumbo-pelvic coordination were larger when carrying an ergonomically modified vs. a normal backpack as well as when jogging versus walking. The larger changes in lumbo-pelvic coordination when carrying an ergonomically modified backpack were likely due to kinematic restraints imposed by rigidity and enhanced attachments devised in the backpack for increased comfort. Given the role of lower back biomechanics in low back pain, the effects of such larger mechanical abnormalities in the lower back when carrying an ergonomically-modified backpack on risk of low back pain among children requires further investigation.

KEYWORDS: School backpack; Ergonomics; Walking and jogging; Lumbo-pelvic coordination

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CHAPTER 1. INTRODUCTION

1.1 Introduction

As concerns grow globally over the role of heavy school backpacks on lower back pain experience among children (Calvo-Munoz, Gomez-Conesa, & Sanchez-Meca, 2013; Negrini & Carabalona, 2002); the usage of ergonomic school backpacks are promoted as a mitigating strategy (Amiri, Dezfooli, & Mortezaei, 2012; Beale, 2004; MB., 2002). Ergonomically designed backpacks are not intended to decrease the weight of load carried, but to offer greater comfort due to better distribution of carried load on different parts of the trunk. Such changes in load distribution and the resultant changes in the center of mass of the loads inside the backpack will alter lower back biomechanics when carrying an ergonomically designed versus a normal backpack during activities of daily living. Despite the widely recognized causal role of lower back biomechanics in occurrence of LBP, the biomechanical effect on the lower back that might occur with ergonomic versus normal backpack utilization is less known.

Therefore, the objective of this Master's thesis was to investigate differences in backpack-induced changes in lower back biomechanics between an ergonomically modified backpack and a normal backpack. Specifically, we compared the changes in magnitude and timing aspects of lumbo-pelvic coordination between a normal and an ergonomically modified backpack during walking and jogging. Our central hypothesis was that backpack-induced changes in timing and magnitude aspects of lumbo-pelvic coordination during walking and jogging will be smaller when carrying an ergonomically modified backpack versus a normal back pack. We further expected that such differences in backpacked-induced changes in lumbo-pelvic coordination to be task dependent (i.e., being larger during jogging versus walking). Examining the relationship between carrying a heavy backpack and risk of LBP via a mechanical causation pathway, was expected to offer an enhanced understanding that will be applicable for designing interventions aimed at prevention of LBP among children.

1.2 Organization of thesis

For this thesis the chapters are organized as follows: To provide a rationale in support of this project, a review of literature concerning effects of school backpacks on spine biomechanics is presented in Chapter 2. Specific objectives as well as the research hypotheses along with methodological approaches used to test the hypotheses are presented in Chapter 3. Results and discussions are also presented in Chapter 3. Finally, a brief description concerning potential future research is presented in Chapter 4.

CHAPTER 2. EFFECTS OF SCHOOL BACKPACKS ON SPINE BIOMECHANICS DURING DAILY ACTIVITIES: A NARRATIVE REVIEW OF LITERATURE

This chapter is being reviewed in Human Factors as a review paper

2.1 Introduction

Low back pain (LBP) is a growing concern for young people with 40% of 9 –18 year olds in high-income, medium-income, and low-income countries reporting they have had low back pain (Calvo-Munoz et al., 2013; Negrini & Carabalona, 2002). Reported annual prevalence of LBP ranges from 22% to 51% in children aged 12–16 years (Watson et al., 2002) and is responsible for missed school days and sleeping problems in 20% and 50% of children, respectively (Roth-Isigkeit, Thyen, Stoven, Schwarzenberger, & Schmucker, 2005).

The weight carried in a backpack has been shown to play a pathogenic role in the development of LBP in children (Negrini & Carabalona, 2002; Nicolet, Mannion, Heini, Cedraschi, & Balague, 2014). Furthermore, 82% of children aged 11–14 years with LBP attribute their pain to backpack use (Shymon et al., 2014). Backpack loads for young people have increased over the past two decades, raising concerns among medical practitioners and parents about the possible detrimental effects (Al-Khabbaz, Shimada, & Hasegawa, 2008) on their health. Recent studies from different countries have shown average backpacks in school children are heavier than the recommended amount of 10%–22% body weight (BW) (Brzek et al., 2017; Mackenzie, Sampath, Kruse, & Sheir-Neiss, 2003; Negrini & Carabalona, 2002; Sheir-Neiss, Kruse, Rahman, Jacobson, & Pelli, 2003; Whittfield, Legg, & Hedderley, 2001). This is concerning because LBP at a young age has been suggested to play an important role in developing chronic LBP in adulthood

(Negrini & Carabalona, 2002). Despite concerns regarding the negative health effects of heavy backpacks, there is limited knowledge about the mechanism(s) linking carrying a heavy backpack with development of LBP in young people.

Repetitive loading of the lumbar spine increases the risk of LBP through cumulative or overuse injuries to spinal tissues (Michael A. Adams, 2013; Mackie & Legg, 2008). Both the frequency and magnitude of loads acting on the spine contribute to risk of cumulative injuries (Brinckmann, Biggemann, & Hilweg, 1988). Backpacks constitute a considerable daily "occupational" load for schoolchildren (Shymon et al., 2014); backpacks are often carried during repetitive or prolonged activities of daily living such as standing, walking, jogging, and stair climbing. Under such conditions, spinal loads are likely to increase considerably. The added mechanical demands of the backpack load on the lower back alters trunk muscle response and recruitment (e.g., involving co-activation) because of muscle fatigue and/or spinal instability (Cholewicki, Panjabi, & Khachatryan, 1997; Granata & Orishimo, 2001; Potvin & O'Brien, 1998).

Vertebrae ossification is not complete until the mid-20's and the relatively high amount of cartilage in the skeletons of children put them at greater risk of overuse injuries compared to adults (O'Day, 2008). Vulnerability of cartilage to shear stresses and repetitive trauma decrease soft-tissue flexibility and induce muscle imbalances (O'Day, 2008). Given that overuse injuries in spinal tissues are likely to have a role in developing LBP, the objective of this review is to summarize the findings of studies that have investigated the effects of carrying school backpacks on the lower back mechanics of young people. Specifically, how backpacks alter forces and deformations of lower back tissues – also referred to as the mechanical environment of the lower back throughout this review – will be examined.

