DOI: 10.37190/ABB-02522-2024-02

Effect of Backpack Loads on Shoulder Strap Tension in Male Adolescents: A Biomechanical Study

Yunqi Tang[1], Jiachen Fan[1], Meilian Lyu[2], Tao Zhou[3], Xie Wu[4], Kezhun Cao[5], Shutao Wei[3,6*]

[1]College of Bioresources Chemical & Materials Engineering, Shaanxi University of Science & Technology, Xi'an, China
[2]Liming Vocational University, Quanzhou, China
[3]361° (CHINA) CO., LTD., Xiamen, China
[4]School of Exercise and Health, Shanghai University of Sport, Shanghai, China
[5]School of Physical Education, Jimei University, Xiamen, China
[6]Physical Education Department, Xiamen University of Technology, Xiamen, China
[*]Corresponding author: Shutao Wei, Physical Education Department, Xiamen University of Technology, Xiamen, China, e-mail address: st.wei@361sport.com

Submitted: 2nd October 2024
Accepted: 14th November 2024

Abstract

Purpose: The widespread use of heavy backpacks among adolescents raises concerns about the impact on musculoskeletal health. This study aims to investigate the effects of different backpack loads on shoulder strap tension during walking and running, using a spring-loaded shock-absorbing backpack.

Methods: Fifteen healthy male adolescents participated in the study. Each carried a backpack with loads of 3.5 kg, 7 kg, and 10.5 kg while walking at 2 m/s and running at 4 m/s. Shoulder strap tension was measured using custom-made tension sensors, and kinematic data were collected with a 3D motion capture system. Statistical Parametric Mapping (SPM) was applied to analyze tension variations across different gait phases.

Results: Shoulder strap tension increased significantly with heavier loads during both walking and running ($p < 0.001$). The tension varied throughout the gait cycle, with distinct patterns observed between walking and running. During walking, tension peaked at mid-stance, while in running, tension decreased during the absorption phase and increased sharply during propulsion. Significant differences between 7 kg and 10.5 kg loads were noted at specific gait intervals ($p < 0.05$).

Conclusion: Backpack load significantly influences shoulder strap tension, with variations closely linked to gait phases. These findings highlight the importance of ergonomic backpack design, particularly for reducing shoulder strain in adolescents.

Keywords: adolescents, backpack load, shoulder strap tension, shock-absorbing backpack, statistical parametric mapping

1. Introduction

In recent years, the increasing academic demands placed on adolescents—defined as individuals aged 10 to 24 years [17]—have led to the widespread use of heavy backpacks to carry textbooks, laptops, and other study materials [8]. This issue has raised significant concerns regarding the potential health implications for adolescents, as heavy backpack loads are known to cause musculoskeletal problems, particularly in the shoulders and back [15]. Studies show that over 50% of school-aged children experience discomfort or pain associated with backpack use, with some developing chronic conditions that affect their posture and overall well-being [16] . These physical strains not only impact the health of adolescents but also have the potential to hinder their academic performance and quality of life [15]. Therefore, understanding how backpack load influences musculoskeletal stress, particularly during dynamic activities like walking and running, is critical to addressing this public health issue.

Previous research has established a clear link between excessive backpack weight and musculoskeletal discomfort in adolescents [12, 13] . Studies have identified various factors that contribute to this discomfort, such as shoulder strap width [9], load placement [3], and total backpack weight [6]. For example, narrower straps tend to increase pressure on the shoulders, causing greater discomfort, while improper load placement exacerbates stress on the spine and shoulder regions. Most of these studies [3, 8, 9, 19], however, have focused on static measurements or generalized discomfort ratings, without accounting for the dynamic variations in shoulder strap tension during walking or running.

Despite the known adverse effects of heavy backpack use, there is limited research investigating how backpack load affects dynamic shoulder strap tension during movement. Few studies have explored the biomechanical implications of different backpack weights on shoulder tension during activities like walking or running. This gap in the literature is crucial because dynamic activities such as walking and running are common in adolescents' daily lives, and understanding the specific biomechanical stresses during these activities can inform better backpack designs to mitigate discomfort and injury.

