A KINEMATIC COMPARISON OF GAIT WITH A BACKPACK VERSUS A TROLLEY FOR LOAD CARRIAGE IN CHILDREN.

1. INTRODUCTION

Recommendations for a safe backpack load in children are generally proposed for up to 10%–15% of the child´s body weight (BW) (American Physical Therapy Association, 2016; Asociación Española de Pediatria, 2014), although recent studies have demonstrated that many children carry an excessive backpack load on a daily basis (Al-Saleem et al., 2016; Farhood, 2013; Ibrahim, 2012). In this way, backpack load appears to contribute to the problem of back pain among backpack users, altering posture, specifically by increased trunk and neck flexion, both of which have been identified as factors that increase the intensity of pain felt by schoolchildren (Adeyemi et al., 2017).

With respect to postural adaptations to carrying a loaded backpack, previous studies have reported increases in trunk flexion when carrying loads between 15% to 20% of BW (Hong and Brueggemann, 2000; Li et al., 2003; Li and Hong, 2004; Orantes-Gonzalez et al., 2017). Previous studies clarified that this thorax flexion, as a loading response, is an adaptation to counterbalance the extra load on the back; thorax flexion seems to increase the force experienced by the spine from 7.2-fold the added weight while maintaining a neutral spine position to 11.6-fold the added weight with a 20° forward posture (Hansraj et al., 2018). Together with trunk flexion, the pelvis also plays an important role in load carriage because it is responsible for supporting the weight from the spine to the lower limbs during standing (Hodges and Richardson, 1997). Under load conditions (from 15% to 20% BW), the pelvis segment adapts its movements, reducing rotation and obliquity movements (Chow et al., 2005; Orantes-Gonzalez et al., 2017), together with an increase in the anterior pelvis tilt trend (Orantes-Gonzalez et al., 2017; Smith et al., 2006). Analysis of the distal joints (knee or ankle) under backpack carriage has been more scarce. Studies have reported that under carriage conditions, changes were more marked in the proximal joints (pelvis and hip) than in the distal ones (Chow et al., 2005; Orantes-Gonzalez et al., 2017).

As an alternative option to the backpack, school trolleys are being more frequently used for students while attending elementary school, as shown in previous studies. The school trolley was the favourite option for 5% of students in Texas (Forjuoh et al., 2003), 14.5% in Saudi Arabia (Al-Hazzaa, 2006), 16% in Iraq and Egypt (Fadhil Farhood, 2013; Ibrahim, 2012), and between 37% to 44% in Spain (Saborit and Pitarch, 2002; Zurita et al., 2014). In countries such as Greece, use of the school trolley was even higher than that of the backpack, being the favourite option for 46% of children, while 38% used the backpack (Rontogiannis et al., 2017).

To analyse the effects of pulling a school trolley on children´s posture, a previous study compared the effect of pulling a trolley with various loads (10%, 15% and 20% BW) to unloaded walking, concluding that the main adaptations were seen in the increased flexion of the thorax, hip, and pelvis as children pulled the trolley with 15% and 20% of BW (Orantes-Gonzalez and Heredia-Jimenez, 2017). Only one study compared gait kinematic adaptations while pulling a school trolley and carrying a backpack with 15% BW (Orantes-Gonzalez et al., 2017). In that study, the authors reported that the use of a backpack required greater flexion of the thorax (27%), pelvis (10%) and hip (44%) than the use of a trolley with the same load. Nevertheless, there have been no previous studies analysing the effects of load carriage with a backpack or a trolley to understand the kinematics as load increases using both devices.

Recommendations regarding the use of school trolleys have been proposed for situations in which school children have to carry high loads (American Academy of Pediatrics, 2016; Asociación Española de Pediatria, 2014). To the best of our knowledge, there have been no previous studies that deeply analyse the effect of pulling various loads in a school trolley in comparison with carrying a backpack to clarify the effects of and recommendations for the use of both types of equipment by scholars.