2.2 Methods

A literature search was conducted to identify all pertinent research studies regarding the effects of backpacks on the spine and lower back biomechanics among young people. InfoKat Discovery, a search engine offered by the University of Kentucky library system, was used to search for peer-reviewed articles using combinations of keywords (Table 1) in the title or abstract. InfoKat Discover searches many scientific and medical databases including PubMed, CINAHL, and Ei Compendex. Initial screening identified studies with at least one keyword from each category in its title or abstract. The reference lists from identified articles were checked for additional sources. The first author conducted the search and provided initial screening of the identified literature. Assistance from the co-authors was provided in secondary screening of articles to assure relevance to this review. Specifically, the inclusion criteria considered for this review were 1) reporting of biomechanical measures related to the lower back and 2) involving backpack use during activities of daily living. Some studies had outcome measures in addition to those related to the lumbar region of the back and were also included in this review. Due to the small number of papers meeting these criteria, no limit on the publication year was set. Information regarding sample size, age, gender, backpack type, loading type and location, load (%BW), measurement method, task and duration, and outcome measures were extracted from the final set of articles and are summarized in Table 2.

Table 2.1 Four groups of keywords were used to search the databases. During the initial search, an article would qualify for additional screening if its title or abstract contained at least one keyword from each category.

Keyword Group 1	Keyword Group 2	Keyword Group 3	Keyword Group 4
Backpack	Stress	Back	Children
Schoolbag	Strain	Lower Back	Teen/Teenager
Book Bag	Shear	Trunk	Young
Book Pack	Kinematics	Lumbar	Adolescences
Demand	Kinetics	Pelvis	School
Carriage	Biomechanics	Spine/Spinal	Juvenile
-	Posture	-	-

All articles were further screened to exclude any studies that did not investigate biomechanical measures in young people related to carrying a backpack. Because most of the identified backpack studies focused on the effects of weight or position of the backpack on the lower back and spine biomechanics during upright standing, walking, and ascending and descending stairs, this review has been organized to present relevant findings according to these variables.

2.3 Results and Discussion

The initial database search identified 42 papers, of which 22 met our criteria and were included in the review (Table 2).

Table 2.2 Summary of the 22 reviewed studies meeting review criteria, sorted alphabetically by last name of first author

Study	**Sample Size**	**Age (years)**	**Gender**	**Backpack Type**	**Loading Type/Location**	**Load (%BW)**	**Task**	**Task Duration**	**Measurement Method**	**Outcome Measurement**
Al-Khabbaz et al. (2008)	19	18-24	M	Normal	Symmetrical	0, 10, 15, 20	Standing	5 sec.	VICON Motion Analysis System and Surface EMG	Trunk Inclination and Muscle Activity
Brackley et al. (2009)	15	10	M, F	Normal	Symmetrical (High, Medium, Low)	0, 15	Standing and Walking	30 min.	Spring Loaded Potentiometers	Spinal Curvature and Trunk Inclination
Brzek et al. (2017)	155	7-9	M, F	Normal	Symmetrical	Varied	Standing	-	Pedi-Scoliometer, Dobosiewicz Methodology	Spinal Curvature and Trunk Inclination
Chow et al. (2007)	15	15-16	M	Normal	Symmetrical	0, 10, 15, 20	Standing	-	5 Camera Motion Analysis	Spinal Curvature and Lumbar Repositioning Ability
Chow et al. (2010)	19	10-11	M, F	Normal	Symmetrical Anterior and Posterior (CG at T7, T12, Or L3)	0,15	Standing	-	6 Gravitationally Referenced Accelerometers	Spine Curvature and Lumbar Repositioning Ability
Devroey et al. (2007)	20	20-27	M, F	Normal	Symmetrical (Thoracic and Lumbar)	0, 5, 10, 15	Standing and Walking	1-5 min.	6 Camera VICON System	Trunk Kinematics and Muscle Activity

Drzal-Grabieca et al. (2015)	162	11-13	M, F	Normal	Asymmetrical	0, 10	Standing	-	Photogrammetry	Spinal Posture
Drzal-Grabieca et al. (2015)	162	11-13	M,F	Normal	Asymmetrical	0, 10	Standing	-	Photogrammetry	Spinal Posture
Goh et al. (1998)	10	18-21	M	Normal	Symmetrical	0, 15, 30	Walking	-	5 Camera Motion Analysis	L5/S1 Joint Deformation
Goodgold et al. (2002)	2	9-11	M	Normal	Symmetrical	0, 8.5, 17	Standing, Walking, And Running	-	Peak 5 Motion Analysis Videography	Trunk Inclination
Grimmer et al. (2002)	250	12-18	M, F	Normal	Symmetrical (High, Medium, Low)	0, 3, 5, 10	Standing	-	Photograph Analysis with Anatomical Markers	Spinal Posture
Hong et al. (2000)	15	10	M	Normal	Symmetrical	0, 10, 15, 20	Walking	~1 min.	3-CCD Camera and Motion Analysis	Trunk Inclination
Hong et al. (2003)	11	9-10	M	Normal	Symmetrical	0, 10, 15, 20	Walking	20 min.	Video Motion Analysis	Trunk Inclination
Hong et al. (2011)	13	11-13	M	Single Strap, Athletic Bag, and Normal Backpack	Symmetrical and Asymmetrical	0, 10 ,15, 20	Stairs Ascending and Descending	-	Video Motion Analysis	Trunk Inclination

Kistner et al. (2013)	62	8-11	M, F	Normal	Symmetrical	0, 10, 15, 20	Standing and Walking	6 min.	Photograph Analysis	Spinal Curvature and Trunk Inclination
Li et al. (2003)	15	10	M	Normal	Symmetrical	0, 10, 15 20	Walking	20 min.	Video Analysis	Trunk Inclination
Mackie et al. (2008)	16	13-14	M	Normal	Symmetrical	0, 5, 10, 12.5, 15	Simulated School Day	~123 min. over 6 days	Video Analysis Using Anatomical Markers	Spinal Posture
Pascoe et al. (1997)	10	11-13	M, F	One & Two Strap Backpack and One-Strap Athletic Bag	Symmetrical and Asymmetrical	-	Standing and Walking	-	Video Analysis	Spinal Curvature and Trunk Inclination
Ramprasad et al. (2010)	209	12-13	M	Normal	Symmetrical	0, 5, 10, 15, 20, 25	Standing	-	Photograph Analysis with Anatomical Markers	Trunk Inclination
Shymon et al. (2014)	15	7-17	M, F	Normal	Symmetrical	0, ~10, ~20	Standing	~10 min.	MRI Scanner	Spinal Curvature and Lumbar Disc Deformation
Singh et al. (2009)	17	7-11	M	Normal	Symmetrical (High, Low)	0, 10, 15, 20	Standing and Walking	6 min.	6 Camera Motion Capture	Trunk Inclination
Walicka-Cupryś et al. (2015)	109	7	M, F	Varied Per Subject	Varied Per Subject	Varied Per Subject	Standing	~50 min.	Ultrasonic 3D Analysis	Spinal Curvature

2.4 Effects of backpack weight

2.4.1 Posture and Kinematics

Backpack loading has been reported to cause immediate changes in the natural curvature of the spine and to affect deformation of lumbar discs with a positive association between loading and deformation (Shymon et al., 2014). Backpack-induced alterations in lumbar curvature have been suggested to adversely affect repositioning ability of the lumbar spine (Brzek et al., 2017; Chow, Leung, & Holmes, 2007; Pascoe, Pascoe, Wang, Shim, & Kim, 1997; Shymon et al., 2014).

