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Trunk-pelvis coordination during load carriage running

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ABSTRACT

Understanding the influence of load carriage on trunk-pelvis coordination and its variability has important functional implications for athletes who need to run with load. The aim of this study was to examine the influence of load carriage on trunk-pelvis coordination in running. Thirty healthy adults performed running while wearing a 20% bodyweight backpack, and without load. Vector coding was used to quantify trunk-pelvis segmental coordination and its variability during the stance phase of running. The four coordination patterns were: 1) anti-phase (segments moving in opposite directions), in-phase (segments moving in same directions), trunk-only phase (only trunk movement), and pelvic-only phase (only pelvic movement). For each plane, the percentage of stance phase spent in a specific coordination pattern was quantified. Coordination variability for each plane was averaged over the stance phase. Mixed effects models were used to analyse the effects of load, adjusted for the covariate of sex, on coordination and its variability. Running with load increased trunk-only coordination in the sagittal plane ($P < 0.001$), increased anti-phase coordination in the frontal plane ($P < 0.001$), reduced trunk-only phase coordination in axial rotation ($P < 0.001$), and increased coordination variability in all three planes (Flexion-Extension: $P < 0.001$; Lateral flexion: $P = 0.03$; Axial rotation: $P < 0.001$). Future studies would benefit from investigating how trunk-pelvis coordination and its variability alters candidate end-point variability indices (e.g. COM displacement), and its functional implications in load carriage running.

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1. Introduction

Running is a popular sport with participation growing over the last few decades (Ahmadyar et al., 2015), especially in trail and ultra-endurance distances (Scheer et al., 2020). These athletes often carry their own sustenance during running, typically accomplished with a backpack (termed as “load”) (Alger, 2014). Carrying load increases the metabolic and mechanical energetic cost of running (Liew et al., 2016; Teunissen et al., 2007). A thorough understanding of segmental biomechanics and coordination may help in optimising the energetics of running with load.

Coordinating the trunk and pelvis segments during running is important because these segments contribute up to 50% of the body’s mass (Dempster, 1955). Anti-phasic trunk-pelvic coordination in running ensures conservation of whole body angular momentum (Pontzer et al., 2009; Preece et al., 2016). Factors that alter trunk-pelvis coordination during gait may impact on the energy cost during locomotion. For example, load carriage reduced

anti-phase trunk-pelvis axial rotation coordination, which was associated with increased metabolic cost during walking (Rosa et al., 2018). Carrying a load while walking also increased in-phase axial trunk-pelvis rotation coordination (LaFiandra et al., 2003) and its variability (Yen et al., 2012). Although load carriage has been shown to alter trunk segment angles in running (Brown et al., 2014), the influence of running with load on trunk-pelvis coordination is yet to be investigated.

The primary purpose of this study was to investigate how load carriage influences trunk-pelvic coordination and its variability in running. We hypothesised that load carriage, in comparison to body-weight (BW) running, would increase in-phase and reduce anti-phase trunk-pelvic coordination across all planes. Like walking (Yen et al., 2012), we also hypothesised coordination variability in all planes would increase when load is added to BW running.

2. Methods

2.1. Participants and design

Thirty healthy adults (16 male, 14 female, mean (standard deviation [SD]) age: 30.35 (9.11) years, mass: 69.13 (12.65) kg, height:

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1.72 (0.76) m) with no self-reported experience in running with a 20%BW load were recruited. Participants were included if they ran a total of greater than 45 min/week over the past year. Participants were excluded if they had any self-reported injuries in the preceding three months, and females currently pregnant. This study was approved by Institutional Human Research Ethics Committee (RD-41-14). Informed written consent was sought prior to study enrolment.

2.2. Experimental set up

An 18 camera motion capture system (Vicon T-series, Oxford Metrics, UK) (250 Hz), with three synchronized in-ground force plates (AMTI, Watertown, MA) (2000 Hz) were used to collect data (Vicon Nexus, v2.3, Oxford Metrics, UK). Force data were used to identify initial contact and toe-off with a threshold of 20 N. The biomechanical model of the trunk and pelvic segments can be found in the [supplementary material](#). Even though markers were placed on the thoracic segment, the present study uses the general term “trunk”. Marker trajectories were low pass filtered at 18 Hz (zero lag, 4th order, Butterworth). All biomechanical processing was performed in Visual 3D.

Participants performed running in their personal running shoes at 3.5 m/s ($\pm 10\%$) over two conditions: BW only and with a 20%BW sandbag-loaded backpack (CAMELBAK, H.A.W.G.[®] NV,14 L), the order of which was randomised (Liew et al., 2016). The backpack was secured to the participant via an adjustable chest strap and waist belt. Loads of up to 10 kg can be carried in ultra-endurance races (Alger, 2014), and previous studies on load carriage running have used loads of up to 20% BW (Baggaley et al., 2020; Fagundes et al., 2017). Timing gates (SMARTSPEED Pro, Fusion Sport Pty Ltd, Australia) were used to measure running velocity. Ten successful running trials were collected where success was achieved when the velocity was within 3.5 m/s ($\pm 10\%$) and at least one full foot strike, regardless of right-left laterality, occurred on a force plate.

