Biomechanical Analysis of Effect of Backpack Load on Postural Sway and Stability

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Abstract

External loads significantly affect the biomechanics of gait, resulting in postural tilt, trunk movement, and lateral instability. This study investigates the effects of backpack and sidepack loads on postural sway and stability. Data are recorded using the Modified Helen Hayes marker arrangement. The study tests three hypotheses: 1) External loading induces postural sway, 2) External loads cause a shift in the center of mass (COM) trajectory, and 3) Uneven weight distribution of sidepack loads induces pelvic tilt, leading to postural instability. Trunk tilt is evaluated in both the sagittal and frontal planes, with postural sway more prominent in the sagittal plane for backpack loads and in the frontal plane for sidepack loads. It is also observed that COM sway is more prominent while standing than walking, as dynamic activity distributes the shift in COM, leading to less noticeable sway.Hence, this comprehensive study evaluates effects of external loading on posture and stability.

Keywords: Postural sway, Biomechanics, Gait analysis, Stability, Kinematics, Backpack load

1. Introduction

Carrying a backpack is a common activity among diverse groups, including schoolchildren, military personnel, hikers, and working professionals. Understanding how external loads influence postural control is crucial for preventing musculoskeletal (MSK) injuries. Postural sway—a measure of body movement during standing or walking—offers valuable insights into postural control, balance function, and fall risk ([1]). While prior research has examined the impact of external loading on gait biomechanics and postural sway using center of pressure (COP) metrics and kinematics, fewer studies have analyzed center of mass (COM) displacement with varying backpack loads. Importantly, there is limited understanding of how backpack load placement influences postural stability and COM trajectory.

Studies such as [2] have shown that backpack loads increase postural sway regardless of load placement, highlighting strong correlations between sway and factors like anthropometric measurements, sex, and age. Similarly, [3] examined the effects of military backpacks on postural sway in females, revealing sex-specific responses to external loads. Additionally, [4] investigated COP control during lateral perturbations in adults, finding that reduced functional stability in "fallers" underscores the need to evaluate how external loads affect balance and posture. The study by Liau et al. [5] investigates the combined effect of wearing high heels and carrying a backpack on trunk biomechanics. They concluded that females who do not wear heels regularly tend to recruit more abdominal muscles to control their posture. Moreover, carrying a backpack induced posterior pelvic tilting and forward head posture. The comprehensive review by Liew et al. [6] evaluated the impact of bilaterally symmetrical backpack systems on walking biomechanics. They found that backpack loads lead to increased trunk flexion angles, increased hip and ankle range of motion, while trunk sagittal plane range of motion remained unchanged. Similarly, another study [7] investigated the biomechanical and metabolic effects of different backpack loads on simulated

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marching. They found that increasing backpack loads proportionally increases metabolic costs and perceived exertion.

Building on these findings, the current study hypothesizes that:

- Both backpack and sidepack loads induce postural sway during standing and walking.
- External loads cause a shift in COM trajectory, leading to compensatory forward trunk lean to maintain vertical alignment of the COM over the pelvis and counteract the posterior moment induced by the load.
- Uneven weight distribution of sidepack loads results in pelvic tilt, contributing to postural instability.

This study aims to advance the understanding of the biomechanical effects of backpack and sidepack loads on postural sway and stability, providing critical insights for designing load-carrying strategies that minimize MSK injury risk.

2. Methods

The experiment was conducted in the Wolf Orthopedic Biomechanics Laboratory at the Fowler Kennedy Clinic. One healthy adult participant (age: 22 years, height: 1.70 m, weight: 80 kg) was recruited for this study. The subject had no history of musculoskeletal injuries or balance disorders.

To collect biomechanical data, a modified Helen Heys marker arrangement was employed. Markers were strategically placed on the participant's body to capture kinematic and kinetic data, as illustrated in 1. Data were recorded for both static (standing) and dynamic (walking) conditions across three different load scenarios: no load, wearing a backpack, and wearing a sidepack.

For the static trials, the participant was instructed to stand still on a force plate under each load condition. The sequence began with standing without any load, followed by standing with a backpack, and finally standing with a sidepack. For the dynamic trials, the participant performed walking trials under the same loading conditions in the same order.

The protocol was as follows:

- No Load Condition: The participant stood still on the force plate, followed by a walking trial without carrying any load (1).
- Backpack Condition: The participant wore a backpack, and data were recorded first in the standing position and then during walking trials (2).
- Sidepack Condition: The participant carried a sidepack, and data were recorded in a standing position, followed by walking trials (3).

This experimental design allowed for the comparison of static and dynamic postural control and biomechanics across different loading conditions.