Therefore, the aims of this study were to evaluate gait kinematics of the lower limbs and thorax in children by first comparing various weights on a backpack or a trolley to unloaded walking and then comparing the backpack to the trolley condition directly with matched loads. To accomplish this, gait kinematics analysis was carried out using statistic parametric mapping (SPM), a statistical approach that allows hypothesis testing by considering the entire kinematic curve without the need for a priori data reduction (Pataky, 2012), thus eliminating the missing or even reversed trends that are occasionally produced by data discretization (Pataky et al., 2008).

2. MATERIALS AND METHODS

2.1. Participants

Forty-nine students from an elementary school participated in this study (26 girls and 23 boys). The average age for the girls was 9.5 (1.8) years, the average mass was 36.7 (11.6) kg, and the average height was 1.41 (0.1) m. For boys, the average age was 10.4 (1.6) years, the average mass was 42.7 (12.6) kg and the average height was 1.47 (0.1) m. Of all participants, 55% carried a backpack on a daily basis to and from school, while the other 45% used a trolley.

As general criterion to participate in this study, the students had to have no history of orthopaedic trauma or neurological problems. The participants in the present study were volunteers, and their parents completed an informed consent form. All participants could withdraw at any time during the study. The university ethics committee approved this study (number: 137/CEIH/2016).

2.2. Procedure

Each participant’s mass and height were measured with a scale and height rod (SECA769, Hamburg, Germany). Prior to data collection, each participant completed a familiarization phase that consisted of walking without the backpack or trolley. Once familiarized, they completed the experimental conditions in a randomized order. Three minutes of rest were provided between conditions.

A 3D-motion capture system (Qualisys AB, Göteborg, Sweden) with nine cameras (8 Oqus 400 and 1 Oqus colour 210) collecting at 250 Hz was used to capture 3D gait kinematics. To analyse the effects of transporting different loads, the children walked in the following experimental conditions: unloaded walking (as control), pulling a school trolley or carrying a backpack, both with 10%, 15%, and 20% BW loads (Figure 1).

“INSERT FIGURE 1 AROUND HERE”

The different loads were achieved by filling the backpack/school trolley with books of different weights. The backpack was a standard model (American Tourister, Samsonite, UK), and it was carried over two shoulders with the bottom of the backpack level with the waist line. The school trolley (TrainingPixel, Chamoe, Spain) had 4 wheels and a 0.38 m-long handle that was pulled using the dominant hand; only two wheels were in contact with the ground when being pulled. All participants were right hand dominant. Each child walked for one minute per condition at their preferred speed along a 15 m walkway. At least 6 trials were recorded per condition, obtaining one left stride and one right stride in each trial that were then averaged and analysed. Infrared cameras were focused on the central three metres of the walkway to discard the acceleration and deceleration phases of the gait.

To capture the 3D gait kinematics, 48 reflective markers were placed on the children’s skin on both sides of the lower limbs and the trunk. Specifically, markers were placed on the first and fifth metatarsal head, base of the second metatarsal, medial and lateral malleolus, the large posterior surface of the calcaneus, the lateral and medial femoral epicondyle, the anterior and posterior superior iliac spine, the acromioclavicular joints, the jugular notch, the xiphisternal joint and the costal cartilage of the seventh rib. A cluster with four markers was placed on the lateral portion of the shank and thigh of both legs. As carrying a backpack obstructed the camera view of the markers on the hips, two additional clusters with three markers were placed on the lateral hips. The lateral and medial markers on the malleolus and on the femoral epicondyles, the posterior superior iliac spine markers and the acromioclavicular joint markers were used only for calibration and were removed prior to dynamic trials.

Visual 3D software version 5.0 (C-Motion-Inc., Germantown, MD, USA) was used to build a geometric model of 8 segments that was subsequently used to obtain the gait kinematic curves. The Cardan sequence order of rotations (XYZ) was selected, assuming that the x-axis represents mediolateral direction, the y-axis epitomizes anterior/posterior direction and the z-axis is in the axial direction.

