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RESEARCH ARTICLE

Altered trunk-pelvis kinematics during load carriage with a compliant versus a rigid system

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ABSTRACT

Load carriage is a key component of hiking and military activity. The design of the load carriage system (LCS) could influence performance and injury risk. This study aimed to compare a traditional and a compliant LCS during walking and a step-up task to quantify differences in oxygen consumption and trunk-pelvis kinematics. Fourteen participants completed the tasks whilst carrying 16 kg in a rigid and a compliant LCS. There were no differences in oxygen consumption between conditions during either task ($p > 0.05$). There was significantly greater trunk-pelvis axial rotation ($p = 0.041$) and lateral flexion ($p = 0.001$) range of motion when carrying the compliant LCS during walking, and significantly greater trunk-pelvis lateral flexion range of motion during the step-up task ($p = 0.003$). Carrying 16 kg in a compliant load carriage system results in greater lateral flexion range of motion than a traditional, rigid system, without influencing oxygen uptake.

Practitioner summary: Carrying 16 kg in a compliant load carriage system during walking and a step-up task allows greater lateral flexion range of motion than a traditional, rigid system without influencing oxygen consumption.

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KEYWORDS
Biomechanics; coordination variability; hiking; backpack design

Introduction

Load carriage plays an important role in occupational tasks, tasks of daily life and leisure activities (Rugelj and Sevšek 2011; Martin et al. 2023). Hiking is one such example of a popular recreational activity that involves load carriage and that can benefit physical and mental health (Mitten et al. 2018). Whilst there are numerous advantages to the individual from participation in hiking, load carriage activity has been associated with injury risk (Knapik and Reynolds 2016; Fox et al. 2020). Military populations who regularly carry load experience relatively high occurrence of lower back pain and injury (Orr et al. 2014). Modifying the task such that it alters the loading on the body may have both positive and negative implications in terms of performance and injury risk.

Load carriage in different forms has been extensively studied, with research demonstrating increased physical demand (e.g. Dominelli, Sheel, and Foster 2012; Phillips et al. 2016) and increased metabolic or oxygen cost when carrying load compared with unloaded (e.g. Patton et al. 1991; Fagundes et al. 2017). Factors such as the amount of additional mass (Huang and Kuo 2014) and the distribution or placement of the load (Legg and Mahanty 1985; Stuempfle, Drury, and Wilson 2004; Pigman et al. 2017) influence oxygen cost. Winsmann and Goldman (1976) suggested that the weight of additional load is more important than the design of the load carriage system (LCS), as long as the weight is 'properly distributed'. However, in load carriage activities, reducing the amount of weight is often not a practical suggestion as the goal of the task may relate to the transfer of required equipment. Therefore, identifying or designing a LCS that can reduce metabolic cost compared with alternative LCS designs whilst carrying a fixed mass, would be of benefit across a broad range of activities and populations.

Modifying the position of the additional load relative to the body's centre of mass (CoM) has been

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shown to influence metabolic cost in healthy males during walking, where a greater distance from the CoM is associated with greater metabolic cost (Legg and Mahanty 1985). Movement of the LCS relative to the body may also influence physiological performance and the biomechanics of locomotion. Huang et al. (2020) reported that carrying 15 kg in a backpack that was allowed to move approximately in the axial direction of the trunk, reduced metabolic cost during walking by 15%. Conversely, Martin and Li (2018) found that an LCS design that was more compliant in the medial-lateral direction, allowing the mass to move relative to a rigid frame, resulted in greater metabolic cost than a fixed design. However, they also found that carrying this more compliant LCS resulted in reduced interaction forces between the LCS and the user, although a greater frontal plane moment was observed. The mass in this previous study was attached to an inverted pendulum that could displace up to 10 cm horizontally. The authors suggested that reduced interaction forces without increased frontal plane moments could be achieved with lower oscillation amplitudes.

In addition to influencing oxygen cost, LCS design can affect relative motion of the pelvis and trunk, as well as comfort. There is interest in the relative motion between the pelvis and trunk as it may help to understand mechanisms for injury development. When comparing individuals with and without lower back pain in cross-sectional studies, it has been reported that those with pain demonstrate reduced lumbar range of motion (ROM) (Laird et al. 2014), including during a step-up task (Mitchell et al. 2017). There is very limited understanding of risk factors for lower back pain, yet characterisation of the kinematics of the trunk and pelvis during load carriage tasks is warranted as different movement strategies likely influence the loading of the tissues and therefore may be influential in injury development. The addition of load during walking has previously been shown to result in reduced transverse plane range of motion of the pelvis and trunk when walking on an incline compared with unloaded walking (Rosa et al. 2018). Inclined walking is an integral component of hiking, where greater incline (Chatterjee et al. 2018) and greater speed (Pandolf, Givoni, and Goldman 1977) both independently increase the metabolic demand of the task. Hiking is an activity which also requires changes of direction and step-up-like movements in order to overcome natural obstacles such as rocks and trees. It remains unclear whether a more compliant LCS may offset some of the reduced range of motion between the pelvis and trunk observed when carrying a load in comparison to a more traditional, rigid LCS design. If more movement is permitted with a compliant LCS, this may increase oxygen consumption, thereby resulting in reduced performance.