Shock-absorbing backpacks, designed to reduce the impact of load carriage by incorporating damping mechanisms, have been proposed as a potential solution to mitigate the strain caused by heavy backpacks [11]. These backpacks aim to distribute weight more evenly across the shoulders and reduce dynamic loads transmitted to the body. However, there is little empirical evidence on how these designs affect shoulder strap tension under varying loads and dynamic conditions such as walking and running.

Thus, the present study aims to fill this research gap by dynamically analyzing shoulder strap tension in adolescents during both walking and running with different backpack loads. We employed a custom-designed spring-loaded shock-absorbing backpack to assess how load impacts shoulder strap tension throughout the gait cycle. We hypothesize that: (1) heavier backpack loads will significantly increase shoulder strap tension, and (2) the variations in shoulder strap tension will correspond closely to specific phases of the gait cycle during both walking and running.

2. Materials and Methods

2.1. Participants

An a priori power analysis was conducted using G*Power software (version 3.1.9.7) to determine the required sample size for the study [22]. The analysis was based on a one-way repeated-measures ANOVA with an effect size of 0.3, an alpha level of 0.05, and a desired power (1-β) of 0.80. The results indicated that a minimum of 15 participants was necessary to detect statistically significant differences. Accordingly, fifteen healthy male adolescents participated in this study (age: 20 ± 0.8 years; height: 178.6 ± 4.7 cm; body mass: 67.2 ± 6.3 kg; BMI: 21.0 ± 1.5 kg/m²). Inclusion criteria required participants to be male adolescents aged between 18 and 22 years, with a BMI ranging from 18.5 to 23.9 kg/m², and in good physical health with no history of musculoskeletal disorders. Exclusion criteria included any shoulder or lower extremity injuries within the past six months, inability to complete the experimental procedures, or failure to provide informed consent. Participants provided written informed consent before the experiment. The study was approved by the Institutional Review Board of Shanghai University of Sport (approval number: 102772023RT082).

2.2. Backpack design

A custom-designed spring-loaded shock-absorbing backpack was used in this study (Figure 1). The backpack features a dual-spring damping module integrated into its carrying system. Constructed from high-carbon steel springs with a stiffness of 784 N/m, the module enables relative displacement during vertical movement, which helps reduce impact transmission between the backpack and the wearer. By utilizing the cushioning effect of the elastic springs, the impact force from each step is mitigated, preventing it from being directly transferred to the shoulders and back. The damping mechanism was housed in a 90 mm by 133 mm casing made of translucent hard rubber and hard plastic. Iron plates and rubber sheets were used to adjust the backpack loads to 3.5 kg, 7 kg, and 10.5 kg, secured inside a rectangular box (15 cm × 24 cm × 34 cm) within the backpack.

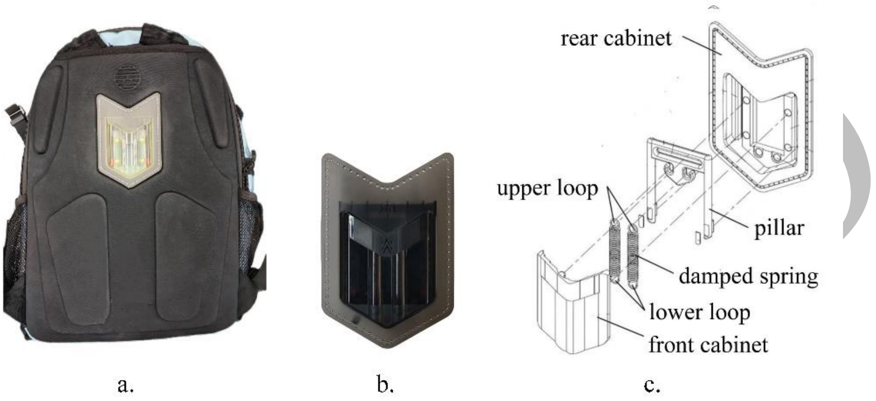

Fig. 1. Schematic of the spring-loaded shock-absorbing backpack design. (a) Exterior view of the backpack featuring the integrated protective panel. (b) Shock-absorbing device used within the backpack panel. (c) Exploded schematic diagram of the shock-absorbing device, showing its structural components, including the front and rear cabinets, damped spring, and connecting loops.