In standing posture, backpack-induced forward trunk inclination, relative to a vertical line, has been reported to range between 3.02° and 6.8° for backpack weights ranging from 10% to 20% of BW (Brackley, Stevenson, & Selinger, 2009; Kistner, Fiebert, Roach, & Moore, 2013; Mackie & Legg, 2008). Backpack-induced forward trunk inclination has also been observed under lighter backpack weights (Ramprasad, Alias, & Raghuveer, 2010). Specifically, Ramprasad et al. (2010) studied 209 males of average age 12.5 years and reported an increase in forward trunk inclination of 3.21° compared to the no-backpack condition when using a backpack weight equal to 5% of BW (Ramprasad et al., 2010).

On the other hand, a study of 19 males with an average age of 21 years found an average trunk backward inclination of 3.43° during standing for backpack weights of up to 20% of BW (Al-Khabbaz et al., 2008). The conflicting results of this study may be due in part to the material used to increase the load. The Al-Khabbaz study used sand, which is more likely to collect at the bottom of the backpack compared to weights or books, which were used in the Ramprasad study.

The effects of alterations on the center of mass of the backpack and its load have been noted in the literature. For instance, alterations in the backpack's center of mass such that it is positioned at the T7, T12 and L3 spinal levels, resulted in 6.0°, 5.4°, and 3.3° increases in lower lumbar spine flexion, respectively (Chow et al., 2010). Compared to the no-backpack condition, Devroey et al (2007) observed ~2° lumbar extension and ~6° hip flexion in standing posture of 20 college-aged students (12 male, 8 female) under a backpack load of 15% of BW (Devroey, Jonkers, de Becker, Lenaerts, & Spaepen, 2007). In studies investigating backpack heaviness during standing, a negative relationship has been reported between flattening of both lumbar lordosis (T12-L3-S1) and thoracic kyphosis (C7-T2-T5) and increased backpack weight. Specifically, an average of ~3° flattening in lumbar lordosis and thoracic kyphosis angles with 10% of BW increase in backpack weight has been shown (Chow et al., 2007; Walicka-Cuprys, Skalska-Izdebska, Rachwal, & Truszczynska, 2015). Negative relationships were drawn between decreased sacrum inclination (backward pelvis tilt) and increased weight of backpack in 109 (58 girls and 51 boys) 7-year-old children. The average change when using a backpack lighter than 10% of BW versus a backpack heavier than 10% of BW was ~5° (Walicka-Cuprys et al., 2015).

During walking, trunk forward inclination has been reported to increase from 4.84° to 19.80° by increasing the backpack's weight from 10% to 20% of BW. Furthermore, backpack-induced forward inclination of the trunk during walking has been reported to intensify as walking distance increases (Goodgold et al., 2002; Hong & Brueggemann, 2000; Hong & Cheung, 2003). Li et al. investigated backpack-induced changes in trunk kinematics among 15 males with a mean age of 10.36 years and found that walking with a backpack heavier than 10% of BW induced a 4.55° increase in forward trunk inclination compared to the no-backpack condition after only 1 minute (Li, Hong, & Robinson, 2003). Goodgold et al. assessed trunk posture for 2 male subjects during running under various backpack weights. They found the average maximum trunk forward inclination angles to be 22.05° and 19.2° for backpack weights of 8.5% and 17.5% of BW, respectively. The maximum average of for the no-backpack condition was 14.2° (Goodgold et al., 2002).

For ascending stairs (33 steps), the lumbar flexion of 13 male children (average age 12.2) was investigated. Carrying backpack loads of 10%, 15%, or 20% of BW were found to result in lumbar flexions with average values of 11.9°,10.7°, and 11.1°, respectively (Hong, Fong, & Li, 2011).

2.4.2 Muscle Activity

During standing, a 100% increase in rectus abdominus and obliques activity and 100% decrease in bilateral muscle activity of the erector spinae longissimus have been reported for a backpack load of 15% of BW when compared to no-backpack condition (Devroey et al., 2007).

Using 10 males of mean age 19.9 years, Goh et al. investigated the effects of backpack loading on lower back net moment during walking. They observed that carrying a given backpack load resulted in a non-linear increase in the L5/S1 joint moment (26.67% for a load of 15% of BW; 64% for a load of 30% of BW) (Goh, Thambyah, & Bose, 1998).

Such disproportionate increase in L5/S1 moment suggests a substantial demand on trunk muscles to offset the task demand.

2.5 Effects of Backpack Position

2.5.1 Posture and Kinematics

In addition to the backpack weight, the position (vertical and horizontal) of the backpack relative to the back affects spine kinematics and kinetics. Most studies indicated that children experience the least amount of postural deviations when the backpack is placed low on the back (Brzek et al., 2017; Grimmer, Dansie, Milanese, Pirunsan, & Trott, 2002; Singh & Koh, 2009). This is contrary to the widespread belief that backpacks should be worn high on the back (Brackley et al., 2009). Apart from changes in spinal posture under symmetric backpack load, studies reported excessive postural deviation, mainly in the coronal plane, under asymmetric load (i.e., backpack on the left or right shoulder) (Brzek et al., 2017; Singh & Koh, 2009).

For standing posture, a study involving 162 children (82 girls and 80 boys) aged 11–13 years found that asymmetric backpack loads compared to no backpack resulted in ~11% reduction in thoracic kyphosis (Drzal-Grabiec, Snela, Rachwal, Podgorska, & Rykala, 2015; Drzal-Grabiec, Truszczynska, et al., 2015). However, none of these studies reported the outcome measures for symmetric loading. When comparing either thoracic placement (top of the backpack on the shoulder line) or lumbar placement (bottom of the backpack carried just above the spina iliac posterior superior) of backpack to the no-backpack condition, there was a significant increase in pelvic forward rotation (~ 4°) and hip flexion (~3°) (Devroey et al., 2007).

