A Biomechanical Model and Simulation of Vertebral Support and Lumbar Spinal Discs in Student Backpacks

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Abstract. Nowadays, many students are having to carry excessive amounts of weight in their backpacks every single day. Thousands of children are treated for backpack-related injuries every year, and the continuous strain has been linked in many studies to chronic spinal injuries in later life. The purpose of this project was to develop and simulate a new potential backpack design utilizing a theoretical biomechanical model in order to analyze the efficiency of applying exterior support to alleviate strain on lumbar spinal discs L4/L5 and L5/S1. Using anthropometric data collected from CDC statistics of 16-year-old male and female high school students, a simulation was conducted based on the 10th, 50th, and 90th percentiles, using the 3DSSPP program. The compression and shear forces were compared between the new design and current backpack models, with results demonstrating a significant reduction of forces, (around 44–67% and 25–38% for compression and shear forces, respectively). Thus, it was concluded that the new design was able to help to prevent the discomfort and pain on back, even at a very heavy backpack weight. Results were discussed and future research directions were given to improve the applicability of the new design.

Keywords: Biomechanics · Ergonomics · 3DSSPP

1 Introduction

1.1 Background Information

Increased backpack carriage loads throughout childhood and adolescence have been generally attributed through research to the chronic degeneration of the intervertebral lumbar spinal discs due to the compression of the vertebrae and the stress on the spine, with disc height decreasing over time [1, 2]. As a disc progresses into prolapse and extrusion due to compression, the nucleus pulposus breaks through the anulus fibrosus, causing the final stage of disc herniation [3]. Moreover, there are many parts of the body affected, stemming from long-term wear of high carriage loads, including the appendicular joints, which can sustain 7 lb of weight for each pound of a load. Additionally, potential nerve damage can occur, with increased reports of numbing appendages resulting from improper usage of the student's backpack [4–8]. The cervical area is strained,

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and the posterior shoulders can become rounded as the four natural curvatures of the body are disrupted, thus affecting the balance and standing weight distribution of the body as well. Therefore, it is imperative that a proper backpack wearing position is established and enforced [9–11].

Chronic lower back injuries are one of the most common health issues present for American people today. Eighty percent of adults in the United States suffer from some degree of lower back pain (LBP) during their lives, according to the United States National Institute of Health [12]. It was reported that back injuries were the cause of 10–30% of medical claims in the United States and Europe, with the rate of back injuries increasing from previous years. Yet, despite heightened awareness of these statistics and taking action to protect the adult workforce, the Centers for Disease Control and Prevention (CDC) reports that back injuries still account for up to 30% of medical compensations cases every year. Additionally, the American Chiropractic Association estimates that a staggering 3.1 million people are suffering from lower back pain in the United States and that one half of the entire American working community has complained of back pain related to their occupation[13]. The total cost of LBP-related injuries could reach more than $90 billion per year in the U.S [14]. Many of such back-pain problems find their root cause in early age and adolescent habits, as studies showed that more than up to 70% of the teens can have a lifetime prevalence of lower back pain, without treatment or preventive intervention/correction [15].

There are many factors that lead to lower back pain, including physical, bodily conditions and health status, sports, and daily, sustained activities such as lifting weights and carrying loads. Among these aforementioned factors, carrying heavy backpacks are one of the most prevalent factors [16], as it exerts a constant load that must be counteracted by the spine, and together with repetitive, dynamic body movement and improper body posture such as excessive slouching and lordosis, it can easily lead to long-term strain, that develops to LBP and disc herniation at an older age. Nowadays, high school students often are found to be carrying more objects and weight in their backpacks, partially due to the increasing level of study and activities involved in the everyday school, as well as disregard for carrying weights exceeding a tolerable threshold. In conjunction, back pain and shoulder/neck discomfort have become more a common problem reported in high school students as well. School backpacks have been found to be directly associated with back pain, especially the strain and forces exerted in the L4/L5 and L5/S1 lumbar discs of the spine: the lumbar and sacral intersection. Exposed to such heavy stress for a sustained period, this can lead to long term – even permanent – back problems and injuries in later adult life. Children under 18 carrying a heavy backpack have higher risks of musculoskeletal disorders, as they are still in a growing developmental phase; their body is more prone to the injuries of the heavy carriage in the back. The American Chiropractic Association recommends a backpack should not weigh more than 10% of a child's body weight; however [17], most high school students often carry backpacks exceeding recommended load.