2.3. Outcome variables

Mean and standard deviation curves (in degrees) averaged for both legs were normalized to the duration of the gait cycle (GC) for each subject (from 0 to 100% of the GC) for the following variables: flexion/extension, adduction/abduction and internal/external rotation of the thorax, pelvis, hip, knee and ankle. Pelvic angle was expressed as absolute angles of the segments with respect to the global coordinate system. The hip angle was determined by the pelvis and femur, the knee angle was determined by the thigh and shank, the ankle angle was determined by the foot and shank, and the hip and thorax segments determined the thorax angle.

2.4. Statistical analysis

Gait kinematics were statistically compared using the open-source 1-dimensional statistical parametric mapping package "SPM1D" (Pataky, 2012). Specifically, two main types of analyses were undertaken.

First, the segment or joint level data from all backpack and school trolley conditions were separately compared to the control condition data. Segment or joint vector-fields were constructed by assembling multicomponent time series of all subjects, e.g., 49 subjects x 101 data nodes x pelvis {x, y, z}, and statistically compared to the control condition data using the vector-field (multivariate) equivalent of the paired t-test, a paired Hotelling's T^2 test (Pataky et al., 2013). Considering that there were five kinematic segments/joints and three weight manipulations (10%, 15% and 20% BW) for the backpack and school trolley conditions, 30 statistical tests were run in total. To avoid inflating the type I error, alpha was corrected for 30 comparisons. Second, a within-condition analysis was undertaken for the backpack and school trolley conditions. Each weight manipulation was compared in pairwise fashion (e.g., 10–15%, 10–20% and 15–20%) using a paired Hotelling's T^2 test, resulting in 15 within-condition comparisons. Alpha was corrected for 15 comparisons within each condition. When vector-field results justified a post hoc test, the same process was used for post hoc comparisons, taking into consideration each of the different kinematic planes (x, y and z).

For those unfamiliar with SPM, the Hotelling's T^2 statistic is calculated at each time node to produce a statistical "map". Random field theory (Adler and Taylor, 2007) is then used to model the behaviour of random vector-fields and determine the critical threshold at which only alpha % of equivalently smooth random data would cross. If the T^2 statistic crosses the critical threshold at any point in the time series, then the null hypothesis is rejected. This analysis controls the false-positive rate more tightly than does selecting arbitrary 0D (e.g., peak) values from the time series (Pataky et al., 2016).

3. RESULTS

The kinematic curves of the thorax, pelvis, hip, knee and ankle in the three planes (sagittal, frontal and transversal) while children were carrying the backpack and pulling the trolley were used for SPM analysis (Figure 2).

"INSERT FIGURE 2 AROUND HERE"

3.1. Vector-field comparisons between control and trolley-backpack conditions

Comparing the backpack conditions to the control condition, the SPM vector-field was significant in the thorax, pelvis and hip throughout the GC, while the knee showed significant differences at the beginning, in the middle and in the last part of the GC.

The ankle showed the main differences in the middle of the GC only in the 20% BW condition.

Comparing the trolley conditions to the control conditions, significant differences were seen in the thorax during the whole GC in the 20% BW condition. In the 10% and 15% BW conditions, the differences in the thorax were significant from the beginning to 70% of the GC and from 80% of the GC to the end of the GC. In the pelvis, differences were seen in the 15% and 20% BW conditions throughout the GC. Non-significant differences were seen in the hip, knee and ankle at all loads analysed.

3.2. Post hoc comparisons: control condition-backpack loads (Figure 3)

"INSERT FIGURE 3 AROUND HERE"

The thorax and pelvis showed significant differences in the sagittal plane during the entire GC in the three backpack load conditions. In the transverse plane, the differences were seen during large periods of the first, second and last third of the GC. The thorax did not show differences in the frontal plane, while the pelvis showed significant differences during most of the GC.