Although there was no significant change in lumbar flexion or thoracic rotation for either placement compared to the no-backpack condition, there was a trend that included lumbar extension for thoracic placement and lumbar flexion for lumbar placement. Placement of backpack on thorax versus lumbar spine was found to cause changes in thorax and lumbar curvature during walking similar to those observed during upright standing, except for an increase in lumbar flexion and trunk range of motion (Devroey et al., 2007).

Both anterior (front of body) and posterior (back of body) placement of backpack on the trunk resulted in changes in spinal curvature; changes that were magnified with increasing backpack load. (Chow, Ou, Wang, & Lai, 2010). When the backpack was placed anteriorly with its center of mass located at the T7 spinal level, an increase in pelvic backward tilt (5.5°) was observed. When placed posterior on the trunk, with the backpack's center of mass at the T7, T12 and L3, there were 6.0°, 5.4° and 3.3° increases in lower lumbar spine flexion, respectively (Chow et al., 2010). Furthermore, for the same positions, there were significant increases in upper lumbar flexion (3.0°), lower thoracic rotation (2.0°), and upper thoracic rotation (4.4°) (Chow et al., 2010). The smallest change in spinal curvature was observed when the backpack's center of mass was positioned in front and at the T12 level (Chow et al., 2010).

For asymmetric backpack loading when ascending stairs, Hong et al. (2011) reported an increase of ~8.3° in trunk lateral bending toward the supported side (strap side) and a decrease of ~2.7° in trunk lateral bending of the loaded side compared to unloaded stairs ascending (Hong et al., 2011). A similar pattern of results was found during stairs descending with a supported side lateral bending equal to 4.2° and a loaded side lateral bending equal to 2.1° (Hong et al., 2011).

2.5.2 Muscle Activity

In general, regardless of backpack positioning, there were significant changes, relative to a no-backpack condition, of bilateral trunk muscle activity for walking tasks (Devroey et al., 2007). These included a 100% increase in activity of rectus abdominus, a 40% increase in activity of the obliques, and a 30% reduction in activity of the erector spinae (Devroey et al., 2007).

2.6 Conclusion:

The objective of this narrative review was to summarize the findings of studies that have investigated the effects of carrying school backpacks on the lower backs of young people. Although narrative reviews serve as useful educational tools, they do not offer a foundation for design of intervention or making clinical decisions (Green, Johnson, & Adams, 2006). When interpreting the results of studies discussed in this review, the readers should keep in mind that the strengths and weaknesses of the reviewed studies that were not discussed due to the nature of this narrative review (e.g., as compared to systematic reviews).

Abnormal mechanics of the lower back, including excessive forces and deformations, have been shown to directly and indirectly irritate pain-sensitive nerve endings in tissue and cause LBP (M. A. Adams, 2004; Marras, 2008; McGill, 2007; White A, 1990). The reported backpack-induced changes in spinal posture and deformation as well as trunk muscle activity in young people appears to negatively affect the mechanical environment of the low back. Particularly, the added load of the backpack along with the reported changes in spine/trunk posture when carrying a backpack is likely to impose considerable demand on trunk muscles to assure equilibrium and stability of the spine. These demands lead to substantial increases in spinal loads even under activities that are not physically demanding (e.g., walking). Despite current recommendations on backpack weight limits (Brackley et al 2004), the impact of backpack weight on spinal loads (i.e., the resultant of internal tissue responses and external mechanical demand of the task) during daily activities remains unclear and should be investigated in the future.

The risk of fatigue failure of spinal tissues under typical repetitions of daily activities (e.g., 10,000 steps walking) is relatively low for the magnitude of spinal loads experienced during most daily activities. However, the risk of fatigue failure substantially increases with even modest increases in spinal loads associated with carrying a backpack (Brinckmann et al., 1988; Gallagher & Heberger, 2013). To better understand the role of carrying a school backpack on the development of low back pain among children, it is therefore important to determine backpack-induced changes in spinal loads due to not only the immediate, but also the prolonged effects of carrying a backpack on lower back mechanics. Related to biomechanical effects of carrying a backpack, most of the reviewed studies reported changes in biomechanical measures with a backpack compared to habitual posture. To our best knowledge, the effects of backpack type on lower back biomechanics has not yet been reported in the literature. Such studies might offer an important foundation for better design of school backpacks via ergonomics principles (e.g., in terms of load distribution and contact with the trunk) that could mitigate the adverse biomechanical effects of current school backpacks.

CHAPTER 3. THE EFFECTS OF BACKPACK TYPE ON LUMBO-PELVIC COORDINATION DURING WALKING AND JOGGING

This chapter is being reviewed in Ergonomics.

3.1 Introduction

Low back pain (LBP) as a result of carrying heavy school backpacks is an increasing concern worldwide (Calvo-Munoz et al., 2013; Negrini & Carabalona, 2002). To mitigate the negative effects of carrying school backpacks on the lower back, ergonomic backpacks have been designed, marketed, and used (Amiri et al., 2012; Beale, 2004; MB., 2002). Although the design of an ergonomic backpack versus a normal backpack may not decrease the weight of the load carried, the geometry of an ergonomic backpack and its connection to the body will change the center of mass and load distribution on different parts of the trunk. Whether/how the differences in design of an ergonomic versus a normal school backpack affect the biomechanics of lower back (i.e., an important contributor to LBP occurrence) is, however, less known.

From a biomechanical perspective, the effects of weight and position of school backpack on the spinal posture and deformations as well as on mechanical demand of activity on the lower back have been reported in the literature (Suri, 2018). Most of these earlier biomechanical studies have focused on walking and jogging. Carrying backpack with weights ranging from 10% to 20% of body weight (BW) has been reported to increase trunk forward inclination between ~ 5° to ~ 20° during walking. Furthermore, such an inclination has been found to increase when the walking distance is extended (Goodgold et al., 2002; Hong & Brueggemann, 2000; Hong & Cheung, 2003) or when jogging instead of walking (Goodgold et al., 2002). Additionally, vertical placement of backpacks closer to the thorax versus lumbar region of the spine has been associated with increases in the lumbar flexion during walking (Devroey et al., 2007). Walking with a backpack load of 15% of BW has been reported to cause a 100% increase in activity of rectus abdominus, a 40% increase in activity of the obliques, and a 30% reduction in activity of the erector spinae from habitual walking condition (Devroey et al., 2007). Increasing a backpack load from 15% to 30% of BW during walking has been shown to be associated with an increase in the net moment at the lower back from 27% compared to no backpack condition up to 64% (Goh et al., 1998). Although these earlier studies highlighted the effects of carrying school backpacks on lower back biomechanics during walking and jogging, to the best of our knowledge no study has investigated the effects of backpack type on lower back biomechanics during these activities (Suri, 2018).