The aim of this study was to compare a traditional load carriage system with a more compliant load carriage system whilst carrying a load of 16 kg during walking and a step-up task. The influence of load carriage system on oxygen consumption and trunk-pelvis kinematics were assessed. It was hypothesised that oxygen consumption would be higher, and that there would be more movement between the trunk and pelvis when carrying the more compliant system than the rigid system in both tasks. Coordination variability and subjective perspectives of the participants in each condition were also obtained in order to further characterise and explain the main findings. Differences in oxygen consumption and kinematics between the walking and step-up task may exist, but this was not of interest in the present study, and thus, was not assessed.

Materials and methods

Participants

Fourteen injury-free participants (6 male and 8 female; mean ± *SD* age: 27.1 ± 4.0 years; height: 173.9 ± 11.2 cm; body mass: 75.0 ± 13.3 kg; torso length: 49.7 ± 4.2) with self-reported experience of either recreational or work-related hiking with a backpack gave written consent to participate in the study. A power calculation based on differences in oxygen consumption when carrying load with and without a hip strap (Pigman et al. 2017) revealed that nine participants was required for a power of 0.8 and alpha = 0.05. A more conservative sample size was recruited given the unknown influence of the compliant LCS. The protocol was approved by the ethics committee of the Norwegian School of Sport Sciences (247 – 290922).

Experimental protocol

Data were collected during four conditions: a walking task and a step-up task, each with the two different LCS. The walking task preceded the step-up task, and the order of LCS in each task was randomised. All tasks were completed during one visit to the laboratory. Both LCS were filled with pellets such that the total mass of each, including the mass of the LCS, was 16 kg. This mass of 16 kg was selected to align with that used in previous load carriage studies in both a hiking (e.g. Foissac et al. 2009) and a military (e.g.

Birrell, Hooper, and Haslam 2007; Birrell and Haslam 2010) context. This mass was also deemed appropriate based on pilot testing of the protocol. One LCS was considered to be more rigid and representative of a traditional LCS design, and this served as the control LCS (TRAD). The other was a prototype, with a carrier frame that was intended to make the system more compliant (Patent Number 332793, (Flem 2012)). The patent document (Flem 2012) for the compliant LCS (COMPL) described the LCS as enabling 'the hips and shoulders to move freely and independently of each other and also independent of the load'. It also states that the structure allows for axial rotation of the spine during use, and that the shoulders and hips can move laterally, 'independent of each other without the load…displaced essentially in relation to the user's center of gravity'. Figures that outline the design of the COMPL system can be seen in the patent document (Flem 2012). The two LCS designs were available on the market at the time of data collection and were designed for the same consumer group. The TRAD LCS was a Fitscape® load carrying system (Osprey UNLTD™ Airscape® 68(L), modified; Cortez, Colorado, USA). Additional parts were removed from the LCS (e.g. removeable day pack) for the purpose of this study. The COMPL LCS was a Spine2 prototype (65 L, Bergans of Norway, Asker, Norway) with altered visual appearance. Participants were blinded as best as possible to each LCS manufacturer and were not aware of the study hypotheses. The brand information was not visible on either LCS, although the TRAD LCS was likely more identifiable than the COMPL, which did not aesthetically resemble a finished, branded product.

Participants first warmed up by walking for 5 min without an LCS at the speed and incline of the walking protocol (detailed below). Participants were familiarised to the step-up protocol (detailed below) by practicing it without an LCS, both with and without the mouthpiece that was used to collect gas exchange for oxygen consumption measurements, until they were comfortable. After familiarisation, reflective markers were secured on the body (information below). The backpacks were then fastened by the same investigator according to manufacturer instructions, adjusting the torso length, shoulder straps and chest straps according to the size of the individuals. It was ensured that the stabiliser straps on the shoulders were not excessively tightened to avoid unnecessary restrictive forces on the body.

During the walking task participants walked on a motorised treadmill (Rodby, Vänge, Sweden), whilst carrying each of the two LCS. Participants walked for 5 min at a speed of $0.8\,m{\cdot}s^{-1}$ whilst the treadmill was inclined at 10°. The walking speed was determined based on Naismith's rule with Langmuir corrections (Langmuir 2013) and pilot testing confirmed that this in combination with the incline felt appropriate, subjectively, for hiking with 16 kg of load. Oxygen consumption was measured in the last 2 min and kinematic measures were obtained for 30 s after 1 and 4 min of walking.

During the step-up task, participants stepped over a 0.3 m plyometric box (Sport-Thieme, Grasleben, Germany) for 5 min. The participants were given specific instructions to take one step onto the box with the first foot, then to step off with the other foot, then to use the first foot again to turn to face the plyometric box in order to repeat the process (Figure 1). The result was that they alternated which foot was used to step onto the box on each step-up. Participants always turned clockwise on one side of the box and anti-clockwise on the other. They were

Figure 1. Step-up protocol. Participants stepped onto the box with one foot, then off with the other foot before turning on the first foot and stepping up onto the box with the second foot. Participants turned clockwise on one side of the box and anticlockwise on the other.

asked to step in time with an audible metronome at 0.92 Hz. Step height and frequency were determined during pilot testing. Oxygen consumption was measured in the last 2 min and kinematic measures were collected for 30 s after 1 and 4 min.