For the hip, significant differences were seen in the sagittal plane during the first middle and the last third of the GC. In the frontal plane of the hip, three peaks were significant during the first part of the GC, 60% of the GC, and during the last part of the GC. In the transverse plane, a small part from 10% to 20% of the GC was significant in the three load conditions.

For the knee, the main differences were seen in the sagittal and transverse planes in the 15% and 20% BW conditions. In the ankle, only slight differences were observed.

3.3. Post hoc comparisons: control condition-trolley loads (Figure 4)

"INSERT FIGURE 4 AROUND HERE"

The thorax showed significant differences in the sagittal plane during the entire GC in the three loads tested, as did the pelvis in the 15% and 20% BW conditions. In the frontal plane, the thorax and pelvis did not show significant differences. In the transverse plane, the thorax showed significant differences at the beginning and at the end of the GC, while the differences in the pelvis were not significant.

3.4. Post hoc comparisons: backpack conditions-trolley conditions (Figure 5)

"INSERT FIGURE 5 AROUND HERE"

A comparison of carrying the backpack and pulling the trolley showed significant differences in the sagittal and transverse planes of the thorax. In the pelvis and hip, differences were seen in the three planes in the three loads analysed. For the knee and ankle, the differences were minimal, except for the knee movements in the transverse plane at the beginning, the middle and the end of the GC.

4. DISCUSSION

Backpacks and school trolleys are widely used to transport school supplies. The present study analysed the gait kinematic adaptations when carrying a backpack and a school trolley with different loads in children to clarify their effects on children´s posture.

In the backpack conditions, the main finding was that an increase in load did not increase differences with respect to the control condition; similar adaptations were seen with the lightest load and the heaviest load. Another consideration was that the effect of increasing load decreased from the proximal joints to the distal ones in concordance with previous studies (Chow et al., 2005; Orantes-Gonzalez et al., 2017). Specifically, the most highly affected joints were the pelvis and thorax in the sagittal and transverse planes. The thorax and pelvis flexed more to compensate for the backward displacement of the child's centre of gravity due to the load being carried on the back (Smith et al., 2006) and reduced rotation movements as a consequence of a decrease in counter-rotation between the thorax and lower body to provide dynamic stability and to reduce the effect of the increased moment of inertia of the backpack

(Chow et al., 2005; Hyung et al., 2016; Smith et al., 2006). Such adaptations would have a negative effect on spine care that could result in back pain or discomfort in elementary students (Ibrahim, 2012) as well as an increase in the force that the backpack has to support (11.6-fold the added weight of the backpack) (Hansraj et al., 2018). In fact, increased trunk and neck flexion were identified as factors that increase the intensity of pain felt by schoolchildren (Adeyemi et al., 2017).

Analysis of the complete kinematic curve in this study identified the most affected gait phases while carrying a backpack. In this way, according to the categorization of gait phases (Perry and Burnfield, 2010), our study showed that walking while carrying a backpack could be related to the inefficiency of weight-bearing stability (loading response phase), limb progression and limb advancement (pre-swing phase and terminal swing phases). Supporting these results, previous studies found that carrying a backpack decreased postural stability during walking (Yen et al., 2011) and standing (Golriz et al., 2014; Pau and Pau, 2010).

With respect to the analyses of kinematic adaptations associated with pulling a trolley and carrying a backpack, the increase in load did not increase the number or the size of kinematic adaptations. In fact, differences in the thorax and pelvis were nearly non-existent in the frontal and transverse planes. In the sagittal plane, increases in thorax and sagittal flexion were reported throughout the entire GC to counterbalance the load of the school trolley (Orantes-Gonzalez et al., 2017; Orantes-Gonzalez and Heredia-Jimenez, 2017). Although pulling a school trolley is an asymmetrical task, the use of a school trolley resulted in kinematic patterns very closely aligned to those of normal walking. In the transverse plane, pulling a trolley showed a similar trend to that of the backpack in relation to decreased rotation movements of the thorax and pelvis, although this was significant only at the beginning and at the end of the GC and with a lower magnitude of effect.