The objective of this study was to investigate the effects of two different backpack types on lumbo-pelvic coordination, as an indicator of lower back biomechanics, during walking and jogging. Specifically, we compared the changes in magnitude and timing aspects of lumbo-pelvic coordination between a normal and an ergonomically modified backpack. It was hypothesized that, relative to habitual walking and jogging, smaller changes in magnitude and timing aspects of lumbo-pelvic coordination would occur when performing the activity with an ergonomically modified versus a normal backpack. Further, we hypothesized that such differences in backpack-induced changes in measures of lumbo-pelvic coordination to be larger when jogging versus walking. The smaller impact of ergonomically modified backpacks is assumed to be due to better and tighter distribution of carried load on the back from extra features such as a rigid frame or extra strap around the hip, shoulder, or chest.

3.2 Methods

3.2.1 Study design and participants

A repeated measure study was designed to compare the alterations in lumbo-pelvic coordination of habitual walking and jogging when carrying a normal and an ergonomically modified backpack. Forty gender-balanced individuals between 18-22 years old were recruited from the

University of Kentucky's campus as well as a local High School. Before conducting any data collection, participants completed an informed consent procedure approved by the Institutional Review Board of the University of Kentucky. Consented individuals were then screened for the following inclusion criteria: no history of neuromuscular disorders, no back pain within the past year, and a body mass index (BMI) between 20 and 30 kg/m^2. The mean (SD) values of stature, body mass, and BMI were respectively 176.8 cm (6.2 cm), 76.0kg (10.8kg), and 24.3kg/m2(2.7 kg/m2) for male and 166.0 cm (6.4 cm), 62.8kg (6.5kg) and 22.8kg/m2(1.9 kg/m2) for female participants.

3.2.2 Description of Backpack and Load

The ergonomically modified backpack was a hiking backpack (Jansport, Model: Klamath 65, Alameda, CA) that was ergonomically improved using GridFit technology (i.e., a torso adjustment system). The improved features included a rigid frame for back support with adjustable height as well as shoulder, hip, and chest straps with adjustable tightness (Fig. 1). This backpack was chosen in lieu of a fully designed and rigorously tested ergonomic backpack due to not having access to such a backpack. The normal backpack, (OGIO, Model number: 670388K, Carlsbad, CA), was only equipped with basic adjustable shoulder straps (Fig. 1). To prevent trunk postural abnormalities and reduce the risk for LBP, earlier studies have suggested that a backpack weight should be limited to 10%-15% of BW (Suri, 2018). Therefore, we filled the backpacks with letter size papers to the extent that the backpack's weight plus the paper load equal to 10% of BW for each participant.

Figure 3-1 The ergonomically modified (left) and normal (right) backpacks used in this study. Each backpack was filled by letter size papers to generate a backpack weight equal to 10% of participant's body weight.

3.2.3 Experimental Procedures

To collect kinematics of thorax and pelvis (50 Hz), wireless Inertial Measurement Units (IMUs; Xsens Technologies, Enschede, Netherlands)[1] were attached on the trunk superficial to the sternum and bilaterally ~ 1cm below the highest point of the left/right iliac crest on the pelvis. Before starting experimental procedures, participants warmed up on a treadmill and were asked to determine speeds most reflective of their natural walking and jogging paces. Afterward, they repeated both walking and jogging activities under three conditions: no backpack, normal backpack, and ergonomically modified backpack. For each activity, the participants were instructed to start the treadmill and get

[1] The Xsens MTw™ system is a miniature wireless inertial measurement unit system incorporating 3D accelerometers, gyroscopes, magnetometers, and a barometer.

to the predetermined pace, and once at the desired pace continue the activity for thirty seconds. Participants were allowed to perform each activity with hands placed comfortably (e.g., holding backpack straps, at their sides, etc.), but without touching the treadmill. The order of the activities (walking and jogging) and the backpack conditions (no backpack, normal backpack, and ergonomically modified backpack) were randomized. Prior to walking and jogging activities, each participant performed three repetitions of trunk forward bending and backward return with no backpack to obtain his/her trunk range of rotation for the purpose of normalization of select kinematics measures (Shojaei, Suri, & Bazrgari, 2018). Specifically, each forward bending and backward return included a 5 second upright standing, bending forward at a self-selected pace up to the participant's maximum comfortable trunk flexed posture, holding the maximum flexed posture for 5 seconds, and then returning to the initial upright standing posture.

3.2.4 Data Analysis

An in-house computer code, developed in MATLAB (The MathWorks Inc., Natick, MA, USA, version 9.2.0), was used to calculate pelvic and thoracic rotations with respect to upright standing posture using the rotation matrices generated by the IMUs' software (MT manager, Xsens Technologies, Enschede, Netherlands) (Vazirian, Shojaei, Agarwal, & Bazrgari, 2017; Vazirian, Shojaei, & Bazrgari, 2017). The lumbar flexion at each instant of activity was calculated by subtracting the pelvic rotation from the thoracic rotation. To exclude any transient changes in measured kinematics at the beginning and at the end (i.e., including only steady state stage of activity), we only considered the middle fifty percent of the data collected (i.e., ~ 15 second of data collection duration) during the walking and jogging activities for subsequent data analyses. In the absence of ground reaction force data, we determined the gait cycles using similar data points on rotation curve of a segment with clear cyclic behavior (e.g., two consecutive maximum values of thoracic inclination in the sagittal plane). The minimum and the maximum thoracic and pelvic forward inclinations (i.e., equal to their respective values of forward rotation relative to standing posture) as well as lumbar flexion were first extracted for each cycle of activity (Fig. 2) and then averaged across all cycles to represent measures of the magnitude aspect of lumbo-pelvic coordination for that activity.