Oxygen consumption

Oxygen consumption (VO_2) was measured using a mixing chamber on the Vyntus CPX platform (Vyaire Medical; Mettawa, IL, USA) which was calibrated before each test with room air and reference gases of known concentrations. The participants wore a mouthpiece for the last 3 min of the 5-min trial. The average oxygen consumption at each 30-s interval from minutes-3 to -5 were obtained, and the average of these four time intervals was used in the analyses.

Kinematics

A 14-camera 3D motion capture system (Oqus 400 and 700-series, and Miqus, Qualisys AB, Gothenburg, Sweden) was used to record the three-dimensional trajectories of reflective markers (12 mm, Qualisys AB) at 150 Hz. Markers were placed on the left and right iliac crest, left and right clavicular acromion junctions and the suprasternal notch. Markers were additionally located superior to the anatomical positions of the left and right anterior superior iliac spine such that they could be positioned on the skin and not on the LCS. The pelvic marker locations were selected based on the ability to place these anatomically without interference from the LCS. To identify the stance phase, a marker was placed on both the left and right calcaneus. Reference frames for the segments were defined during a static trial in which participants stood still with their arms to the side. Data were analysed from minute-1 unless there were issues with marker visibility, in which case data from minute-4 were analysed. This occurred in few cases.

Questionnaire

Immediately after each trial the participants reported their rate of perceived exertion (RPE) on a scale from 1 to 10. After the test protocol the participants were asked to complete a written questionnaire with 12 questions (Supporting Information). The questionnaire asked how each LCS influenced balance and movement, and about the comfort of each. Participants were guided through the questions by investigators, ensuring that terms such as 'lateral flexion' and 'axial rotation' could be demonstrated to aid understanding. The participants were asked to rank each LCS on a scale from 1 to 10 based on how much they affected the subjective experience in each category, with 1 being 'to a small extent' and 10 being 'to a large extent'. All questions were in Norwegian language and participants were Norwegian speaking. These have been translated to English for presentation purposes.

Data analysis

Kinematics

Kinematic data were tracked in Qualisys Tracking Manager (Qualisys AB, Gothenburg, Sweden), after which data analyses were conducted in MATLAB R2023b (The MathWorks Inc, Natick, MA, USA). Data for the walking and step-up tasks were included for 12 and 11 participants, respectively, where some could not be included due to obscuring of the skin-based markers. Marker coordinate data were filtered with a fourth-order Butterworth filter at 6 Hz. Walking stance was identified using the filtered anterior–posterior global position of the calcaneus marker, adapted from a previously reported method (Zeni, Richards, and Higginson 2008; Ellison et al. 2024). In brief, the time periods during which the calcaneus was moving backwards relative to the direction of walking were identified as stance, as this was assumed to indicate foot contact with the treadmill. Walking kinematics were analysed during right foot stance periods. Stride width and stride length were extracted for descriptive purposes during walking only. For the step-up task, a custom MATLAB script was used to determine a full 'cycle' of the step-up protocol that could be used in the kinematics analysis. This was defined as the time between two occurrences of the right calcaneus marker being at peak height over the plyometric box. The peak vertical height of the right calcaneus was considered to represent clearance of the right leg over the box, indicating that the left foot was on the box. The definition of a full cycle as used in the analyses here is therefore represented as such: the cycle starts when the left foot is on the box and the right foot is at maximum height over the box. The participant, then places the right foot on the ground; turns towards the box as they place their left foot on the ground; places their right foot on the box; steps over the box with the left foot and places it on the ground; turns to face the box as they place their right foot on the ground; places their left foot on the box. The analysis period ends when the right foot is at maximum height again.

Relative angles between the pelvis and trunk segments were obtained. The pelvis was defined by the markers on the left and right Iliac crest and left and right anterior iliac spine. The trunk segment was defined by markers on the left and right clavicular acromion junctions and the suprasternal notch. Rotations were defined using floating axes, adapted from Grood and Suntay (1983). Axial rotation was between the medio-lateral pelvis and the floating anterior–posterior axis between the pelvis and trunk; lateral flexion was between the medio-lateral pelvis and the axial trunk; sagittal rotation was between the axial trunk and the floating anterior–posterior axis between the pelvis and trunk. Positive values for axial rotation (about a theoretical superior–inferior axis) corresponded to anticlockwise rotation of the trunk relative to the pelvis (i.e. towards the left if facing forwards); positive values for lateral flexion corresponded to movement of the trunk to the left relative to neutral; positive values for sagittal plane flexion corresponded to backwards rotation of the trunk relative to neutral (i.e. trunk extension). ROM was defined as the difference between the minimum and maximum angle in each plane. To analyse walking, the average of eight stance phases per person was extracted. The time series of eight trials per person were also time-normalised to 101 points and averaged. The mean value for each participant's averaged time series was subtracted such that the resulting time series was centred around zero. This was done for visualisation purposes in order to compare the ROM between LCS conditions. To analyse the step-up task, all of the complete trials per person were averaged.

Coordination variability was assessed via coupling angles. To assess walking, the coupling angle between the trunk and pelvis was calculated during right foot stance in all three planes using modified vector coding, based on the coordination classification system proposed by Needham, Naemi, and Chockalingam (2015). Coupling angles were averaged across participants during the 30-s data collection period using the circular averaging methods of Needham (Needham, Naemi, and Chockalingam 2015). To assess the step-up task, all complete trials per person were averaged.