Comparing the postural adaptations of carrying a backpack and pulling a trolley, the use of a school trolley resulted in kinematic patterns more closely aligned to normal walking than did the backpack, which is concordant with a previous study in which the use of a trolley required 5° less thorax flexion than the use of a backpack with the same load (Orantes-Gonzalez et al., 2017). In this study, carrying the backpack required higher adaptations relative to unloaded walking, i.e., in thorax flexion, carrying the backpack required a higher increase as follows: 33% in the 10% BW, 50% in the 15% BW and 62% in the 20% BW compared to walking without a load. In the trolley analysis, these increases were much smaller, since the lightest condition, 14% of thorax flexion, increased in the 10% and 15% BW conditions and was 20% in the 20% BW condition relative to control walking. Consistent with these findings, Dimitrios et al. (2017) reported a higher incidence of musculoskeletal symptoms in backpack users than in trolley users (65% vs. 43%), despite the average weight of the schoolbag being higher for trolley users than for backpack users (18.6% BW for trolley users and 15% BW for backpack users).

Based on kinematic adaptations, and because carrying even the lightest load (10% BW) required lower significant differences in the school trolley condition than the backpack condition, the use of school trolleys should not be restricted only to transporting heavier loads as previous studies recommended (American Academy of Pediatrics, 2016; Asociación Española de Pediatria, 2014) and should be considered a good option for light load transportation.

Because no specific load recommendations have been proposed for school trolleys, the inclusion of three loads within the range of recommended “safe” loads for backpack carriage (ranges 10%–20% BW) and the comparisons between the different types of equipment (backpack and trolley) allowed a systematic analysis to determine the postural answer to the load and the equipment by children. In the backpack analysis, an increase in loads up to 10% produced some kinematic changes, supporting previous studies in which it was recommended to avoid loads above 10% BW (Devroey et al., 2007). In this way, El-Nagar et al. (2017) concluded that school children who carry school bags between 10.1%–15% and > 15% BW were more likely to suffer from back pain complaints by approximately 2.6 times and 6.1 times, respectively, than those carrying school bags ≤ 10% of their BW.

In contrast to the differences observed between different backpack loads, the school trolley condition showed minimal kinematic adaptations up to 20% BW. These findings confirm that this load does not induce substantial kinematic compensations, yet other considerations, such as lifting the trolley upstairs, may also influence the choice of a 20% BW trolley. Therefore, considering these results and as there are currently no recommended "safe" loads for school trolley users, pulling a school trolley less than 20% BW over ground appears to be appropriate.

Future work could attempt to quantify lower back loads and the stress in the arm-shoulder complex more specifically, e.g., using a musculoskeletal model that could help to estimate the loads experienced by the musculoskeletal system as a consequence of these altered kinematics. In addition, future research should analyse the load magnitudes at which the backpack and trolley kinematics diverge.

5. CONCLUSIONS

Pulling a school trolley loaded between 10%–20% BW allowed children to maintain walking kinematics similar to unloaded walking compared with carrying a backpack at 10% BW or above. The results of this kinematic analysis suggest that children should avoid loads greater than 10% BW when carrying a backpack or greater than 20% BW if using a trolley to maintain unloaded over-ground walking kinematics.