Despite general safety guidelines having been published [18], the studies related to adolescence backpack issues are still very limited, partially due to the complexity and multifactorial nature of the lower back problem and large degree of variability in the human anthropometry and shapes/weights of the different backpack. Heavy backpacks mainly impact the human body by posing external forces and torque on the torso, interacting with internal factors and individual characteristics, thus generating greater internal loads on the individual, altering posture and even gaits to become unnatural. An accurate simulation of LBP should account for both external load and internal loads effects, including the individual human characteristics, spinal structure, spine load model, torso kinematics such as body posture, along with the consideration of human body anthropometric data (stature, body mass distribution, segmental dimensions, age, biological sex etc.) [19].

On the other hand, directly and empirically measuring the pressure exerted on the lower back, especially on the fibrocartilaginous lumbar spinal discs, is nearly impossible. Such physical measures could be surgically invasive, unfeasible, and pose risks and danger to the participants. As an alternative, biomechanical models and simulations provide an accurate, safe and effective way to investigate the impact of various external exertions on the human musculoskeletal system. Biomechanical simulation integrates findings and knowledge from the physical and engineering sciences with the principles of human physiology, biology and behavioral sciences, in order to suggest protection from injuries and disorders from these loads [20]. Biomechanical models have been previously utilized in modeling and predicting lower back pain [19].

As a unique population group, the understanding of impact wearing heavy backpacks on adolescents are still limited, most analyses are focused on the evaluation of current available commercial backpacks. There are few studies that take a further step and utilize biomechanical modeling to simulate the effectivity of a proposed, novel design to actively help mitigate forces exerted on the spinal discs and, thus, chronic LBP. In order to prevent LBP from an early age, a comprehensive analysis based on biomechanical modeling is in demand, improvement of current backpack designs should be based on the results derived from these models.

2 Method

2.1 Problem Description

The objective of this study is to utilize a Biomechanical simulation model to investigate the stress/strain on the vertebral column, specifically focusing on lumbar spinal discs L4-L5 and L5-S1, and the musculoskeletal systems caused by the weight of student backpacks and varying standing postures, to compare and analyze how exterior vertebral back support may alleviate possible damage and excessive stress in order to propose and model a conceptual external structure applied to current function student backpacks that provide sufficient support, reinforces a healthy, normal standing posture, and reduces and prevents possible musculoskeletal disorders, injuries to the spine, deformations, etc.

It is hypothesized that if stress on the lumbar spinal discs from heavy backpack wear disproportionate to human body weight is analyzed mathematically, along with external structures that possibly alleviate the amount of strain, then the proposed structure resulting from the elements derived from previous analyses, which provides additional back support, will be able to sustain a healthy standing posture and substantially minimize the amount of strain on the lumbar spinal discs, which would effectively prevent herniation, bulging, compression, and injury inflicted on the spinal area and nearby tissues from heavy backpacks, as the conceptual model would enforce a straight, perpendicular alignment, not leaning forward on the torso and pushes the waist forward to maintain optimal posture. Additionally, a pivot operated by hand from pushing down on handles extending to the front in order to reduce the amount of weight dragging down on the back may also mitigate the amount of stress caused by the heavy backpack compressing down on the spine.

Therefore, the goal of this project would ultimately be to develop and test a theoretical biomechanical model to compare the efficiency of the new design to previous conditions in students and meeting the design criteria of efficiency would require a substantial reduction in the compression and shear forces acting upon the L4-L5 and L5-S1 lumbar spinal discs.

2.2 Biomechanical Model

At the Backpack Level: Figure 1 illustrates the biomechanical model at the backpack level.