Figure 1: Position of markers based on modified Helen Heys arrangement

Figure 2: Subject standing with backpack load

The data are analyzed for both static and dynamic conditions to investigate postural sway under different load conditions. To examine the data in the dynamic state and compare the three different loading conditions, important gait phases—heel

Figure 3: Subject standing with sidepack load

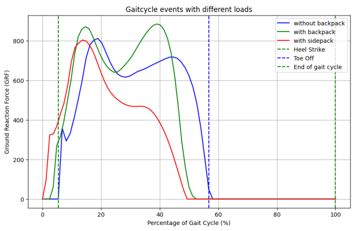

Figure 4: Heel strike and Toe-off phases of gait cycle under three different load conditions

strike and toe-off—are identified. These phases are determined by the vertical ground reaction forces acting on the foot. Heel strike occurs when the vertical ground reaction force exceeds 20 N, and toe-off is identified as the phase when the vertical ground reaction force falls below 10 N ([8]). The stance phase is the time difference between toe-off and heel strike as $stancephase = Time_{\text{toeoff}} - Time_{\text{heelstrike}}$. Once stance phase is identified (typically 60% of gait cycle [9]), the gait cycle percentage for every frame is computed as :

$$T_{\text{stance}} = (T_{\text{Toe-off}} - T_{\text{heel-strike}})$$

$$T_{\text{swing}} = (T_{\text{gait-cycle}} - T_{\text{stance}})$$

$$\text{Gait cycle\%} = \left(\frac{T_{\text{Phase}}}{T_{\text{gait-cycle}}}\right) \times 100$$

where T = Time and Phase= stance/swing
The percentage gait cycle mapped for three loading conditions is shown in Figure 5. Postural sway is defined as the change in the Center of Mass (COM) trajectory normalized by hip width. The full-body COM is evaluated by computing the COM for individual segments. The COM is computed as:

$$COM_{\text{segment}} = P + p \times (D - P)$$

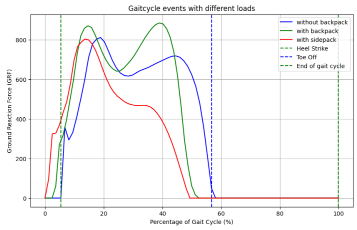

Figure 5: Time phases as percentage of gait cycles

Where:

- P: Position of the **proximal landmark** (e.g., hip for thigh, knee for shank).
- D: Position of the **distal landmark** (e.g., knee for thigh, ankle for shank).
- p: Anthropometric proportionality constant for the segment (e.g., 0.433 for the thigh).

The computation is applied for each coordinate x, y, and z as:

$$x_{\text{COM}} = x_P + p \cdot (x_D - x_P)$$

$$y_{\text{COM}} = y_P + p \cdot (y_D - y_P)$$

$$z_{\text{COM}} = z_P + p \cdot (z_D - z_P)$$

The total body CoM is computed as a weighted average of the segment COM:

$$COM_{\text{full body}} = \frac{\sum(COM_{\text{segment}} \cdot m_{\text{segment}})}{\sum m_{\text{segment}}}$$

Where m_{segment} is the mass of each segment, calculated as:

$$m_{\text{segment}} = m_{\text{body}} \cdot k$$

with m_{body} being the total body mass and k the mass proportion for the segment.
COM trajectory is normalized by hip width : $\frac{\mathbf{COM}_{\text{full body}}}{hipwidth}$. The COM sway is calculated in terms of the percentage for the load of the backpack and the side pack without backpack condition by using following equation:

$$\text{COM sway\%} = \left(\frac{COM_{\text{backpack}} - COM_{\text{no-backpack}}}{COM_{\text{backpack}}}\right) \times 100$$

Trunk tilt is rotation of trunk about saigttal, frontal and transversal axes.In this study, tilt is observed in sagittal and frontal plane both for standing and walking condition.The results are discussed in next section.

3. Results and Discussion

Sway in the COM trajectory is analyzed for both backpack and sidepack loads. No backpack data are considered as the baseline. Figure 6 compares the sway percentage for individuals walking with a backpack, a sidepack, and without any load. It

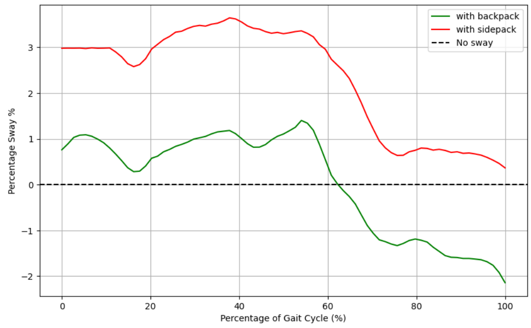

Figure 6: Dynamic COM sway

can be observed that the sway percentage remains close to baseline for the backpack load, with slight fluctuations, indicating balance and stable posture with the backpack. However, the sway percentage is consistently higher across the gait cycle for the sidepack load, indicating lateral instability, likely due to uneven weight distribution. Figure 7 demonstrates the sway percentage for individuals standing with a backpack, with a sidepack, and without any load. However, postural sway is