2.3. Experimental setup

Kinematic data were captured using the Vicon Nexus motion capture system (Vicon Motion Systems Ltd., Oxford, UK) with eight infrared cameras operating at a 200 Hz sampling frequency. Reflective markers were placed on anatomical landmarks including the head, trunk, pelvis, and lower limbs according to the Plug-in Gait model. Two miniature tension sensors (sampling frequency: 1000 Hz) were custom-made to measure shoulder strap tension[18], calibrated using standard weights prior to testing. Participants' anthropometric data, including height, weight, and BMI, were measured using an ultrasonic height and body composition analyzer (Model TZG, Jiangsu Zhongfang Manufacturing Co., Ltd., Jiangsu, China). SMARTSPEED timing gates

(Fusion Sport, Coopers Plains, QLD, Australia) were used to monitor walking and running speeds.

2.4. Experimental procedure

Prior to the experiment, participants performed a 5-minute warm-up consisting of light aerobic exercises and stretching. Reflective markers were affixed to the participants' anatomical landmarks (Fig.2). All participants wore standardized athletic attire and footwear. During testing, the bottom of the backpack was precisely aligned with each participant's third lumbar vertebra [7]. This standardized positioning ensured consistency across all participants, thereby minimizing variations due to differing backpack placements.

Participants completed walking trials at 2 m/s and running trials at 4 m/s while carrying backpack loads of 3.5 kg, 7 kg, and 10.5 kg. During both walking and running trials, participants were instructed to keep their eyes forward, avoiding looking down or to the sides [20]. The order of load conditions was randomized to avoid bias, and each load condition was tested in three trials for both walking and running. Participants traversed a 10-meter walkway with timing gates, and data were collected during the trials. A 2-minute rest period was provided between trials to prevent fatigue.

Fig. 2. Participant fitted with reflective markers and backpack with shock-

absorbing device.

2.5. Data processing

Kinematic data were processed using Vicon Nexus software and exported as C3D files for biomechanical analysis in Visual3D (C-Motion Inc., Germantown, MD, USA). Marker trajectory data were low-pass filtered using a fourth-order Butterworth filter with a 12 Hz cutoff frequency [24]. Shoulder strap tension data were synchronized with the kinematic data and filtered using a fourth-order Butterworth low-pass filter with a 100 Hz cutoff frequency to eliminate high-frequency artifacts.

The gait cycle for walking was defined as the interval from the right heel strike to the subsequent right heel strike [4]. Gait phases were divided into stance (loading response, mid-stance, terminal stance, pre-swing) and swing (initial, mid, terminal) phases. For running, the gait cycle was divided into absorption, propulsion, initial swing, and terminal swing phases [2, 5]. Data from three successful trials for each load were averaged and normalized to 101 points representing 0–100% of the gait cycle for comparison across participants and conditions [23].

2.6. Statistical analysis

Statistical Parametric Mapping (SPM) was used to analyze continuous shoulder strap tension data across the gait cycle [22]. A one-way repeated-measures ANOVA was conducted for each shoulder (left and right) to assess the effect of load on shoulder strap tension during walking and running conditions. Post-hoc pairwise comparisons were performed using paired t-tests with Bonferroni correction, adjusting the significance level to $\alpha = 0.017$. Assumptions of normality and sphericity were tested using the Shapiro-Wilk and Mauchly's tests, respectively. All analyses were conducted using MATLAB R2020a (The MathWorks Inc., Natick, MA, USA) with the SPM1D package (http://spm1d.org) [10].

3. Results

3.1. Walking condition

SPM analysis assessed the effects of different backpack loads on shoulder strap tension during walking for both the right and left shoulders (Fig.3).

For the right shoulder, the SPM statistic exceeded the critical threshold ($\alpha = 0.05$) throughout the gait cycle, indicating significant differences among the three load conditions ($p < 0.001$). Post-hoc SPM{t} tests showed that shoulder strap tensions for the 7 kg and 10.5 kg loads were significantly higher than for the 3.5 kg load across the entire gait cycle ($p < 0.001$). Significant differences between the 7 kg and 10.5 kg loads were observed at specific intervals: 6%–50%, 60%–64%, and 68%–98% of the gait cycle ($p < 0.05$).