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7. FIGURE LEGENDS

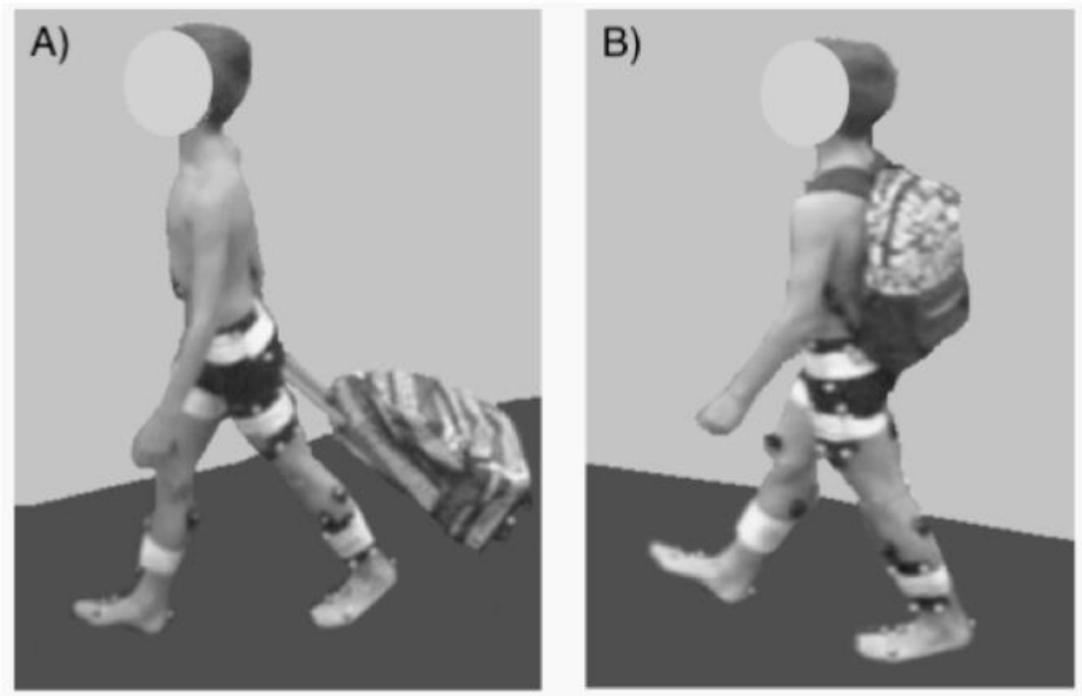

Figure 1. Subject walking pulling a school trolley (A) and carrying a backpack (B).