Statistical analysis

Paired samples *t*-tests were conducted in Python Anaconda software (Version 3) to compare oxygen consumption and angular ROM between TRAD and COMPL. Tests were conducted separately for each task with an alpha level of 0.05. Comparisons between the two conditions for oxygen consumption and angular ROM were presented as mean and 95% confidence intervals, with individual mean values presented in overlaid swarm plots. Cohen's *d* (Cohen 1988) effect size were reported where $p < 0.1$. Coupling angles were reported qualitatively and were not statistically assessed. Questionnaire data were compared using the Wilcoxon test (Python 3.11, scipy.stats module).

Results

Oxygen consumption

There were no significant differences in oxygen consumption between LCS conditions during walking ($p = 0.591$) nor during the step-up task ($p = 0.885$) (Figure 2).

Walking kinematics

There were no differences in stride length (TRAD: 1.18 (0.11) m; COMPL: 1.16 (0.09) m, p = 0.402) or stride width (TRAD: 0.13 (0.03) m; COMPL: 0.13 (0.02) m, p = 0.357) between the two LCS conditions during walking. There was significantly greater axial rotation ROM between the trunk and pelvis when walking with COMPL compared with TRAD ($p = 0.041$, $d = 0.79$, Figures 3(A) and 4(A)). There was significantly greater lateral flexion ROM between the trunk and pelvis when walking with COMPL compared with TRAD ($p = 0.001$, $d = 1.20$, Figures 3(B) and 4(B)). There was no difference in sagittal flexion ROM between the

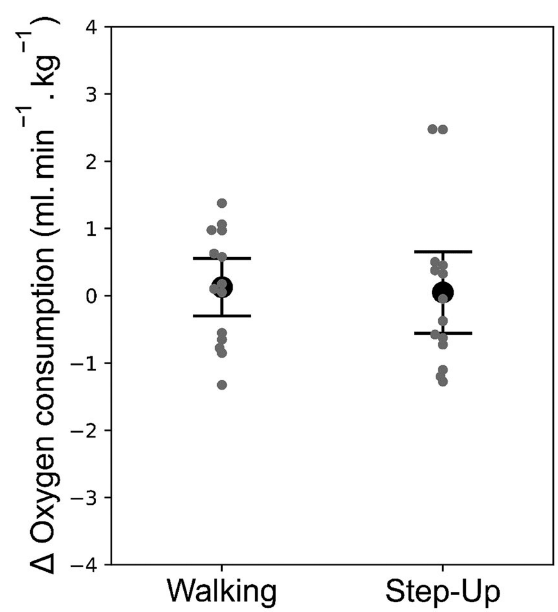

Figure 2. Difference in oxygen consumption between the two LCS conditions (COMPL - TRAD) during walking and step-up tasks ($n = 14$). Large black circles are the mean; error bars represent the 95% confidence intervals. Overlaid swarm plots are individual mean values.

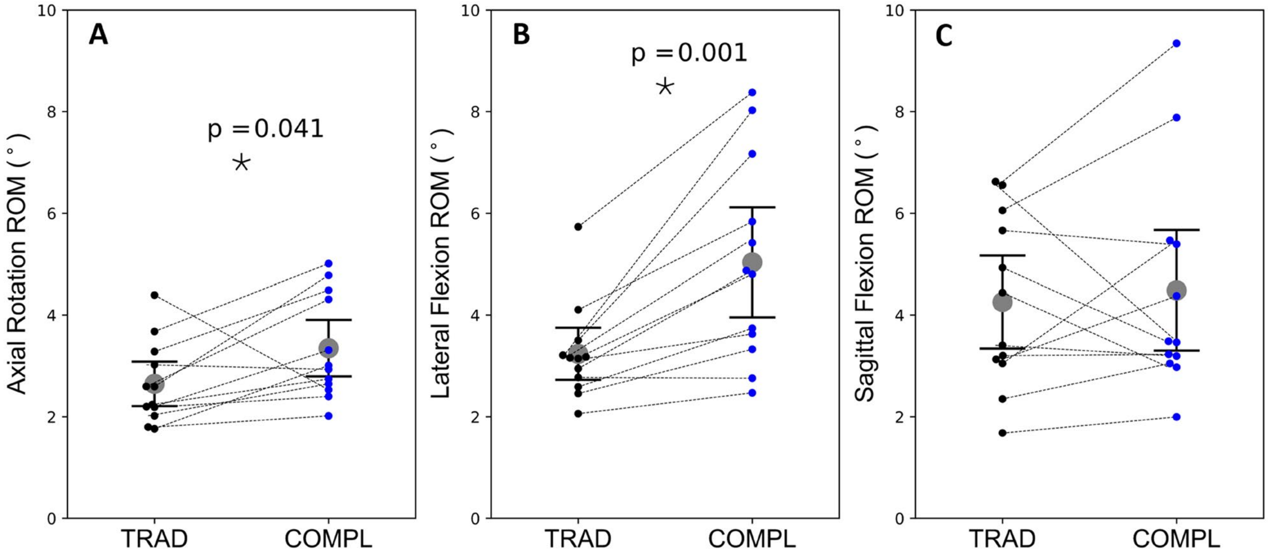

Figure 3. Axial rotation (A), lateral flexion (B) and sagittal flexion (C) range of motion of the trunk relative to the pelvis in the two LCS conditions during walking ($n = 12$). Large grey circles are the mean; error bars represent the 95% confidence intervals. Overlaid swarm plots are individual mean values. Dashed lines indicate which two data points correspond to each individual. *Significant difference between LCS conditions. TRAD = Traditional; COMPL = Compliant.

trunk and pelvis when walking with COMPL compared with TRAD (Figure 3(C), $p = 0.648$). Time series analyses are presented in Figure 4 (axial rotation and lateral flexion) and in the Supporting Information (sagittal flexion).