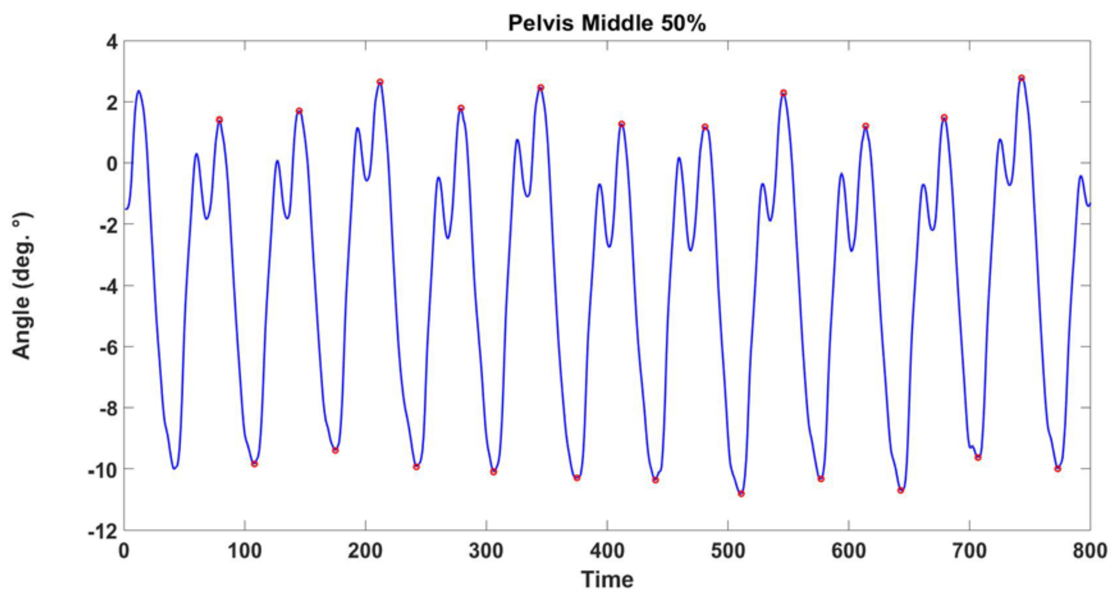

Figure 3-2 Example plot of pelvic inclination for middle 50% of the gait cycle with maximum and minimum values marked.

The timing aspect of lumbo-pelvic coordination was characterized using measures of continuous relative phase between thorax and pelvis during each cycle of each activity (Vazirian, Shojaei, Agarwal, et al., 2017; Vazirian, Shojaei, & Bazrgari, 2017). To do this, the thoracic and pelvic rotations were first reformatted for each activity cycle to set their median value as the new zero (i.e., rotations change between equal positive and negative values). The phase angle for each rotation was then calculated as the tangent inverse of the Hilbert transformation of the reformatted rotation over the reformatted rotation. The continuous relative phase between thorax and pelvis for that activity cycle was then calculated by subtracting the pelvic phase angle from the thoracic phase angle at each time instant of the activity cycle. Two specific measures, the mean absolute relative phase (MARP) and the deviation phase (DP), were calculated from the above described continuous relative phase between thorax and pelvis for each activity cycle. The average values of MARP and DP across all cycles of each activity were considered to represent the timing aspect of lumbo-pelvic coordination during that activity (Vazirian, Shojaei, Agarwal, et al., 2017; Vazirian, Shojaei, & Bazrgari, 2017). MARP values closer to 0 represent a more ‘‘in-phase’’ lumbo-pelvic coordination or a more synchronous movement of pelvis and thorax segments, whereas values of MARP closer to π represent a more ‘‘out-of-phase’’ lumbo-pelvic coordination or less synchronous movement of pelvis and thorax segments. Furthermore, smaller values of DP represent a lumbo-pelvic coordination with less trial-to-trial variability or a more stable motion pattern.

3.2.5 Statistical analysis

The changes in all outcome measures when performing the activity with versus without a backpack were first calculated for both backpack types under each activity. Changes in measures of timing aspects of lumbo-pelvic coordination for each backpack condition were then normalized to corresponding values under no backpack condition. Some measures of magnitude aspects of lumbo-pelvic coordination under no backpack condition were very small (i.e., $<< 1°$) resulting in unrealistically large number when used for normalization. As such, we normalized measures of magnitude aspects of lumbo-pelvic coordination using corresponding value obtained from trunk forward bending and backward return task. Specifically, changes in measures of magnitude aspects of lumbo-pelvic coordination were normalized to ranges of thoracic, pelvic and lumbar rotation/flexion obtained during trunk forward bending and backward return. For instance, for each person and backpack condition, the changes in maximum and minimum forward thoracic inclinations were normalized to thoracic range of rotation obtained during forward bending and backward return for that person. Since lumbo-pelvic coordination is affected by gender (Shojaei, Vazirian, Salt, Van Dillen, & Bazrgari, 2017), it was included in the statistical analysis to capture potential interaction effects of backpack type with these factors. Mixed-model analysis of variance (ANOVA) tests were conducted on the dependent variables with gender (male and female) as the between-subjects factor, and backpack type (ergonomically modified and normal) and activity (walking and jogging) as the within-subject factors. All statistical procedures were conducted in SPSS (IBM SMSS Statistics 24, Armonk, NY, USA), mixed-model ANOVA assumptions were verified, and a p value ≤ 0.05 was considered to be statistically significant.

3.3 Results

3.3.1 Baseline measures:

The mean value of measures corresponding to magnitude and timing aspects of lumbo-pelvic coordination under habitual (no backpack) walking and jogging are summarized in Table 3.1.

Table 3.1 Summary of outcome measures including mean (SD) for the baseline (no backpack) condition. Positive and negative values denote respectively forward and backward rotation/flexion with respect to standing posture.

Baseline measures (°)	Activity	
	Jogging	*Walking*
Max. Thoracic Forward Inclination	21.3(8.9)	8.9(6.8)
Max. Pelvic Forward Inclination	9.4(5.4)	3.1(3.8)
Max. Lumbar Flexion	23.5(9.0)	13.0(7.5)
Min. Thoracic Forward Inclination	8.8(7.6)	2.0(6.0)
Min. Pelvic Forward Inclination	-4.6(5.8)	-6.3(4.7)
Min. Lumbar Flexion	1.7(9.0)	1.2(7.1)
MARP	0.25(0.10)	0.24(0.07)
DP	0.79(0.11)	0.87(0.08)

The ranges of thoracic, pelvic, and lumbar rotations/flexion, obtained from forward bending and backward return task, were respectively 115.1°, 39.2°, and 82.8°.

3.3.2 Interaction Effects

There was a three-way interaction effect involving backpack type, gender, and activity on changes in the maximum lumbar flexion (Table 3.2). Specifically, during jogging the simple effects of backpack type on changes in the maximum lumbar flexion were significant (F=11.20, p=0.005) only for the male group such that the reduction in maximum lumbar flexion was larger in ergonomically modified (-6.7%) vs. normal backpack (0.3%).

