Impact of Backpacks on Ergonomics

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Among load carriage systems, the backpack (BP) is certainly one of the most widespread in the world, with tens of million people using them every day for shorter or longer periods since early childhood. The effects of load carriage packs on human gait biomechanics, physiology and metabolism depend on the weight carried, the design of the pack and its interaction with the user.

Keywords: backpack ; ergonomics ; gait ; oxygen uptake ; load carriage

1. Introduction

Among load carriage systems, the backpack (BP) is certainly one of the most widespread in the world, with tens of million people using them every day for shorter or longer periods since early childhood [1].

In fact, in most developed countries, students start elementary school at 5–6 and finish high school at 18–19: this means that they are carrying a load 5–6 days a week for more than a decade, which has a non-negligible impact on their physical development and psychosocial well-being.

Even among adults, the BP represents a very frequently used accessory both in professional life and in sports. Regarding sports, in particular, a comfortable, functional and well-fitting BP is crucial for both performance and safety in several disciplines, such as hiking, mountaineering, ski-mountaineering, jogging, etc.: it has been found that a suboptimal BP affects lateral stability and balance [2] and, intuitively leads to excess energy expenditure and discomfort, which can disrupt the athlete's concentration while walking on uneven grounds and promote injuries.

The military frame is a shining example of how important a properly designed pack can be: in fact, it is not uncommon for soldiers to transport loads that exceed 40% of their body mass BM [3] for several hours in a day, with peaks of 60–70% BM when carrying the full gear [4]. Such a task cannot be performed using a BP with unevenly distributed loads or inadequately padded shoulder straps.

Overall, a BP compared to the unloaded condition results in changes in gait mechanics, metabolism, muscle activity, comfort and performance depending on the load, speed and duration of the effort [5][6][7]. Such variation in relation to the absence of equipment has also been reported for other types of sports equipment.

For running shoes compared to the unshoed condition: it has recently been suggested that the most appropriate footwear is the one that induces the least adaptations (i.e., changes) compared to unshoed walking, and allows the athlete to deviate as little as possible from the so-called preferred pattern [8]. It is reasonable to assume that this could also apply to wearing BP so that the ideal condition would produce only minor objective and subjective changes compared to unencumbered conditions.

Such alterations are physiological adaptations, and their absence would denote the lack of capacity to adapt ourselves to the changes in our environment, which would compromise our well-being. However, if alternations are excessive and prolonged, they can hinder movements or, in the worst cases, provoke fractures, paralysis, paresthesia or numbness, as well as increase fatigability [9][10][11][12].

In addition, it has been reported that the totality of adaptations depends on various factors, such as anthropometry, body mass index (BMI), training level and gender [5][13][14].

Therefore, it is important to know the above changes due to wearing in order to establish guidelines for designing an optimal carriage system.

2. Biomechanics

2.1. Kinematics

Head, Neck, and Shoulders

Children: It has been reported that wearing a BP causes significantly greater forward head tilt in obese children than in normal weight students [15] and also in nonobese prepubescent children when the load overcomes 10–15% BM with respect to the unloaded condition [1][16][17].

It has been reported that only load itself, but also its placement on the back plays a role in kinematic adaptations, as a significant increase in craniovertebral angle (i.e., a smaller difference compared to the unloaded condition) was observed when carrying a load of 15% BM placed lower on the back than when placed medium or high, suggesting that a low position represents the best load [17].

The same load was found to have significantly different effects depending on the design of the carrying system: a modified DP (i.e., with most of the load in the BP and less in the front pack (FP)) promotes a more neutral posture, with respect to a BP and a DP with the load evenly distributed on the front and back; therefore, this type of design seems to be recommended [18]. Moreover, the type of carrying (i.e., on one shoulder, asymmetrically, or two shoulders, symmetrically) was found to produce significant differences in shoulder and scapulae asymmetry when a load of 10% and 15% BM was carried on one shoulder only, compared to the unloaded condition [19][20].