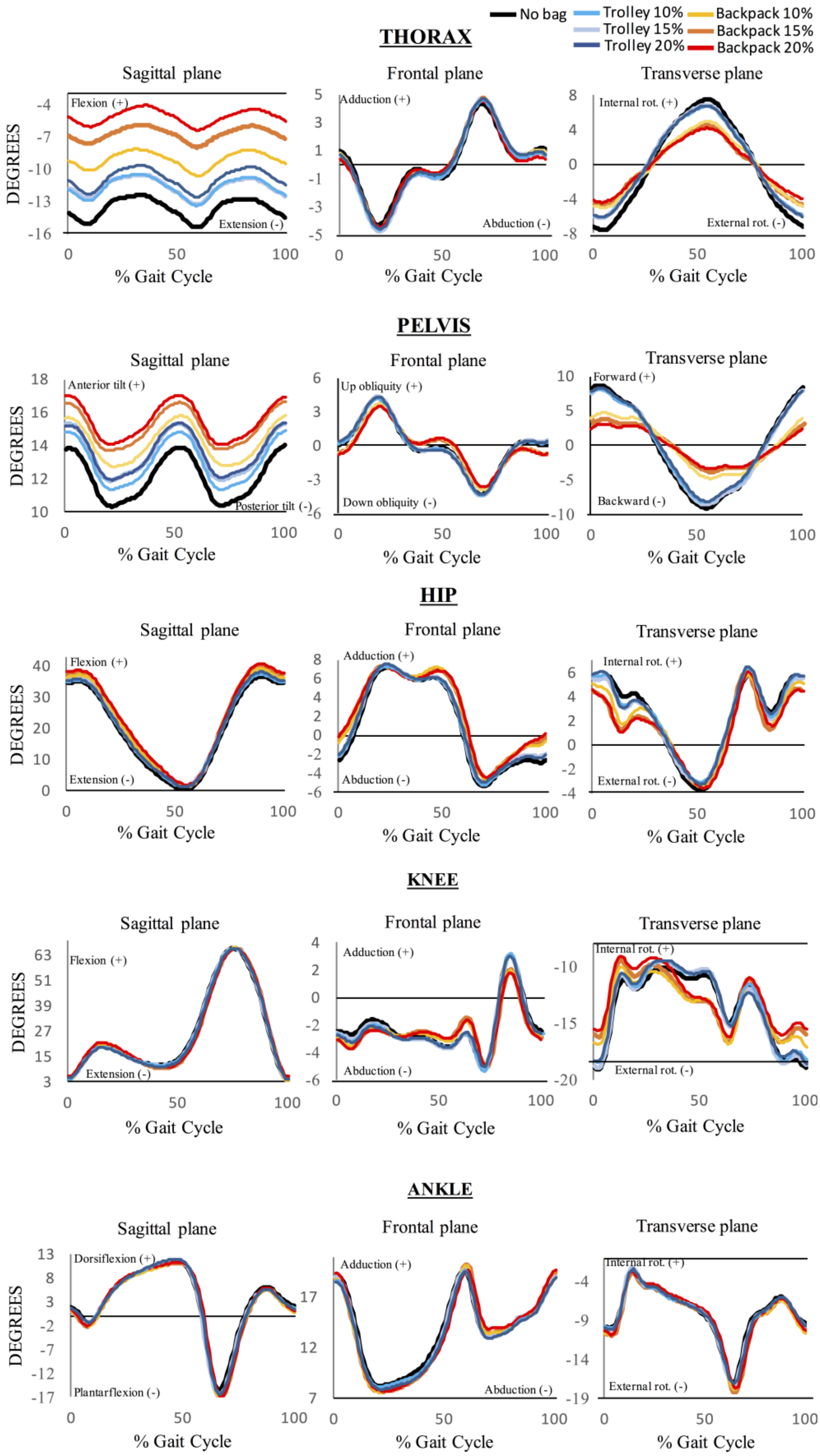

Figure 2. Multi-planar kinematic waveforms for thorax, pelvis, hip, knee and ankle in each of the experimental conditions analysed. GC: gait cycle.

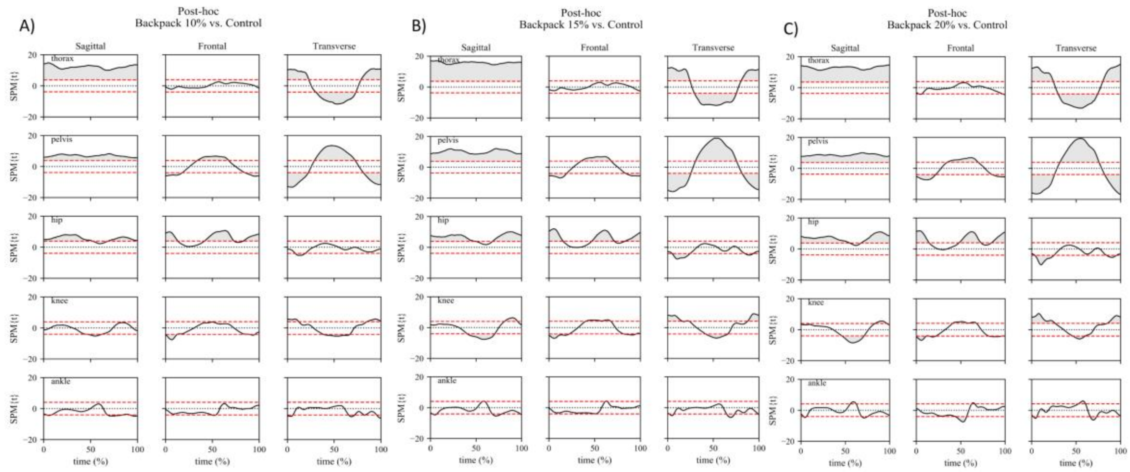

Figure 3. Results of Hotelling's T^2 test for post hoc comparisons between thorax, pelvis, hip, knee and ankle for the unloaded condition versus carrying a backpack with 10%, 15% and 20% BW. The red dashed line indicates the critical threshold. The area of the T^2 curve that crosses the critical threshold is shaded in grey and indicates the temporal location of significant kinematic differences.