For the left shoulder, the SPM statistic also exceeded the critical threshold ($\alpha = 0.05$) throughout the gait cycle ($p < 0.001$). Post-hoc comparisons indicated that shoulder strap tensions for the 7 kg and 10.5 kg loads were significantly higher than for the 3.5 kg load across the entire gait cycle ($p < 0.001$). Significant differences between the 7 kg and 10.5 kg loads occurred at 0%–2%, 9%–14%, and 17%–100% of the gait cycle ($p < 0.05$).

Shoulder strap tension varied over the gait cycle for both shoulders. For the right shoulder, tension increased during the loading response phase (0%–10%) and reached a peak at mid-stance (~30% of the gait cycle). Tension decreased during terminal stance and pre-swing phases (30%–50%) and increased again during the swing phase (50%–100%). The left shoulder displayed similar patterns, with tension changes corresponding to the gait phases.

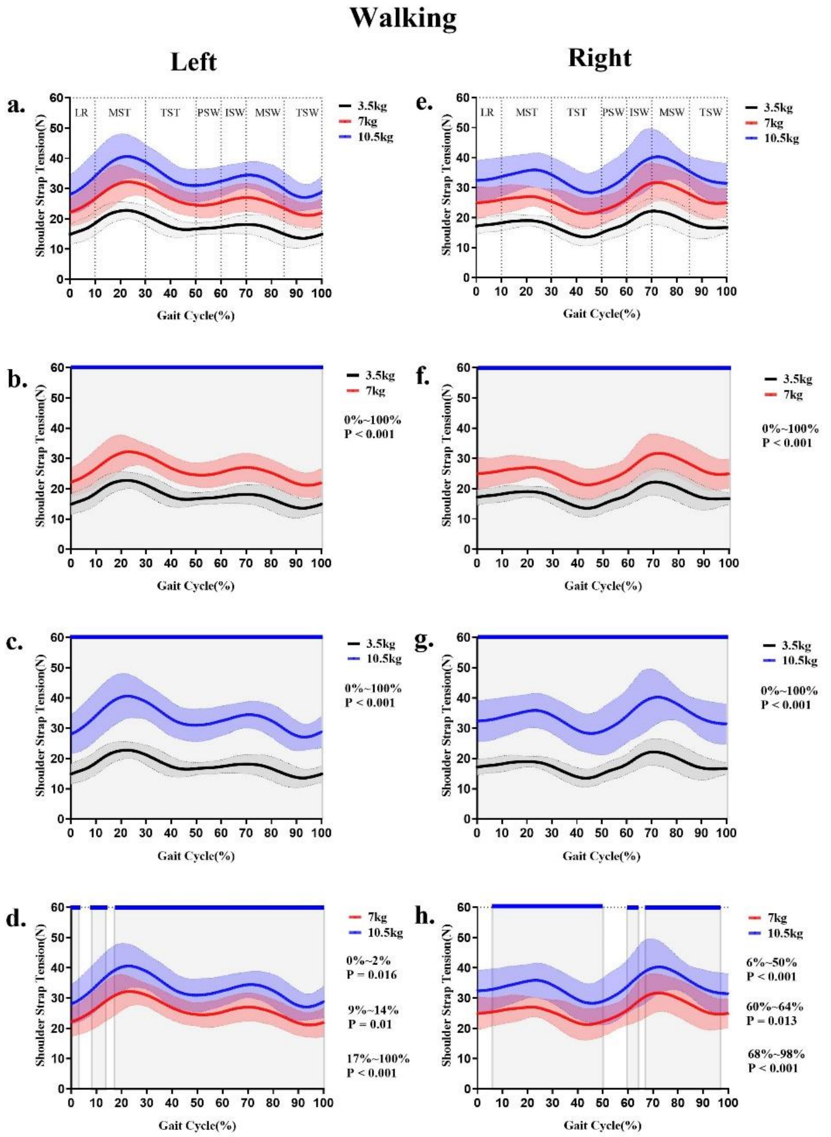

Fig. 3. Shoulder strap tension during the gait cycle for walking. LR: loading response. MST: midstance. TST: terminal stance. PSW: preswing. ISW: initial swing. MSW: midswing. TSW: terminal swing.

3.2. Running condition

SPM analysis evaluated the effects of backpack load on shoulder strap tension during running for both shoulders (Fig.4).