Adults: contradictory results have been reported for the head and neck. Indeed, in some studies, it was observed the head-neck inclination increased significantly when a load of 15–40% BM was applied during walking compared to the unloaded condition [21][22][23]; in contrast, other studies reported no significant differences in head position in both static conditions and during walking due to the load [24]. As for the shoulders, a significant reduction in the range of motion in the transverse plane was found when carrying a load of 25% BM compared to the unloaded condition, during inclined walking [25].

Regarding the influence of design, a comparison between BP and FP loaded up to 10–15% BM revealed significant differences in neck posture in both cases, but in the opposite direction, compared to the unloaded condition [26]. It was found that the head angle in the sagittal plane at a load of 15–25% BM was significantly different when wearing a TP compared to BP, with the former providing a posture closer to the unloaded condition than the latter [23].

Strap length has been reported to have significant effects on head and neck posture: in particular, BPs with a weight of 15% BM and long shoulder straps result in a significant reduction in the cranial spine, both compared to shorter straps and in the unloaded condition [27].

Trunk ad Thorax

Children: Obese children were found to have a significantly higher forward tilt of the trunk compared to both the unloaded condition and to normal weight students when the load increased to 15% and 20% BM [15]. In normal weight school children, during level walking or static standing position, a significant increase in the forward tilt of the trunk was observed between 0% and 10 to 25% BM [1][15][16][17][20][28] and a significant decrease in the rotational plane of the trunk in the transverse plane [29] was observed. Nevertheless, some studies reported a significant increase in backward inclination compared to unloaded conditions [30].

It was found that wearing a BP asymmetrically resulted in significant differences in trunk lateral flexion (i.e., in the frontal plane): a load of 10% and 15% BM resulted in a significant tilt on the unloaded side compared to the unloaded condition [19][20]. Moreover, a load of 15% BM did not produce significant differences in trunk forward lean depending on high, medium, or low placement on the back [1].

Adults: the forward tilt of the trunk increased significantly when the load was increased from the unloaded condition to 40% BM during the stance phase in both level and inclined walking [21][22][23][24][25]. In the latter, adding a load of 25% BM was found to change the coordination pattern between the shoulders and pelvis [25]. A significant decrease in the trunk rotation in the transverse plane was observed with loads of 40% BM with respect to the unloaded condition [31].

In addition, a significant interaction between walking speed and load has been found, producing greater differences between loaded and unloaded conditions in the trunk and thoracic kinematics as speed increased [25][31].

Regarding the design, a significant decrease in thoracic rotation in the transverse plane was observed only for the thorax at a load of 40% BM compared to the unloaded condition [31]. Nonetheless, a significantly higher amplitude of thoracic rotation was observed when the same load (40% BM) was carried in a BP with a hip belt compared to the no-belt condition, suggesting that the belt is beneficial; furthermore, pelvic-thoracic coordination in the transverse plane showed a more stable pattern compared to the no-belt condition [32].

In addition, it was reported that a traditional double-strap BP can induce different effects on trunk posture depending on the design of the straps: non-flexible straps caused a non-significant forward tilt of the trunk during gait with respect to the unloaded condition, while traditional straps did so when loaded up to 10% BM, suggesting that the formers as optimal [33]. It was found that the torso angle in the sagittal plane at a load of 15–25% BM was significantly different when worn with a TP compared to BP, with the former allowing a posture closer to the unloaded condition [23].

Spine

Children: Significant differences in spine length were found in school children; in particular, those carrying school BPs heavier than 10% BM presented lower values than those carrying lighter loads [34].

Further investigations on the effects of weight-bearing on lumbar lordosis are needed. In fact, some groups reported that as the weight of the BP increased, a significant decrease in the length and angle of the lumbar lordosis and the inclination of the sacrum was observed compared to the unloaded condition [34]. Conversely, other studies found no difference in lordosis angle when a load of up to 15% BM was applied [17].