Visual inspection of the coupling angle time series during walking stance shows similar strategies in the transverse plane (Figure 5) between LCS conditions. In the frontal plane, a difference in coupling between the pelvis and trunk was observed between approximately 20–40% stance (Figure 6). Until approximately 20% of stance, the segments are in-phase in both LCS conditions. From 20% to 40%, with TRAD, participants transition to out-of-phase with the trunk flexing to the left whilst the pelvis continues to flex to the right indicating that this motion is led by the trunk. Conversely, with COMPL, participants transition to out-of-phase with the pelvis flexing to the left whilst the torso continues to flex to the right indicating that this motion is led by the pelvis. The strategy in the sagittal plane (Supporting Information) was visibly more similar between conditions.

Step-up kinematics

There was no difference in axial rotation ROM between the trunk and pelvis during the step-up protocol in COMPL compared with TRAD ($p = 0.080$, $d = 0.80$, Figure 7(A)). There was significantly greater lateral flexion ROM between the trunk and pelvis during the step-up protocol in COMPL compared with TRAD ($p = 0.005$, $d = 1.60$, Figure 7(B)). There was no difference in sagittal flexion ROM between the trunk and pelvis during the step-up protocol in COMPL compared with TRAD ($p = 0.987$, Figure 7(C)). No visual differences were observed in coupling angle time series in any direction (Supporting Information).

Questionnaire

Participants reported no significant difference in RPE between the load carrying systems during walking (mean TRAD: 4.4/10, COMPL: 4.2/10, $p = 0.48$) nor during step-up (TRAD: 5.1/10, COMPL: 4.9/10, $p = 0.317$). When participants were asked: 'To what extent is lateral flexion restricted by the LCS', a significant difference was observed between LCS conditions at the trunk (TRAD: 3.5/10, COMPL: 2.2/10, $p = 0.024$) and pelvis (TRAD: 3.6/10, COMPL: 2.4/10, $p = 0.009$).

In response to the question: 'to what extent is [axial] rotation restricted by the LCS', a significant difference was observed between LCS conditions at the pelvis (TRAD: 3.4/10, COMPL: 2.5/10, $p = 0.025$), but not at the trunk. When asked: 'to what extent do you experience a swinging/throwing momentum due to the LCS?' a significant difference was found during walking (TRAD: 3.0/10, COMPL: 1.9/10, $p = 0.042$), but not during the step-up task. The responses to the remaining questions did not reveal any significant differences between LCS systems.

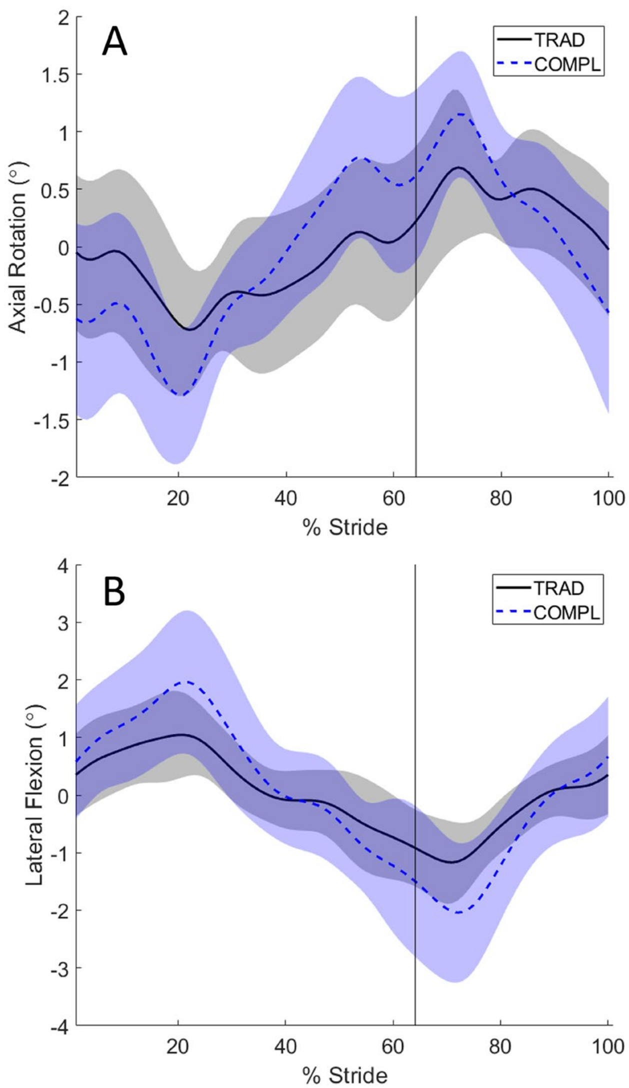

Figure 4. Time histories of mean axial rotation (A) and lateral flexion (B) of the trunk relative to the pelvis in the two LCS conditions during a walking stride ($n = 12$). Shading represents the standard deviation. The vertical line indicates where the stance phase ends. TRAD = Traditional; COMPL = Compliant.