For the right shoulder, the SPM statistic exceeded the critical threshold ($\alpha = 0.05$) throughout the gait cycle ($p < 0.001$). Post-hoc SPM{t} tests showed that shoulder strap tensions for the 7 kg and 10.5 kg loads were significantly higher than for the 3.5 kg load across the entire gait cycle ($p < 0.001$). Significant differences between the 7 kg and 10.5 kg loads were observed at specific intervals: 0%–24%, 41%–82%, and 94%–100% of the gait cycle ($p < 0.05$).

For the left shoulder, the SPM statistic also exceeded the critical threshold ($\alpha = 0.05$) throughout the gait cycle ($p < 0.001$). Post-hoc comparisons indicated that shoulder strap tensions for the 7 kg and 10.5 kg loads were significantly higher than for the 3.5 kg load across the entire gait cycle ($p < 0.001$). Significant differences between the 7 kg and 10.5 kg loads occurred at 0%–18%, 42%–50%, and 93%–100% of the gait cycle ($p < 0.05$).

During running, shoulder strap tension varied over the gait cycle for both shoulders. For the right shoulder, tension decreased during the absorption phase (0%–15%) after foot contact, increased during the propulsion phase (15%–40%) reaching a peak, decreased during the initial swing phase (40%–60%), and increased again toward terminal swing (60%–100%). The left shoulder displayed similar tension patterns corresponding to the gait phases.

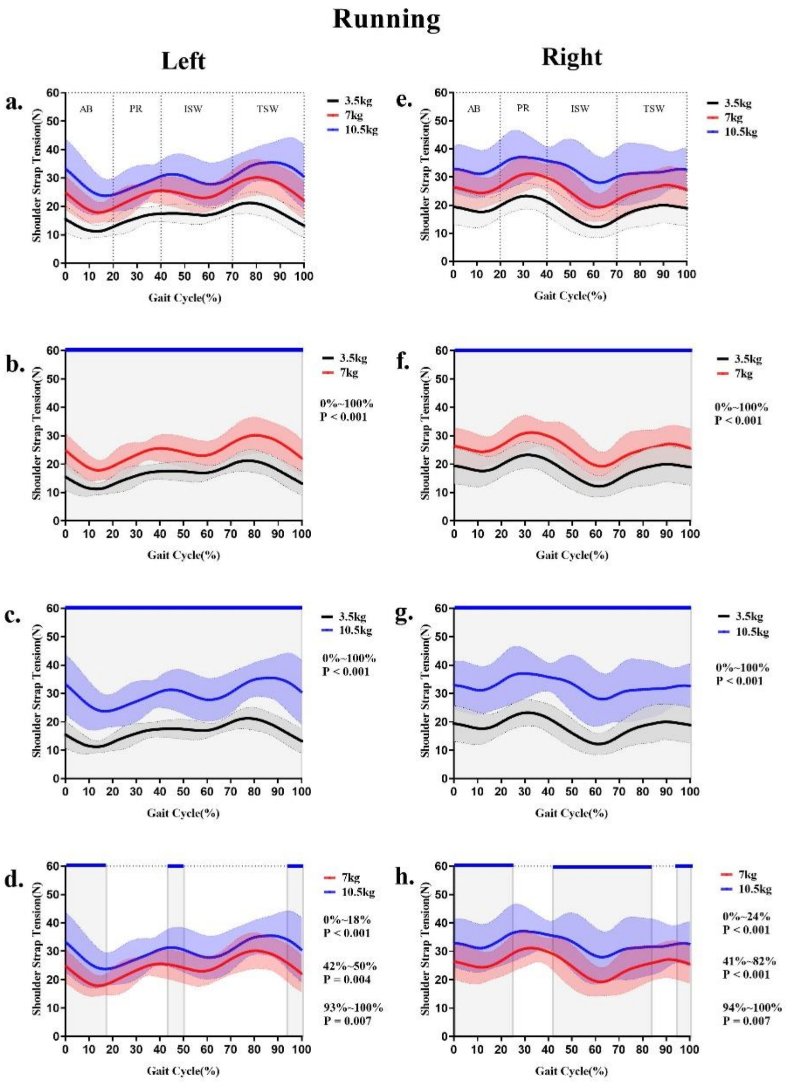

Fig. 4. Shoulder strap tension during the gait cycle for running. AB: absorption, PR: propulsion, ISW: initial swing, TSW: terminal swing.