Adults: Significant decreases in lumbar lordosis and upper thoracic kyphosis were found in adults by applying a load between 5 to 20% BM compared to the unloaded condition [35].

Moreover, it has been reported that wearing a BP as heavy as 10% BM and lumbar support significantly reduces the effect of loading on the lumbar spine compared to a BP without support, with non-significant differences compared to the unloaded condition [36].

Pelvis and Center of Mass—COM

Children: in adolescents with and without idiopathic scoliosis, a significant reduction in the range of motion of the pelvis with increasing the load up to 15–20% BM has been found in the transverse and frontal plane compared to the unloaded condition [29].

Adults: Similar results were reported in adults compared to the unloaded condition for loads as high as 25–40% BM in both level and inclined walking [25][31]; in addition, a significant interaction between walking speed and load was found, with grater differences produced between loaded and unloaded conditions with increasing speed [31]. Furthermore, a significant increase in pelvis anteversion was observed when the load was greater than 10% BM compared to the unloaded condition [24]. A significantly higher amplitude of pelvic rotation in the transverse plane was observed when the same load (40% BM) was carried in a BP with a hip belt compared to the no-belt condition, indicating the belt is beneficial [32].

In the last stance, it was reported that the mean height of the trajectory of the system (subject + load) COM increases with increasing load, while the shape remained similar under all loading conditions between 12.5 and 40% BM [22].

2.2. Kinetics

Ground Reaction Force—GRF

Children: *Vertical*—Significant differences in vertical GRF (i.e., the force exerted by the ground on a body in contact with it) were found between normal weight and obese students when transporting a BP as heavy as 15–20% BM compared to the unloaded condition [15][37], with obese subjects showing higher values [15].

Anterior-posterior—A significant increase was found in normal weight students when the load was increased from 0 to 15–20% BM [15][37].

Medial-lateral—A significant increase was reported as the load is 20% BM in obese pupils [15] and 15% BM in normal weight adolescent students [37] compared to the unloaded condition.

Adults: *Vertical*—In adults, significant increases not only in GRF impulse but also in peak value during the loading response and terminal stance as a result of loading increase by up to 35% BM were observed compared to the unloaded condition [7][23][38][39]. In other studies, the same loading produced significantly different vGRF peaks depending on pack design (TP vs. BP, with the former showing higher peaks) [23].

Anterior-posterior—In adults, no agreements have yet been reached in the scientific literature. Indeed, in some studies a significant increase was observed with loads of 20–30% BM compared to no load [7][39]; conversely, no differences were observed with loads of ~30–35% BM [40].

Medial-lateral—Conflicting results have been reported in adults: in some studies, a significant increase was observed with loads of 30–40% BM compared to no load [7], and the same was true for impulse at similar loads during inclined walking [39]; in other studies, no significant differences were found [41].

Joint Moments

Children: In adolescent students, significant increases in peak moments of hip internal and external rotation and an increase in peak moments of hip abduction and flexion were observed during stance when the load BP increased. Moreover, an increase in peak flexion moment was observed during the forward swing when the load increased up to 15% BM compared to the unloaded condition [37][42].

Knee—Significant increases in knee extension and valgus moments during stance were observed with a load (15% BM) compared to the unloaded condition in adolescent students [37][42].

Ankle—The plantarflexion moment showed a significant increase in adolescent students as the load was increased up to 15% compared to the unloaded condition [37].

Adults: *Hip*—In adult military personnel, significant increases in hip extension moment were observed in late stance between no load, 15% and 30% BM [43]; significant differences in frontal and sagittal hip moments were observed when carrying loads of 15% and 25% BM with a TP compared to BP, with the former yielding higher values [23].

Knee—Significant increases were observed in maximum knee flexion, maximum and mean valgus moment, and mean extension moment when carrying loads between 15 and 40% BM compared to the unloaded conditions [23][39][43]. The adduction moment of the knee was found to be significantly higher in loaded conditions (20% BM) than in unloaded conditions. No significant differences were found in knee moments with FP compared to BP [44], but they were significantly lower in the sagittal plane when loads of 15% and 25% BM were carried with a TP compared to traditional BP [23].