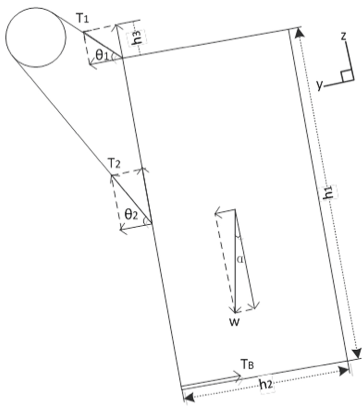

Fig. 1. Biomechanical model at the backpack level. h_1: length of the backpack, h_2: depth of the backpack; w: weight of the backpack; h_3: distance from the top of the backpack to the shoulder; T_1, T_2: forces on the backpack straps; T_B: forces acting on the touching point of the backpack to torso; θ_1, θ_2, α: angles of the straps and backpack to the reference axis.

According to the Newton's law, at the backpack level, the condition of equilibrium requires

$$\sum \vec{F} = 0, \sum \vec{M} = 0 \tag{1}$$

The force is denoted by F and the torque is denoted by M.

So we have

$$\begin{cases} W \cdot \cos\alpha = T_1 \cdot \sin\theta_1 + T_2 \cdot \sin\theta_2 \\ W \cdot \sin\alpha + T_1 \cdot \cos\theta_1 + T_2 \cdot \cos\theta_2 = T_B \end{cases} \tag{2}$$

And

$$T_B \cdot (h_1 + h_3) = W \cdot \cos\alpha \cdot \frac{h_2}{2} + W \cdot \sin\alpha \cdot (\frac{h_1}{2} + h_3) \tag{3}$$

Giving the value of backpack weight and dimensions, we can derive the value of the forces on shoulders.

At the Shoulder Level: Figure 2 illustrates the biomechanical model at the shoulder level.

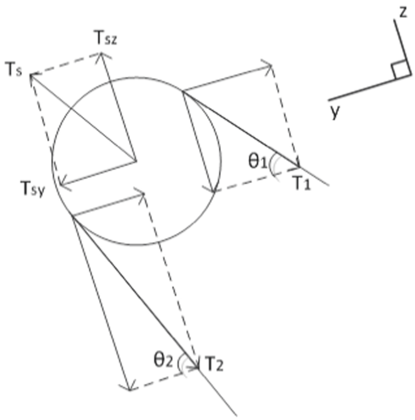

Fig. 2. Biomechanical model at the shoulder level. T_S: counter forces of the shoulders on the backpack straps; T_{SY}, T_{SZ}: forces components on the y and z axis; θ_1, θ_2: angles of the straps to the reference axis.

At the shoulder level, according to the Newton's law,

$$\begin{aligned} T_{SZ} &= T_1 \cdot \sin\theta_1 + T_2 \cdot \sin\theta_2 \\ T_{SY} &= T_1 \cdot \cos\theta_1 + T_2 \cdot \cos\theta_2 \end{aligned} \tag{4}$$

At the Lower Back Level: Figure 3 illustrates the biomechanical model at the L5/S1 level.

$$\sum \overrightarrow{M_{L5/S1}} = 0 \tag{5}$$

Or

$$b\left(\vec{mg}\right) + h\left(\vec{F_{load}}\right) + E(\vec{F_m}) = 0 \tag{6}$$

The forces acting parallel to the disc compression forces can be described as

$$\sum \overrightarrow{F_c} = 0 \tag{7}$$

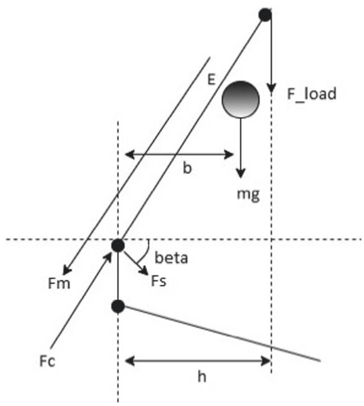

Fig. 3. Biomechanical model at the lower back L5/S1level. F_m: muscle forces on the lower back; F_c: compression force; F_s: sheer force; b, h: distance of the center of gravity and external forces to the lower back; beta: angle of the shear forces to the horizontal axis; E: distance of muscle force to the spine.