3.3. Vertical Displacement of Center of Mass

Figure 5 illustrates the vertical displacement of the center of mass (CoM) during walking and running. In both modes of locomotion, the CoM exhibits a regular, oscillatory pattern. However, the figure shows that, compared to walking, the CoM is positioned higher during running, with a relatively lower oscillation frequency. During walking, the CoM reaches its lowest point at approximately 10% and 60% of the gait cycle, whereas during running, the CoM's nadir occurs around 20% and 70% of the cycle. Additionally, both the peak and trough positions of the CoM are slightly elevated during running compared to walking.

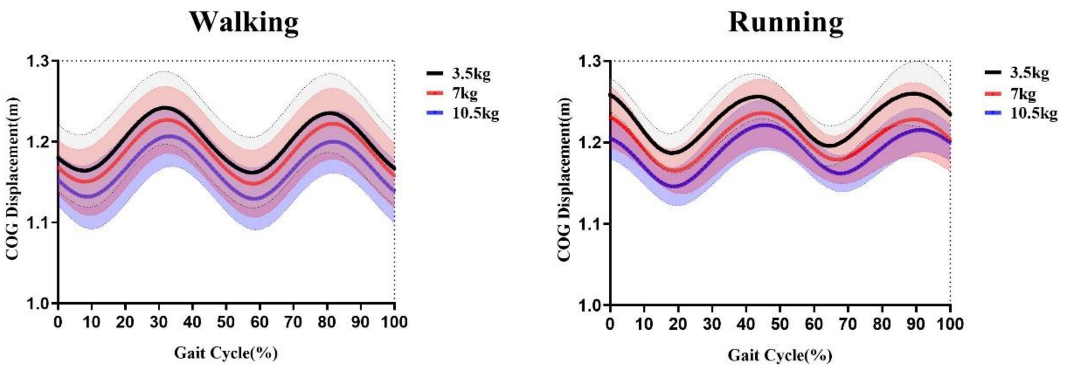

Fig. 5. Vertical displacement of the center of mass during walking and running.

4. Discussion

This study investigated the effects of different backpack loads on shoulder strap tension during walking and running in adolescents using a spring-loaded shock-absorbing backpack. The results demonstrated that shoulder strap tension significantly increased with heavier loads during both walking and running conditions ($p < 0.001$). Additionally, the patterns of shoulder strap tension variation differed between walking and running, closely corresponding to specific gait phases. These findings support our hypotheses that increased load leads to higher shoulder strap tension and that tension changes are associated with gait phases.

The significant increase in shoulder strap tension with heavier loads indicates that backpack weight imposes a considerable burden on the shoulders. When the load increased from 3.5 kg to 7 kg, shoulder strap tension rose significantly throughout the gait cycle in both walking and running. This suggests that lighter loads exert less compressive force on the shoulders, whereas heavier loads substantially increase tension. Interestingly, the differences in shoulder strap tension between 7 kg and 10.5 kg loads were significant only at certain intervals of the gait cycle. This may imply that the body's biomechanical adaptation reaches a limit at higher loads, resulting in less pronounced tension changes beyond a certain threshold.

The study found distinct differences in shoulder strap tension patterns between walking and running. During walking, tension increased during the loading response phase as the foot contacted the ground and peaked at mid-stance, likely due to the body's center of mass shifting over the supporting leg[14]. Tension decreased during terminal stance and pre-swing phases and increased again during the swing phase, possibly related to inertial effects as the leg swung forward[21].

In contrast, during running, shoulder strap tension decreased during the absorption phase after foot contact, potentially because the backpack continued to move upward due to inertia while the body descended, leading to temporary slackening of the straps. Tension then increased sharply during the propulsion phase as the body accelerated upward and forward. These differences highlight the impact of gait dynamics on shoulder strap tension, with running involving greater accelerations and inertial forces compared to walking[1].

Our findings align with those of Mackie et al.[13], who reported that backpack weight significantly affects shoulder strap forces and shoulder pressure, with backpack weight having the greatest effect. Similarly, Dai et al.[6] found that higher backpack loads increase shoulder pressure, particularly on the lateral clavicle and medial trapezius regions. However, unlike previous studies that primarily focused on static measurements or general discomfort levels, our study provides a dynamic analysis of shoulder strap tension throughout the gait cycle during walking and running, offering more detailed insights into how tension varies with load and movement.