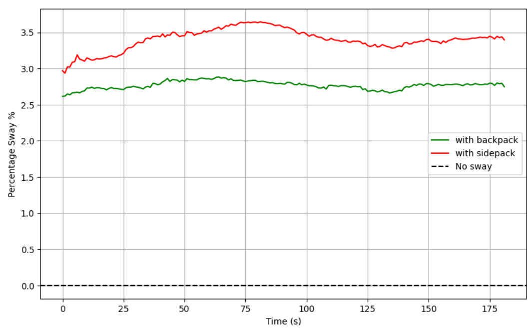

Figure 7: Static COM sway

higher when a person is standing with a backpack load than when observed during walking. This is because the person has to continuously make small adjustments to maintain balance. In contrast, walking, being a dynamic activity, distributes the shift in COM, leading to less noticeable sway. Thus, standing requires more active postural control than walking.

Trunk tilt was evaluated in both the sagittal and frontal planes for both static and dynamic states. Figures 8 and 9 demonstrate that trunk tilt due to the backpack is more prominent in the sagittal plane because the position of the load creates a backward moment (further detailed analysis can be found in the attached Jupyter Notebook file), hence forcing the trunk to lean forward to maintain balance.

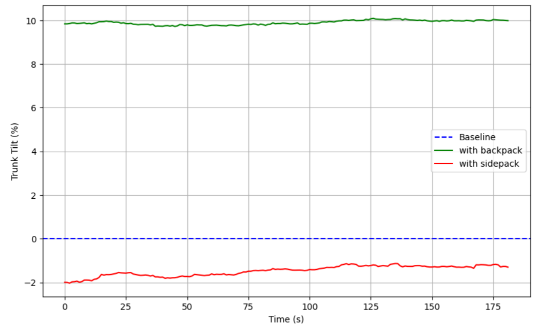

Figure 8: Trunk Tilt in Sagittal Plane (Static)

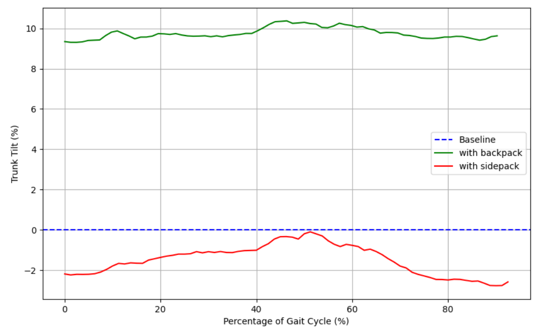

Figure 9: Trunk Tilt in Sagittal Plane (Dynamic)

In contrast, Figures 11 and 10 demonstrate that the sidepack creates more of a lateral shift in the frontal plane, causing less noticeable tilt in the sagittal plane. The backpack influences the body's forward-backward alignment, while the sidepack influences side-to-side adjustment.

Hence, the above results justify the hypothesis that external load causes a shift in COM, and to keep the COM aligned, the trunk leans forward in the backpack case and side-to-side with the sidepack load.

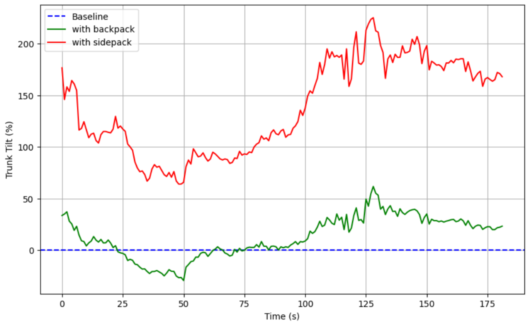

Figure 10: Trunk Tilt in Frontal Plane (Static)

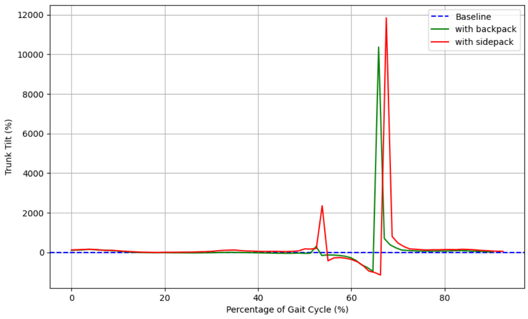

Figure 11: Trunk Tilt in Frontal Plane (Dynamic)

4. Conclusions

This study focused on a comprehensive biomechanical analysis of the impact of backpack and sidepack loads on postural sway, which is more prominent when a person is standing than walking. COM trajectory sway and trunk tilt were evaluated in the sagittal and frontal planes, and the study supports three hypotheses: 1) external loading induces postural sway, and 2) uneven weight distribution of the sidepack load results in postural instability.

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