Or

$$\cos(beta)\left(\vec{mg}\right) + \cos(beta)\left(\vec{F_{load}}\right) + \vec{F_m} + \vec{F_c} = 0 \tag{8}$$

The reactive shear force across the L5/S1 disc can be solved by the similar equilibrium conditions.

$$\sum \vec{F_s} = 0 \tag{9}$$

Or

$$\sin(beta)\left(\vec{mg}\right) + \sin(beta)\left(\vec{F_{load}}\right) - \vec{F_s} = 0 \tag{10}$$

2.3 Biomechanical Simulation

With data on commercial backpack dimensions and anthropometrics (including weight and dimensions and angles of the torso), we can easily derive the physical forces acting on the shoulders. However, for the L4/L5 and L5/S1 lumbar spinal discs, the measures of compression and shear forces can only be estimated by considering the external forces on the shoulder based on the static model outlined above, and human anthropometric data. This data includes body stature and weight. In this case, a static strength simulation software, 3D SSPP was used to predict the compression force and shear forces operating at the L4/L5 and L5/S1 disc level. Developed by the Center for Ergonomics at the University of Michigan, 3D SSPP is aimed at investigating and analyze human material handling tasks. It utilizes principles and models in Biomechanics to derive the static strength exerted for tasks such as lifting, pushing and carrying loads (Umich.edu). Figure 4 shows a screenshot of the 3D SSPP software.

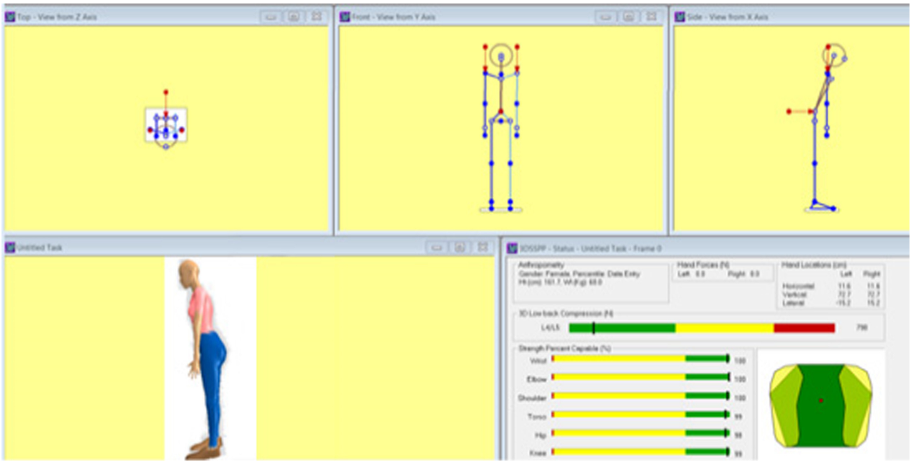

Fig. 4. Screenshot of 3D SSPP.

2.4 Data Collection

Human anthropometric data was retrieved from the Center of Disease Control and Prevention, more specifically, the 10th, 50th (mean) and 90th percentile value on body height and body weight for U.S female and male at the age of 16 (Fig. 5) [21]. The student backpack dimensions were collected from online retail. Using Eqs. (1)–(4), the external forces on the shoulder level and lower back were calculated, by using three levels of backpack weight (7 kg, 10.5 kg and 14 kg, respectively, simulating the backpack weight of 5%, 10% and 15% of the average male body weight).

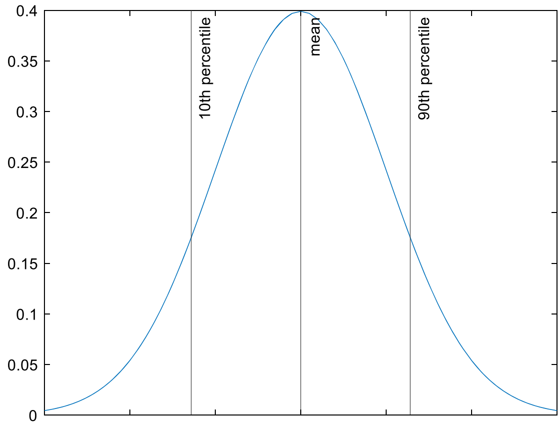

Fig. 5. Illustration of normal distribution percentile value

2.5 New Design Prototype

Based on the analysis of posture and main areas affected from backpack carriage load, a conceptual model of a new backpack design was proposed, with a mechanism providing optimum back support and enforcing proper posture when carrying a heavy backpack (sketches, etc.). Three factors were included in the new design: the strap design, the lumbar support pad and manually operated pivot first-class lever support at the waist to redistribute and mitigate partial carriage weight. A new posture and weight were used to derive forces on shoulders and lower back utilizing the equilibrium conditions, as seen in Fig. 6.