The results have important implications for backpack design. Based on our findings, where shoulder strap tension showed no significant difference at certain intervals within the gait cycle under load conditions of 7 kg and 10.5 kg, we recommend that backpack manufacturers set an optimal load limit of 7 kg or less for routine use, especially for adolescents and young adults, to reduce shoulder strain from carrying heavier loads. Additionally, since shoulder strap tension varies throughout the gait cycle—peaking during the swing phase of walking and the propulsion phase of running—we suggest incorporating adjustable, dynamic tension systems into shoulder strap designs. Features like padded or elastic components could effectively absorb and dissipate peak tension forces, thereby enhancing both comfort and support.

This study has several limitations. First, despite efforts to control for posture and backpack position, individual gait variations among participants were unavoidable. Additionally, all participants were healthy male adolescents, which limits the generalizability of the findings to females and other age groups. Future research should include a more diverse population to address this limitation. Second, the study was conducted in a controlled laboratory environment, which may not fully represent real-world conditions, where factors like uneven terrain and prolonged load carriage are prevalent. Third, only walking and running at specific speeds were analyzed, leaving other activities and a wider range of speeds to be investigated in future studies. Lastly, the short duration of load carriage in this study does not capture the potential cumulative effects of prolonged use, warranting further research into longer-term impacts.

5. Conclusions

In conclusion, this study demonstrated that backpack load significantly influences shoulder strap tension in adolescents during walking and running, with variations closely linked to gait phases. These findings contribute to a better understanding of the biomechanics involved in load carriage and underscore the need for ergonomically designed backpacks to reduce shoulder strain. Implementing design improvements and educating users on safe load practices can enhance comfort and reduce the risk of musculoskeletal issues among adolescents.

Acknowledgements

This research was supported by MOE (Ministry of Education in China) Liberal Arts and Social Sciences Foundation(No.23YJAZH132); Shaanxi Provincial Social Science Foundation of China (No. 2023J014) and the Research Foundation of Shaanxi University of Science and Technology (No.2023BJ-44).

Disclosure statement

The authors have no conflicts of interest to declare.

References

[1] AGHILONE G.CAVACECE M., *Intra–subject Variability of Impact Shock of Foot on the Ground during Walking and Running Activities.* Universal Journal of Public Health, 2018.**6**(4):167-172, DOI:10.13189/ujph.2018.060401.

[2] BERTUIT J., FEIPEL V.ROOZE M., *Temporal and spatial parameters of gait during pregnancy.* Acta Bioeng Biomech, 2015.**17**(2):93-101.

[3] CHEN Y.L.MU Y.C., *Effects of backpack load and position on body strains in male schoolchildren while walking.* PLoS One, 2018.**13**(3):e0193648, DOI:10.1371/journal.pone.0193648.

[4] COSTA FILHO C.F., E AQUINO G.D.A.COSTA M.G.F. *Gait analysis: determining heel-strike and toe-off events*. in *17th International Symposium on Medical Information Processing and Analysis*. 2021. SPIE.

[5] CZERNIECKI J.M., *Foot and ankle biomechanics in walking and running. A review.* Am J Phys Med Rehabil, 1988.**67**(6):246-252.

[6] DAI Y., LI J., CUI W.LI J., *Coupled effect of load weights and belt use on male shoulder pressure redistribution.* Ergonomics, 2024:1-14, DOI:10.1080/00140139.2024.2328357.

[7] DEVROEY C., JONKERS I., DE BECKER A., LENAERTS G.SPAEPEN A., *Evaluation of the effect of backpack load and position during standing and walking using biomechanical, physiological and subjective measures.* Ergonomics, 2007.**50**(5):728-742.

[8] GENITRINI M., DOTTI F., BIANCA E.FERRI A., *Impact of Backpacks on Ergonomics: Biomechanical and Physiological Effects: A Narrative Review.* Int J Environ Res Public Health, 2022.**19**(11), DOI:10.3390/ijerph19116737.

[9] GOLRIZ S., HEBERT J.J., BO FOREMAN K.WALKER B.F., *The effect of shoulder strap width and load placement on shoulder-backpack interface pressure.* Work, 2017.**58**(4):455-461, DOI:10.3233/WOR-172651.