Ankle—In adults, significant increases in maximum and mean ankle plantarflexion moments and maximum dorsiflexion moments of the ankle when loads of 15–40% BM were applied compared to unloaded conditions [39][43].

3. Physiology

The most studied energy-related parameter is oxygen uptake (VO_2, i.e., diffusive oxygen transport in the lungs and microvasculature [45]): several studies in civilian and military settings have been conducted to understand the correlation between load carriage and oxygen demand.

For running, carrying a light BP (i.e., 5% BM) has been reported to produce a significant increase in VO_2, energy cost and heart rate (HR) [46][47] with respect to unloaded conditions. A significant increase in VO_2 due to higher loads (25–46% BM) was also observed during walking compared to the unloaded condition [48].

In the military population, carrying loads has been reported to be significantly more demanding in terms of maximal oxygen uptake (VO_{2max}: this parameter provides information on the capacity of the organism to take up, transport and utilize oxygen, predominantly in contracting muscle mitochondria [45]), VO_2, HR, pulmonary ventilation (VE) and caloric expenditure during the same performance as altitude increases [49].

Moreover, significant differences have been observed in VO_{2max}, VE and HR during a 40-min marching trial at 6 km/h with 0%, 15% and 30% BM loads [43]. Consistent results were observed in studies at higher loads (30, 50 and 70% of lean subjects BM) during the same experiment, where a similar trend was observed in VO_{2max} and HR [4]; in particular, combining these results with previous studies [43], a quasi-direct relationship can be observed for load increases between 0 and 70% BM for VO_{2max} and HR.

In such studies, energy expenditure was found to be 41% VO_{2max} with a load of 30% BM [43], as high as the recommended working limits of 33–40% VO_{2max} [50][51], with other studies suggesting values up to 50% VO_{2max} [52].

Consistently, other studies have reported a load of 37% BM to require a VO_{2max} of less than 50% which is stable over time, while a load of ~60% BM, has been reported to require a relative work intensity that both significantly increases over time and is well above 50% VO_{2max} as a critical threshold that could lead to exhaustion if exceeded [53].

The design of the BP was found to have significant effects on VO_2: specifically, DP was reported to be less exhausting than conventional BP with loads up to 30% BM. This effect is more pronounced in female subjects; no significant differences in respiratory exchange ratio (RER) in the same scenario [54]. In addition, VO_2 and minute ventilation were reported to decrease significantly when the load (25% BM) was carried in a higher position on the back compared to a low and central position, suggesting a higher position is optimal [55]. Lastly, it has been reported that carrying a BP weighing 15% BM with a mono-shoulder strap system in schoolchildren results in a significant decrease in forced vital capacity and expiratory volume compared with a bilateral shoulder belt [56].

Relevant differences were found with regard to muscle hemodynamics. According to studies performed with LED (light emitting diode) and LDF (laser doppler flow) technologies [57][58], both mean muscle oxygenation and brachial arteries are negatively affected by load carriage.

In fact, when the weight of BP was increased by 11–23% BM [57], a decrease of up to 22 ± 23% in mean muscle oxygenation was observed. This finding was always accompanied by a sharp decrease in microvascular flow and perceived shoulder pain.

As far as brachial artery flow, a decrease of 43% has been observed in a 20% BM backpack [58]. One of the most impacting factors was the microvascular flow in the fingers, which decreased by 100%. This phenomenon has led to resulting subjective paresthesia at the hand after wearing the BP for 10 min.

Both studies have been conducted considering conventional backpacks.

On the other hand, blood flow reduction and nerve compression are two common effects of load carriage [58] and usually disappear a few minutes after the load is removed.

Intuitively, decreased blood flow corresponds to a decreased mean muscle oxygenation that led to an overall discomfort feeling in the user.