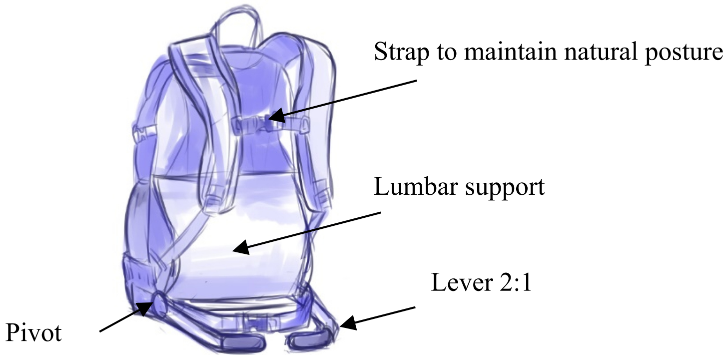

Fig. 6. Illustration of normal distribution percentile value

Therefore, the proposed design would ultimately lead to a substantial reduction in the compression and shear forces acting upon the L4/L5 and L5/S1 lumbar spinal discs. The proposed backpack design is simulated using the 3DSSPP program to compare the forces between typical conventional backpack use in students without enforcement of proper posture and with the proposed design. The above comparison was repeated for female and male anthropometric data, at 10^{th}, 50^{th} and 90^{th} percentile values and for 7 kg, 10.5 kg and 14 kg backpack weight, respectively.

3 Results

3.1 Data

Anthropometry Data and Backpack Data. The following Table 1 shows the anthropometric data from CDC.

Table 1. Anthropometric Data

		10th	50th	90th
Female	Height (cm)	151.9	161.7	172.1
	Weight (kg)	46.9	60.0	95.3
Male	Height (cm)	166.0	174.5	182.3
	Weight (kg)	55.7	68.7	96.1

The backpack data are determined as follows

Length = 18 in. (h_1)
Width = 11 in.
Depth = 8 in. (h_2)
Shoulder distance to backpack = 3 in. (h_3)

3.2 Simulation Results

Based on the backpack weight of 7 kg, 10.5 kg and 14 kg, the lower back simulation results are summarized in Table 2 and 3, for female and male, respectively.

Table 2. Lower back simulation results for female

Weight (KG)	Forces (Newton)	Old design			New design		
		10%	50%	90%	10%	50%	90%
7	L4/L5 compression	644	798	1195	302	377	575
	L4/L5 Shear	140	165	233	82	106	169
	L5/S1 compression	704	872	1305	202	250	376
	L5/S1 Shear	192	230	331	123	158	255
10.5	L4/L5 compression	713	867	1261	403	482	687
	L4/L5 Shear	164	189	256	99	123	186
	L5/S1 compression	787	955	1386	265	316	447
	L5/S1 Shear	221	258	360	144	180	276
14	L4/L5 compression	782	936	1326	503	587	799
	L4/L5 Shear	187	212	279	116	140	204
	L5/S1 compression	869	1037	1466	328	382	517
	L5/S1 Shear	249	287	389	166	202	298

Table 3. Lower back simulation results for male

Weight (KG)	Forces (Newton)	Old design			New design		
		10%	50%	90%	10%	50%	90%
7	L4/L5 compression	773	948	1276	385	472	647
	L4/L5 Shear	167	208	269	104	129	183
	L5/S1 compression	870	1069	1440	261	317	431
	L5/S1 Shear	244	290	383	174	216	304
10.5	L4/L5 compression	842	1008	1333	480	572	752
	L4/L5 Shear	202	231	292	115	140	194
	L5/S1 compression	955	1145	1513	321	380	497
	L5/S1 Shear	275	319	412	196	237	325
14	L4/L5 compression	902	1067	1389	575	672	852
	L4/L5 Shear	225	254	315	127	152	203
	L5/S1 compression	1031	1220	1586	381	443	559
	L5/S1 Shear	303	347	440	217	259	344

To further summarize the results, the main differences between female and male, between the current design and proposed design are illustrated in Table 4.