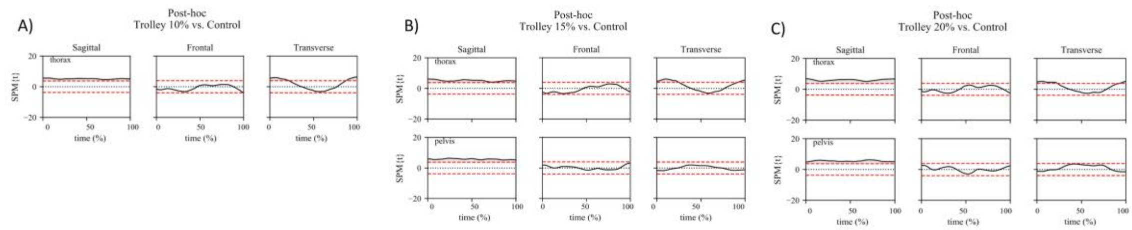

Figure 4. Results of Hotelling's T^2 test for post hoc comparisons between thorax, pelvis, hip, knee and ankle for unloaded walking versus pulling a school trolley with 10%, 15% and 20% BW. The red dashed line indicates the critical threshold. The area of the T^2 curve that crosses the critical threshold is shaded in grey and indicates the temporal location of significant kinematic differences.

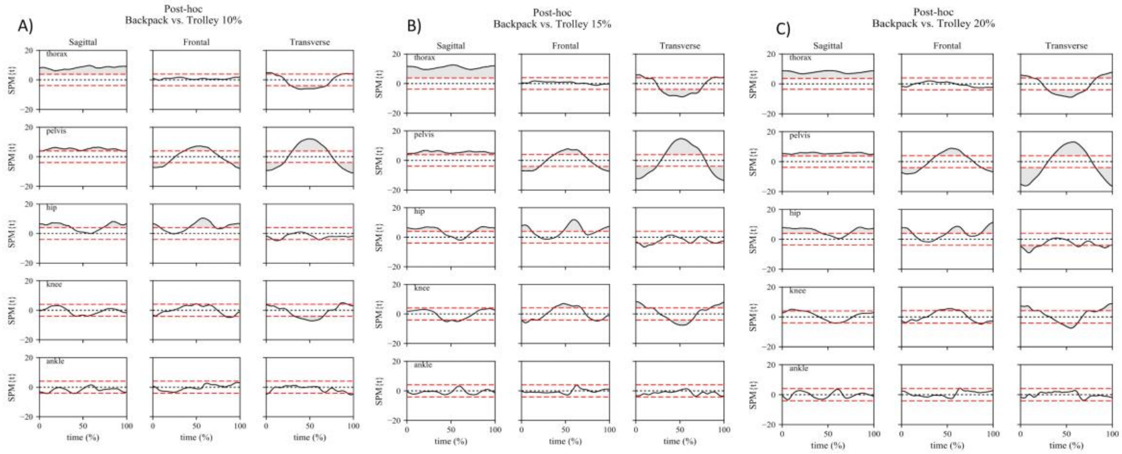

Figure 5. Results of Hotelling's T^2 test for post hoc comparisons between thorax, pelvis, hip, knee and ankle for carrying a backpack versus pulling a school trolley. The red dashed line indicates the critical threshold. The area of the T^2 curve that crosses the critical threshold is shaded in grey and indicates the temporal location of significant kinematic differences.