4. Muscle Activity

4.1. Neck and Shoulders

Children: significant differences in neck muscle activity were found when carrying a load of 15% BM with differently designed packs. Specifically, electromyography (EMG) amplitude was lower with a modified DP, where most of the weight was on the back, compared to a traditional BP and a DP, where the load was evenly distributed on the front and back, suggesting that the modified DP is the optimal solution [18].

Trapezius activity has been reported to be significantly higher than in the unloaded condition when wearing both a traditional BP and a DP with loads up to 15% BM [1][18], yet no significant differences were observed between these two designs [18]. Additionally, no significant differences have been observed in the placement of the load (higher or lower on the back) [1].

Adults: No significant differences were found compared to the unloaded condition in adults with loads up to 15% BM when carrying a traditional BP [24].

It was reported that the trapezius and deltoid were significantly unloaded (i.e., showed less muscle activity) when the shoulder belt was elevated with respect to a lower configuration with a similar weight BM [59].

In addition, female university students were found to have significantly higher trapezius activity on the side on which the load is carried (when carried asymmetrically) in both the unloaded and double-strapped conditions and at loads of 10% BM [1].

4.2. Back

Children: it was reported that erector spinae activation was significantly higher in children when the load was increased between 5 to 15% BM compared to the unloaded condition; the position of the load (higher or lower on the back) did not significantly change the activity [1].

Adults: Erector spinae activation has been reported to be significantly decreased in adults carrying a load between 5 to 15% BM compared to the unloaded condition [24]; however, other studies found no differences at comparable loads, namely 20% BM [30].

Regarding asymmetry, wearing a single strap BP resulted in significantly higher activity of the erector spinae on the contralateral side with a load of 10% BM compared to no-load condition; the latissimus dorsi showed no significant differences in its activations between single and double strap BP designs at a load of 10% BM compared to the 0% load condition [60].

4.3. Lower Limbs

Adults: contradictory results have been reported: some studies found significant differences in increasing the load to 15–40% in the Tibialis Anterior, Medial and Lateral Gastrocnemius, Peroneus Longus, Biceps Femoris, Vastus Lateralis and Rectus Femoris [61][62]; other studies showed no significant differences due to a load, compared to the unloaded condition [30].

5. Comfort

5.1. Neck and Shoulders

Children: it has been reported that the placement of the load and the load unity cause significant differences in neck and shoulder comfort in schoolchildren because the higher is the load (10% BM) the greater will be the perceived discomfort, which also depends on the higher or lower placement on the back [1].

Adults: significant differences in the perceived neck and shoulder comfort were found between traditional and more vertical load distribution, in college students wearing a BP, with the latter found to be more comfortable at a load of 10% BM [63].

Other studies found no difference in neck and shoulders comfort based on load placement, but only on load entity (15 to 40% BM, compared with 0%) [24][64][65]. In the last stand, it was reported that the rate of perceived exertion (RPE) was significantly lower when the BP was worn with the support of a hip belt [66].

Regarding the influence of design, no significant differences in shoulder comfort were found between FP and BP at a load of 10 to 15% BM [26], but the strap length has been reported to exert significant effects on shoulder pain: specifically, in BPs weighing 15% BM were observed to have significantly higher discomfort with longer shoulder straps compared to shorter ones [27].

5.2. Back

Adults: significant differences in upper back comfort were observed when the load increased up to 15% BM compared to 0%. However, these differences did not depend on the placement of a higher or lower load, but only on the entity of the load [24]. On the other hand, some studies reported non-significant differences in upper back comfort at loads between 0–40% BM [65]. Therefore, the influence of load on upper back comfort remains unclear. As for RPE, it was reported to be significantly lower when the BP was worn with the support of a hip belt [66].

Regarding perceived comfort in the lower back, significant differences were found between traditional and more vertical load distribution, with the latter reported to be more comfortable when carrying a load of 10% BM [63]. Regarding the influence of the design, no significant differences in lower back comfort were found between FP and BP when the load is up to 10–15% BM [26].

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