Table 4. Mean Differences (in Newton/percentage) between two design for female and male

Mean force differences (N/percentage)	Female	Male
L4/L5 compression	423.00/44.87%	459.00/43.50%
L4/L5 shear	66.67/33.93%	90.67/38.11%
L5/S1 compression	699.78/67.00%	804.33/66.92%
L5/S1 shear	79.44/29.44%	82.33/25.10%

Results demonstrated that with the new design (reduced load by the waist/hand lever support) and improved body posture (curved lumbar support and new strap design), the forces of both L4/L5 and L5/S1 discs will be significantly reduced, as shown in Table 3. This implies that the new design will help to relieve the pressure forces at the lower back for adolescent populations of varying anthropometric profiles, thus preventing the lower back from injury as a result of carrying a heavy backpack load.

4 Discussion and Conclusions

Students are carrying heavy backpacks that exceed the recommended carriage limit; long term exposure to heavy loads leading to discomfort at the lower back level, especially back pain and injury in the L4/L5 and L5/S1 disc in the vertebrae. This lower back pain largely is due to the unnatural posture caused by the load and unbalanced weight distribution of the backpack on the torso. A new design of student school backpacks was proposed based on the principles of human biomechanics, more specifically to use proper design of straps and lumbar support to reinforce a more natural standing posture and alleviation, including distributing external forces on the shoulder and lower back by using a pivot lever at the waist level. A theoretical biomechanics model was developed and a simulation study was conducted based on the 10^{th}, 50^{th} and 90^{th} percentile high school 16-year old student anthropometric data in the 3DSSPP program. The compression force and shear force were compared between the new designed back pack and current backpack model with varying weights, with results showing that with the reinforced natural posture, the reduction of the forces on the L4/L5 and L5/S1 are significant (with around 44%–67% for the compression force and about 25%–38% for the shear force, respectively), thus helping to prevent discomfort and back pain, even at the very heavy carriage level. The design was able to meet the goals and criteria originally established in that it was able to decrease significantly the strain on the lumbar vertebrae and discs, ultimately aiding in the prevention of backpack-related injuries.

The study utilized a theoretical biomechanics model to assess the effectiveness of the new design. In order to simplify the model, it was assumed that the center of gravity of the backpack was at the center of the backpack, although this could change with different sizes of the backpack and different load distribution; additionally, the friction and materials of the backpack were not considered, which could have possibly correlated with an effect on the comfort of carrying the backpack.

For the future direction of this study, a physical prototype shall be developed to conduct human testing, including the pressure measurement at different locations of the body to obtain a more precise assessment. Participants should include a variety of anthropometric profile, such as different sex, different body sizes/weight and a broader range of weight to be carried in the backpack. These tests will accommodate the variability of the backpack carriage and present a more realistic assessment on the effectiveness of the new design.

According to the U.S. Consumer Product Safety Commission, at least 14,000 children are treated for backpack-related injuries every year. Quite often, students' backpacks are too heavy in relationship to their own body weight, as the American Academy of Orthopedic Surgeons recommends that a backpack should be no more than 10–15% of a student's bodyweight, while many children are carrying backpacks as heavy as forty, fifty, and sixty pounds due to the amount of textbooks and classwork required in school every day. Furthermore, many students develop consistent, poor habits, wearing backpacks incorrectly on one shoulder or hanging far too low, or having a poor, hunched posture, therefore increasing the compression on the spine and increasing the risk for injury. This research and investigation are important scientifically in that it analyzes and tests a possible conceptual way to provide back support on a conventional backpack that efficiently reduces strain and reinforces a healthy posture, which is crucial to students, especially in middle and high school as coursework becomes more demanding, tiring, and rigorous. Many will suffer from chronic back problems and pain in the future and irreversible damage to the spine, surrounding muscles, ligaments, and tissues stemming from a constant compression from a heavy backpack are a key factor of many of the back problems resulting later on in elderly life as well. If the design of the model can be put to use and commercialized in the market, it can considerably resolve the preventable health issues of the youth today.

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