Discussion

The identical oxygen consumption observed when carrying a rigid and a compliant load carriage system during both uphill walking and a step-up task shows that there was no metabolic cost benefit from carrying either LCS at the intensities and short durations of the activities in the present study. The reported oxygen consumptions were moderate to heavy (Jetté, Sidney, and Blümchen 1990) and RPE indicated the participants perceived the effort as 'somewhat severe' to 'severe' (Williams 2017). It is possible that differences in oxygen consumption and RPE could be observed with greater effort or if the loads were carried over longer durations.

In support of the hypothesis, there was greater frontal and transverse plane ROM between the trunk and pelvis during walking when carrying the compliant compared with the rigid system, and this trend was observed in the large majority of participants (Figure 3(A,B)). This suggests a less restricted movement pattern when carrying the same load in the more compliant system. Importantly, this was achieved without costing more in terms of oxygen consumption and without increased perceived exertion. Furthermore, participants perceived less restriction in the transverse and frontal plane when carrying the compliant LCS, which supports the findings of the kinematic results.

Increased transverse plane rotation between the trunk and pelvis, as observed in the present study, has previously been suggested to enable increased stride length (Wagenaar and Beek 1992; van Emmerik and Wagenaar 1996), whilst in the present study no differences between stride length were observed. Therefore, it is unclear why this strategy was adopted. Participants may be able to adapt their stride length more freely when carrying the compliant LCS, if it were beneficial to the task, although this suggestion is speculative. It has previously been shown that the addition of load results in reduced trunk-pelvis rotation compared with unloaded walking (LaFiandra et al. 2003), but it is not clear whether a greater range of motion with a more compliant system is beneficial or detrimental in terms of injury risk. There is very limited evidence to demonstrate how kinematics during load carriage relate to risk of injury, and prospective studies and randomised controlled trials are required to investigate this.

The greater lateral ROM observed during walking with the compliant compared with the rigid LCS occurred whilst stride width remained similar between conditions. The CoM of the combined trunk and LCS would be expected to deviate less and to remain more centrally located when carrying the compliant LCS than the rigid LCS during lateral flexion. This is because lateral flexion of the trunk will move the body's CoM laterally, but in the case of the compliant LCS this can be offset to some extent, unlike with the rigid LCS, where the additional mass will more closely follow the movement of the trunk. This would allow greater lateral flexion with the more compliant LCS, without compromising stability, as the CoM would remain within the limits of stability without requiring a wider stride. This could be indicative of a greater stability when carrying the complaint LCS, although this hypothesis should be tested with further investigation. The kinematic results were again supported by the questionnaire results, which showed that participants

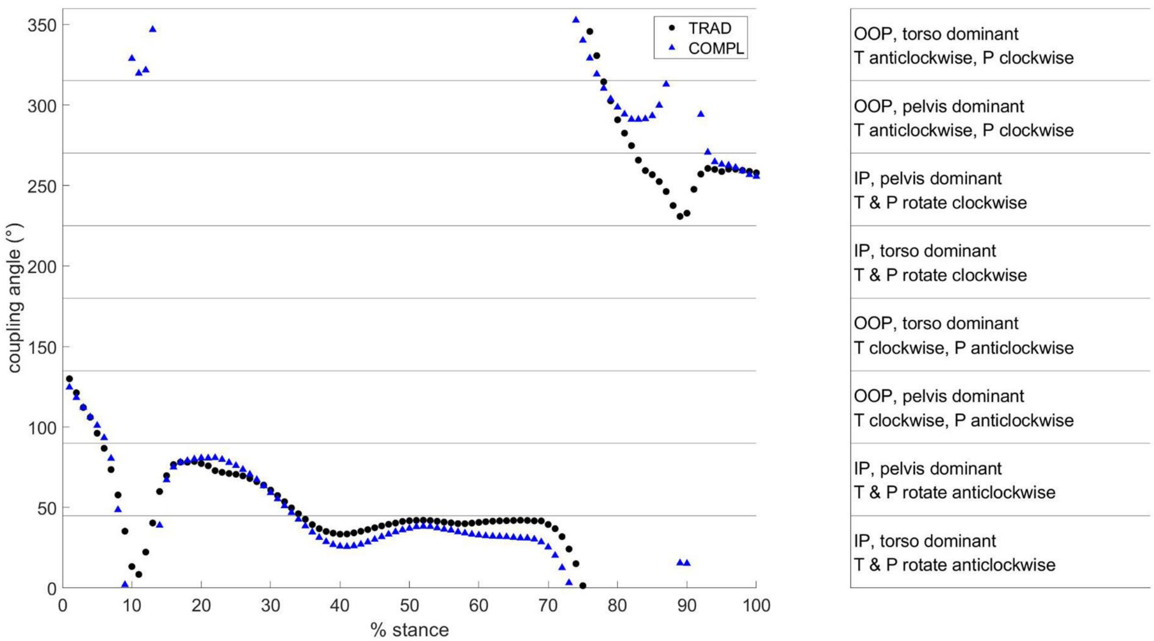

Figure 5. Mean transverse plane coupling angle during stance. Horizontal lines refer to the different movement strategies, interpreted according to the text within each boundary. OOP = out-of-phase; IP = in-phase; T = trunk; P = pelvis. TRAD = Traditional; COMPL = Compliant.