3.3.3 Main Effects

The minimum pelvic forward inclination was different between the backpack condition (*F*=10.83, *p*=0.003) such that it increased ~ 11% for ergonomically modified while decreased ~4% for normal backpack (Table 3.2, and Table 3.4). Additionally, the MARP increased (5.46%) under normal backpack but decreased (-6.73%) under ergonomically modified backpack (*F*=9.22, *p*=0.005; Tables 3.3 and 3.4). Finally, the maximum and the minimum forward trunk inclination reduced under both backpack conditions, but the reduction was larger under jogging versus walking (F>5, *p*<0.026; Tables 3.2 and 3.4)

Table 3.2 Summary of statistics results for the effects of backpack type (normal backpack and ergonomically modified backpack), gender (male and female), and activity (walking and jogging) on the changes (%) in magnitude aspects of lumbo-pelvic coordination during walking and jogging.

Changes (%)	**Magnitude of lumbo-pelvic coordination**											
	Max. Thoracic Forward Inclination		*Max. Pelvic Forward Inclination*		*Max. Lumbar Flexion*		*Min. Thoracic Forward Inclination*		*Min. Pelvic Forward Inclination*		*Min. Lumbar Flexion*	
	F	*p*	*F*	*P*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
Backpack (B)	3.47	0.075	0.07	0.799	18.54	**<0.001**	0.89	0.356	10.83	**0.003**	2.62	0.119
Gender (G)	1.49	0.234	<0.00	0.987	0.29	0.593	0.76	0.393	1.38	0.252	0.06	0.805
Activity (A)	5.64	**0.026**	0.69	0.415	0.04	0.836	9.96	**0.004**	0.06	0.807	0.01	0.895
B X G	0.02	0.878	3.77	0.064	2.36	0.138	0.19	0.661	2.38	0.136	0.96	0.338
B X A	0.01	0.906	1.50	0.232	0.85	0.365	3.55	0.072	2.85	0.104	0.36	0.553
G X A	0.09	0.762	3.30	0.082	1.06	0.314	0.17	0.680	2.22	0.149	2.87	0.103
B X G X A	0.72	0.404	0.27	0.609	4.58	**0.043**	0.51	0.484	0.34	0.563	1.03	0.322

Table 3.3 Summary of statistics results for the effects of backpack type (normal backpack and ergonomically modified backpack), gender (male and female), and activity (walking and jogging) on the changes (%) in timing aspects of trunk kinematics for walking and jogging.

Changes (%)	**Timing of lumbo-pelvic coordination**			
	MARP		*DP*	
	F	*p*	*F*	*p*
Backpack (B)	9.22	**0.005**	0.06	0.806
Gender (G)	0.19	0.658	0.27	0.606
Activity (A)	2.57	0.118	2.17	0.150
B X G	0.44	0.443	2.32	0.137
B X A	1.61	0.214	0.29	0.590
G X A	<0.00	0.991	0.75	0.394
B X G X A	0.08	0.783	0.65	0.427

Table 3.4 Summary of outcome measures including mean (SD) for the effects of backpack type (normal backpack and ergonomically modified backpack), gender (male and female), and activity (walking and jogging) on the changes (%) in magnitude and timing aspects of trunk kinematics for walking and jogging.

Changes (%)	Backpack Type		Gender		Activity	
	Normal	*Ergonomics*	*Male*	*Female*	*Walking*	*Jogging*
Max. Thoracic Forward Inclination	-1.5(5.2)	-3.2(6.0)	-3.3(5.7)	-1.17(5.3)	-1.4(4.2)	-3.3(6.6)
Max. Pelvic Forward Inclination	-10.1(29.7)	-7.8(31.8)	-8.9(30.1)	-9.0(31.5)	-5.8(29.2)	-12.1(32.0)
Max. Lumbar Flexion	0.3(9.8)	-6.7(8.2)	-3.9(10.9)	-2.4(8.0)	-3.1(7.1)	-3.3(11.7)
Min. Thoracic Forward Inclination	-1.9(5.1)	-2.7(4.66)	-2.9(4.9)	-1.6(4.7)	-1.5(4.6)	-3.1(5.0)
Min. Pelvic Forward Inclination	-3.8(40.6)	11.2(39.1)	-2.1(30.2)	10.4(49.1)	3.0(11.4)	4.34(56.2)
Min. Lumbar Flexion	-0.1(10.3)	-2.8(8.4)	-1.8(10.6)	-1.1(8.1)	-1.7(7.3)	-1.3(11.3)
MARP	5.5(49.2)	-6.7(42.1)	1.7(47.8)	-3.1(44.2)	6.8(39.8)	-8.0(50.7)
DP	-1.4(10.3)	-1.1(13.4)	-0.5(12.1)	-2.0(11.7)	-2.7(10.6)	0.2(13.0)

3.4 Discussion

The purpose of this study was to investigate changes in the magnitude and timing aspects of lumbo-pelvic coordination of habitual walking and jogging when carrying an ergonomically modified and a normal backpack. Contrary to our primary hypothesis, changes in measures of lumbo-pelvic coordination, wherever significant, were larger when performing the activity with ergonomically modified versus the normal backpack. Regardless of backpack typed carried, the observed changes in measures of lumbo-pelvic coordination were larger when jogging compared to walking (i.e., confirming our secondary hypothesis).

It has been suggested that carrying school backpacks can play a pathogenic role in developing LBP among young people (Negrini & Carabalona, 2002; Nicolet et al., 2014). Among children (11-14 years-old) who experience LBP, 82% attribute their pain to carrying backpacks (Shymon et al., 2014). However, the relationship between carrying a heavy backpack and development of LBP is not well understood. The average school children carry backpack loads that are greater than the recommended amount of 10% of BW and reach even up to 22% of BW (Brzek et al., 2017; Mackenzie et al., 2003; Negrini & Carabalona, 2002; Sheir-Neiss et al., 2003). Cumulative or overuse injuries in spinal tissues could occur when carrying heavy backpack during repetitive activities like walking and jogging, and hence can increase the risk of developing LBP. While being essential activities of daily living, walking and jogging expose the lower back tissues to a very repetitive loading condition with up to ~ 13000 loading cycle per day (i.e., equal to typical number of step per day in college students and younger children) (Tudor-Locke et al., 2011). Exposure to such high level loading cycles can pose a risk of tissue fatigue failure, if the peak load experienced in each cycle is even about half the static threshold of tissue injury. This is especially true in children who have a relatively high amount of cartilage in their skeletons which puts them at a greater risk of overuse injuries compared to adults (O'Day, 2008).