[10] HERB C.C., CUSTER L., BLEMKER S., SALIBA S., HART J.HERTEL J., *Gait kinematics and kinetics in patients with chronic ankle instability and healthy controls: A statistical parametric mapping analysis.* Foot (Edinb), 2024.**59**:102089, DOI:10.1016/j.foot.2024.102089.

[11] HUANG L., YANG Z., WANG R.XIE L., *Physiological and biomechanical effects on the human musculoskeletal system while carrying a suspended-load backpack.* J Biomech, 2020.**108**:109894, DOI:10.1016/j.jbiomech.2020.109894.

[12] KOROVESSIS P., KOUREAS G.PAPAZISIS Z., *Correlation between backpack weight and way of carrying, sagittal and frontal spinal curvatures, athletic activity, and dorsal and low back pain in schoolchildren and adolescents.* Clinical Spine Surgery, 2004.**17**(1):33-40.

[13] MACKIE H.W., STEVENSON J.M., REID S.A.LEGG S.J., *The effect of simulated school load carriage configurations on shoulder strap tension forces and shoulder interface pressure.* Appl Ergon, 2005.**36**(2):199-206, DOI:10.1016/j.apergo.2004.10.007.

[14] MALLOGGI C., SCARANO S., CERINA V., CATINO L., ROTA V.TESIO L., *The curvature peaks of the trajectory of the body centre of mass during walking: A new index of dynamic balance.* J Biomech, 2021.**123**( ):110486, DOI:10.1016/j.jbiomech.2021.110486.

[15] OZDEMIR S., GENCBAS D., TOSUN B., BEBIS H.SINAN O., *Musculoskeletal pain, related factors, and posture profiles among adolescents: a cross-sectional study from Turkey.* Pain Management Nursing, 2021.**22**(4):522-530, DOI:10.1016/j.pmn.2020.11.013.

[16] RATEAU M.R., *Use of backpacks in children and adolescents. A potential contributor of back pain.*

Orthop Nurs, 2004.**23**(2):101-105, DOI:10.1097/00006416-200403000-00004.

[17] SAWYER S.M., AZZOPARDI P.S., WICKREMARATHNE D.PATTON G.C., *The age of adolescence.* The lancet child adolescent health, 2018.**2**(3):223-228.

[18] TANG Y., GUO X., ZHOU T., LI L., GAO J., WANG Y., HUANG L.WEI S., *Effects of shoelace tightness on lower limb biomechanics and subjective perception during lateral shuffle in basketball.* Acta Bioeng Biomech, 2023.**25**(4):145-154, DOI:10.37190/abb-02400-2024-02.

[19] TOGHROLI R., REISY L., MANSOURIAN M., AZAR F.E.F., ZIAPOUR A., MEHEDI N.NEJHADDADGAR N., *Backpack improper use causes musculoskeletal injuries in adolescents: A systematic review.* Journal of Education Health Promotion, 2021.**10**:237, DOI:10.4103/jehp.jehp_306_20.

[20] VAN ANDEL S., SCHMIDT A.R.FEDEROLF P.A., *Distinct coordination patterns integrate exploratory head movements with whole-body movement patterns during walking.* Scientific Reports, 2023.**13**(1):1235.

[21] VAN DER KOOIJ H., FRICKE S.S., VAN'T VELD R.C., PRIETO A.V., KEEMINK A.Q., SCHOUTEN A.C.VAN ASSELDONK E.H., *Identification of hip and knee joint impedance during the swing phase of walking.* IEEE transactions on neural systems rehabilitation engineering, 2022.**30**:1203-1212.

[22] WANG Y.A.RHEMTULLA M., *Power analysis for parameter estimation in structural equation modeling: A discussion and tutorial.* Advances in Methods and Practices in Psychological Science, 2021.**4**(1):2515245920918253.

[23] WINTER D.A., *Biomechanics and motor control of human movement*. 2009: John wiley & sons.

[24] ZHU Z., FU W., SHAO E., LI L., SONG L., WANG W.LIU Y., *Acute Effects of Midsole Bending Stiffness on Lower Extremity Biomechanics during Layup Jumps.* Applied Sciences, 2020.**10**(1):397.