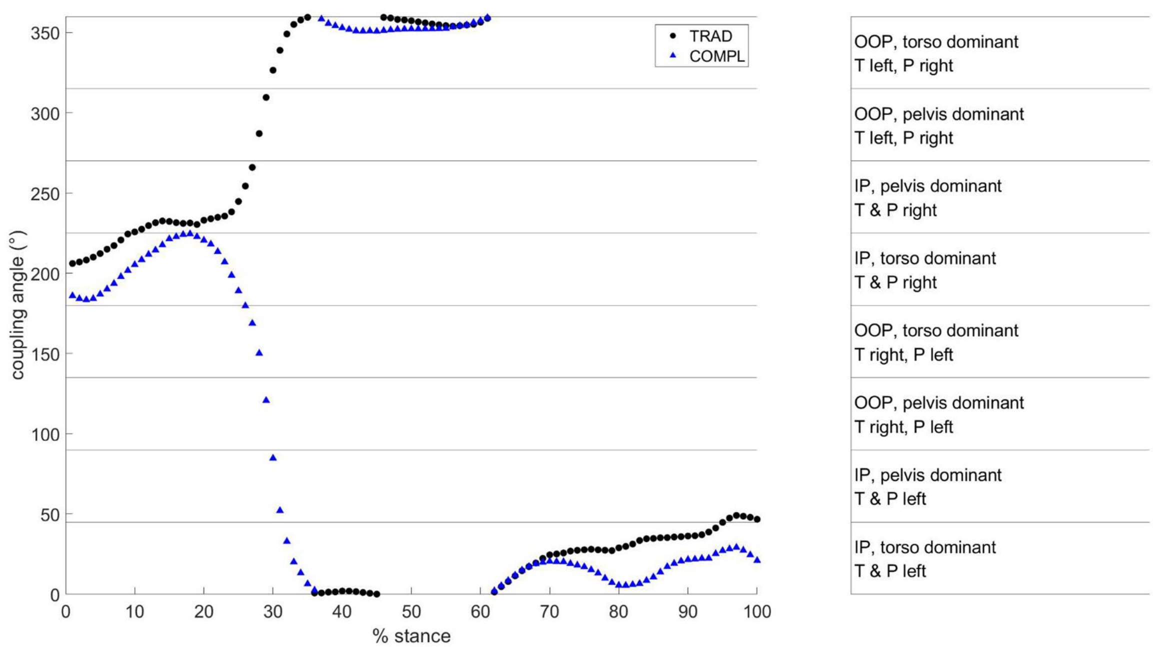

Figure 6. Mean frontal plane coupling angle during stance. Horizontal lines refer to the different movement strategies, interpreted according to the text within each boundary. OOP = out-of-phase; IP = in-phase; T = trunk; P = pelvis. TRAD = Traditional; COMPL = Compliant.

perceived less of a 'swinging' effect applied by the compliant system compared with the rigid system.

The coordination variability analysis provides further insight into the movement strategies adopted when carrying the two systems. The only visible difference in strategies between load carriage systems was in the frontal plane, where opposite strategies were used between approximately 20–40% walking stance. At this early phase of stance, the participants transitioned to out-of-phase motion in both conditions with the trunk leading the motion in the TRAD condition and the pelvis leading in the COMPL condition. Interestingly,