To the best of our knowledge, no earlier study has investigated the effects of carrying different types of backpack on lumbo-pelvic coordination during walking and jogging. However, studies investigated effects of carrying a normal backpack on lumbo-pelvic coordination during these activities have reported conflicting results concerning the effects (Suri, 2018). While some reported an increase in trunk forward inclination with backpack (Brackley et al., 2009; Goodgold et al., 2002; Hong & Brueggemann, 2000; Hong & Cheung, 2003; Kistner et al., 2013; Mackie & Legg, 2008; Ramprasad et al., 2010) others have suggested a decrease (Al-Khabbaz et al., 2008). Our results indicated a decrease in trunk forward inclination for both backpack conditions and both activities. Notwithstanding the differences in experimental methods between our study and earlier studies, differences in participant age might have also played a role in the above described conflicting results. Specifically, the studies reporting decrease in trunk inclination with backpack involved college age participants whereas the other studies involved younger children (Suri, 2018).

It has been reported that placement of a backpack closer to the body’s center of mass results in a smaller change in the posture and trunk kinematics when carrying the load (Kinoshita, 1985). We, however, observed larger changes in pelvic forward inclination and lumbar flexion (only in males during jogging) with ergonomically modified backpacks despite the fact that the loads were stacked more vertically and were, therefore, closer to the body's center of mass. Such results can be due to the specific way the ergonomically modified backpack is connected to the body using straps, around pelvis and thorax, that can significantly affect lumbo-pelvic coordination during walking and jogging (Suri, 2018). Stokes et al. (1989) observed that the pelvis rotates opposite the shoulders around the vertical axis, meaning that as the left (right) side of the pelvis rotates forward the left (right) shoulder rotates backward (Stokes, Andersson, & Forssberg, 1989). Pelvis rotation also is an indicator of leg position during stride cycle and, therefore, when one leg strikes the ground the shoulder opposite this leg is lifted and rotated forward (Stokes et al., 1989). The observed larger changes in magnitude aspects of lumbo-pelvic coordination could be in part due to restriction imposed to such inverse coupling by straps of the ergonomically modified backpack. Inhibition of such an inversely-related coordination (i.e., shoulder and pelvis rotation) has been shown to trigger a compensatory trapezius and back muscles activation to allow the proper coordination of the pelvis and shoulders (Holewijn, 1990). Therefore, the kinematics restriction imposed by the ergonomically modified backpack, for the sake of better load distribution on the trunk, may have resulted in larger muscle forces and spinal loads on the lower back during walking and jogging activities.

There was a 12.2% difference in MARP between carrying an ergonomically modified and a normal backpack. The smaller MARP noted with ergonomically modified backpack, also known as phase-locked or rigid coordination, has been referred as a protective motor control strategy in patients with LBP to reduce the likelihood of large deformation of spinal tissues and injury. In previous studies investigating timing aspects of lumbo-pelvic coordination (Shojaei et al., 2017; Vazirian, Shojaei, Agarwal, et al., 2017; Vazirian, Shojaei, & Bazrgari, 2017), it has been reported that more rigid coordination patterns occur when there is an increase in the demand of the activity (i.e. fast paced motion, loads in hands, asymmetry trunk motion). Although, the reduction in MARP with increase in task demand could likely be a protective strategy against risk of large deformation of spinal tissues and injury, our observation of larger decrease in MARP with the ergonomically modified backpack is likely due to the rigid connection between segments resulting from the backpack straps and negatively effects the synchronized motion of the segments.

Recruitment efforts towards individuals younger than 18 years old was restricted in this study due to challenges in getting approved participation (e.g., presence of a parent during the study). For this reason, we did not include such individuals even though frequent use of heavy backpacks and its relation to LBP is also a concern for individuals younger than 18 years old. This study chose to utilize a professional hiking backpack, that included several ergonomic design features, instead of a so-called ergonomic school backpack to increase our chances of finding significant differences in outcome measures. Therefore, it should be noted that an ergonomic school backpack might not have the same level of ergonomic features as the backpack used in this study. Additionally, as this study only examined acute effects of backpack type on measures of lumbo-pelvic coordination during activities of daily living, the long-term effects of backpack type on such measures remains to be investigated in future

In conclusion, our results indicated larger alterations in magnitude and timing aspects of lumbo-pelvic coordination during walking and jogging with an ergonomically modified backpack vs. a normal backpack. Such larger alterations are likely due to kinematic restraints imposed by rigidity and enhanced attachment (via straps) devised in ergonomically modified backpack for increased comfort. The observed lumbo-pelvic coordination suggests larger demand on trunk muscle to perform walking and jogging with an ergonomically modified backpack but remains to be tested in future. Finally, better understanding of the relationship between backpack type and risk of LBP through mechanical pathways requires quantification of muscle forces and spinal loads (both instantaneous and cumulative) as well as the long-term effects of backpack type on such measures.

CHAPTER 4. FUTURE WORK

There has been much work done relating to the effects of backpacks on the biomechanics of the lower back with the primary focus being on postural deviations. However, little research has been done on studying different backpack types on the biomechanical effects on the lower back. This thesis aimed to bridge this gap by studying the effects of backpack type during walking and jogging, but further research should be done to better understand the relationship between backpack type and risk of LBP.

Future studies should look to build upon and improve from this study in a few areas. First, the population for this study was college aged students, but a population of younger individuals would serve to better understand the role backpacks could play in chronic LBP starting at adolescence continuing into adulthood.

Although acute effects of backpack type are important, future studies should observe the prolonged effects of backpack types as school aged children typically wear them throughout the week under varying circumstances. Further, to properly assess the effects of backpack type, studies should look to isolate the effects of specific features and not the entire backpack. This will allow for better understanding of how load placement, center of mass, and other variables might positively or negatively affect the user. This will help future designs to have a better idea of a standardized way for how the load should be carried.

Further, to better understand how different backpack types alter the risk of LBP requires quantification of muscle forces and spinal loads (both instantaneous and cumulative) and the acute and long-term effects of these measures. Specifically, for muscle forces EMG's should be used to record trunk muscle activity while carrying different backpack types. Additionally, linked-segment models could be utilized to estimate net reaction forces and moments at the lower back. Used in conjunction, this will begin to help researchers create a broader picture of the strain created by different backpack types and hopefully guide the development of more ergonomically sound backpacks.

Appendix

Explanation of Terminology

Segment Rotation/Motion – Refers to relative rotations of segments of the body rotating with respect to their orientation at habitual posture (i.e. Thorax and Pelvis). Measured in degrees.

Joint Flexion/Rotation – Refers to movements increasing or decreasing the angle between two body segments that occurs in the sagittal plane (i.e. lumbar flexion). Measured in degrees.

Inclination – Refers to angle between segment orientation (or segment local coordinate system) and a reference coordinate system. Measured in degrees.

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