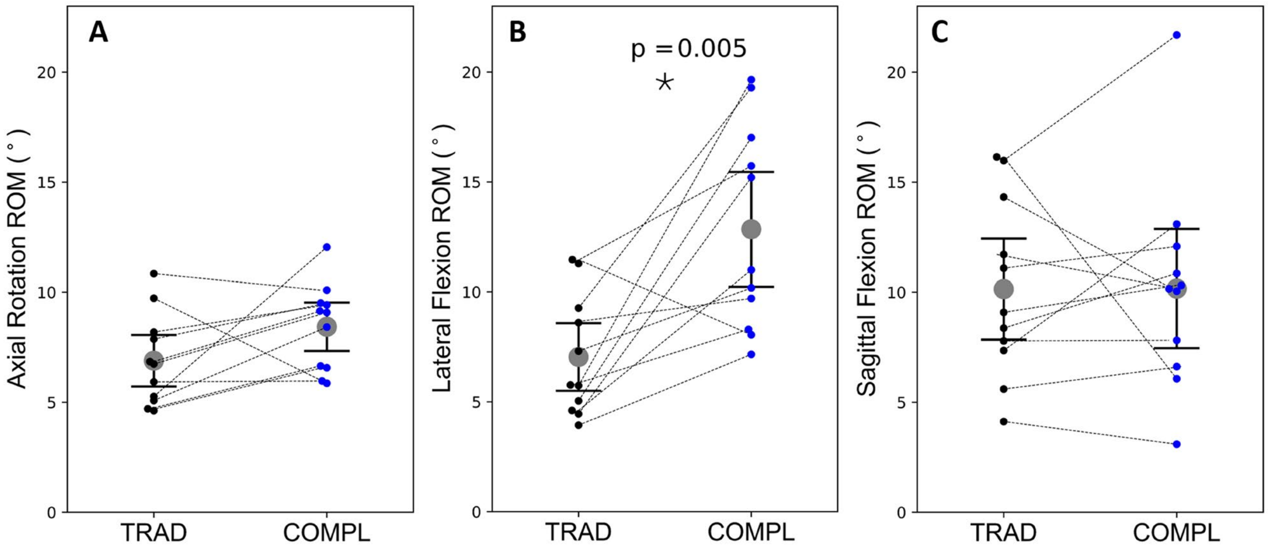

Figure 7. Axial rotation (A), lateral flexion (B) and sagittal flexion (C) range of motion of the trunk relative to the pelvis in the two LCS conditions during the step-up task ($n = 11$). Large grey circles are the mean; error bars represent the 95% confidence intervals. Overlaid swarm plots are individual mean values. Dashed lines indicate which two data points correspond to each individual. *Significant difference between LCS conditions. TRAD = Traditional; COMPL = Compliant.

participants perceived less axial restriction at the pelvis with the compliant system, but no differences between condition were perceived at the trunk. However, the perceived differences between LCS were reportedly in the transverse plane rather than the frontal plane. It may have been difficult for the participants to identify exactly how and why the two systems felt different.

It is not clear whether there are benefits to either strategy as they were equivalent in terms of oxygen consumption. However, the frontal plane strategy when carrying the compliant system was much more similar to unloaded walking in healthy individuals (Konishi, Ozawa, and Kito 2022) whereas the strategy when carrying the rigid system was the opposite from approximately 20–40% of stance. It could therefore be interpreted that walking with the more compliant system allows coordination of the trunk and pelvis that is more similar to unloaded walking than when carrying the more rigid system. The coupling angles in the transverse and sagittal planes, which were similar in both conditions, were also qualitatively similar to unloaded walking (Konishi, Ozawa, and Kito 2022). In summary, it appears that walking with a traditional, rigid load carriage system results in altered frontal plane trunk-pelvis coordination compared with unloaded walking, whereas when carrying the compliant system, a strategy more similar to unloaded walking is used.

Although there were no differences in sagittal plane range of motion between the two LCS, it appears that there were a range of individual responses (Figures 3 and 7). Furthermore, the coordination strategies slightly differed between approximately 40 – 60% of stance (Supporting Information Figure S1) whereby the trunk and pelvis were more in-phase with the compliant LCS and more out-of-phase with the rigid LCS. The main focus of the present study was the transverse and frontal planes due to the design features of the compliant system, where the influence of load carriage in the sagittal plane has been more widely reported (Walsh and Low 2021).

The step-up task was considered more complex than inclined walking. There were no differences in transverse plane trunk-pelvis ROM, but there was greater frontal plane motion with the more compliant LCS, in partial support of the hypotheses. This may be indicative of a freedom to achieve greater lateral flexion without compromising stability during the step-up task, as postulated during walking. However, it is unclear whether this is a positive or negative outcome, as there were no differences in oxygen consumption. Unlike during walking, there were no observed differences in coordination variability (not statistically tested) between conditions in the frontal plane, nor in the transverse or sagittal planes during the step-up task. In summary, it appears there are limited differences between load carriage systems when completing the step-up task at a fixed pace. A more challenging, varied or longer-duration task may yield different results.

Limitations

To characterise the two different load carriage systems, a protocol was developed that was relevant to hiking activity, whilst allowing for controlled experimental design. This introduces limitations and requires compromises in terms of ecological validity. The participants were required to conduct the activities at fixed speeds, and with a given load, which may not have reflected what they would do in reality. Participants only carried the load for short durations, whereas energy cost has been shown to increase during prolonged periods of load carriage (Patton et al. 1991). Furthermore, whilst participants had experience of carrying load during hiking-type activity, they were given only a short, acute period in which to become accustomed to the specific LCS assessed here. It was not possible to fully blind participants to the two different systems. Brand recognition, based on the shape and style of the control LCS, may have influenced the results, particularly in relation to the questionnaire.

The main focus of the study was on understanding trunk-pelvis kinematics and oxygen consumption, as the design of the compliant system was intended to predominantly influence rotation of these segments and it was important to understand if any change in kinematics occurred alongside changes in performance. Measuring oxygen consumption provides information about metabolic cost whereas it is difficult to interpret kinematics in the context of risk of injury without large, prospective studies. Quantification of the CoM location, kinetics, muscular activity and stability would have allowed a more comprehensive characterisation of the two different load carriage systems.

Conclusions

Carrying 16 kg in a compliant load carriage system during walking influences the frontal and transverse plane motion between the trunk and pelvis, resulting in greater range of motion than a traditional, rigid system. Oxygen consumption was equivalent during walking whilst carrying the two systems, indicating no performance benefit from either system during during walking. During a step-up task, greater lateral flexion range of motion between the trunk and pelvis was observed when carrying the compliant system than the traditional system, again with no difference in oxygen consumption.

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