2.3. Biomechanical variables

Trunk and pelvic segment angles were individually calculated with respect to the laboratory's coordinate system. The following axes convention was used: X-axis pointing laterally; Y-axis pointing anteriorly; Z-axis pointing superiorly. A Cardan XYZ sequence was used for the trunk, whilst a ZYX sequence used for the pelvis (Baker, 2001). Angular waveforms in the stance phase were time normalized to 100 points. In total, seven running stance phases from both the right ($n = 4$) and left stance ($n = 3$) were available for each participant and condition for further. The present study focused on the stance phase of running as energetic cost in stance is much greater compared to flight (Bertram and Hasaneini, 2013). Vector coding to quantify inter-segmental coordination and its variability was based on a previously published method (Needham et al., 2014); and used the coordination phase classification of Chang et al. (Chang et al., 2008) (Table 1).

2.4. Statistical analysis

For each plane, the dependent variable of coordination was reported in terms of percentage of stance phase spent in a specific coordination pattern. The coordination variability for each plane was averaged over the stance phase to provide the second dependent variable. All results were adjusted for sex as a covariate by including its main effect into the model. A generalized linear mixed model regression with a Poisson distribution was used to analyse the effects of load on coordination. A Bonferroni corrected alpha value of 0.0125 (0.05/4) - for each of the four coordination patterns, was set as a threshold for significance. A linear mixed model

Table 1
Scheme used to categorize coordination patterns.

| Coordination pattern | Coupling angle (CA) definitions | Explanation (example) |
|----------------------|--|--|
| Anti-phase | $112.5^\circ \leq CA < 157.5^\circ$, $292.5^\circ \leq CA < 337.5^\circ$ | Segments moving in the opposite direction (e.g. trunk clockwise rotation, pelvis anticlockwise rotation) |
| In-phase | $22.5^\circ \leq CA < 67.5^\circ$, $202.5^\circ \leq CA < 247.5^\circ$ | Segments moving in the same direction (e.g. trunk clockwise rotation, pelvis clockwise rotation) |
| Trunk-only | $0^\circ \leq CA < 22.5^\circ$, $157.5^\circ \leq CA < 202.5^\circ$, $337.5^\circ \leq CA \leq 360^\circ$ | No pelvis movement, only trunk movement. |
| Pelvic-only | $67.5^\circ \leq CA < 112.5^\circ$, $247.5^\circ \leq CA < 292.5^\circ$ | No trunk movement, only pelvis movement. |

regression model was used to analyse the effects of load on coordination variability, with significance determined by an alpha value of 0.05. Vector coding and statistical inference were performed in R software (v 3.2.5).

3. Results

The mean (SD) running velocity across both conditions was 3.51 (0.11) m/s; whilst stride lengths were 2.58 (0.21) m and 2.45 (0.22) m, for BW and load running, respectively. Group average (SD) angular waveforms are reported in Fig. 1, coupling angle and coordination variability are reported in Figs. 2 and 3, respectively.

In the sagittal plane, running with load significantly reduced anti-phase ($z = -5.0$, $P < 0.001$) and pelvic-only coordination ($z = -13.9$, $P < 0.001$), but increased trunk-only ($z = 16.1$, $P < 0.001$) when compared to BW running (Fig. 4). The addition of load significantly increased trunk-only ($z = 7.3$, $P < 0.001$), in-phase ($z = 5.7$, $P < 0.001$), and anti-phase coordination ($z = 7.9$, $P < 0.001$); but reduced pelvic-only coordination ($z = -12.4$, $P < 0.001$) compared to BW running in the frontal plane (Fig. 4). In the transverse plane, running with load significantly increased pelvic-only ($z = 5.7$, $P < 0.001$), increased in-phase coordination ($z = 9.1$, $P < 0.001$), reduced trunk-only ($z = -21.0$, $P < 0.001$), and anti-phase coordination ($z = -4.2$, $P < 0.001$) (Fig. 4). Male runners had reduced pelvic-only ($z = -3.42$, $P = 0.001$), but increased anti-phase coordination ($z = 3.90$, $P < 0.001$) in the frontal plane, compared to female runners. The influence of sex on coordination in other planes were not significant.

Load increased coordination variability in all three planes in compared to BW running (Flexion: $t = 4.3$, $P < 0.001$; Lateral flexion: $t = 2.3$, $P = 0.03$; Axial rotation: $t = 14.0$, $P < 0.001$) (Fig. 5). Male runners had greater variability in all three planes compared to female runners (Flexion: $t = 2.73$, $P = 0.011$; Lateral flexion: $t = 3.06$, $P = 0.005$; Axial rotation: $t = 4.41$, $P < 0.001$).

4. Discussion

The purpose of this study was to investigate how load carriage influenced trunk-pelvic coordination in running. In contrast to our first hypothesis, carrying load did not increase in-phase and reduce anti-phase trunk-pelvic coordination across all planes. Our second hypothesis was supported as coordination variability across all planes increased with load carriage compared to BW running.

Given the importance of anti-phase trunk-pelvis coordination in conserving rotational angular momentum (Pontzer et al., 2009), a reduction in anti-phase axial rotation coordination may increase the metabolic cost of running with load. In addition, the position of the load on the trunk may interact with load magnitude on

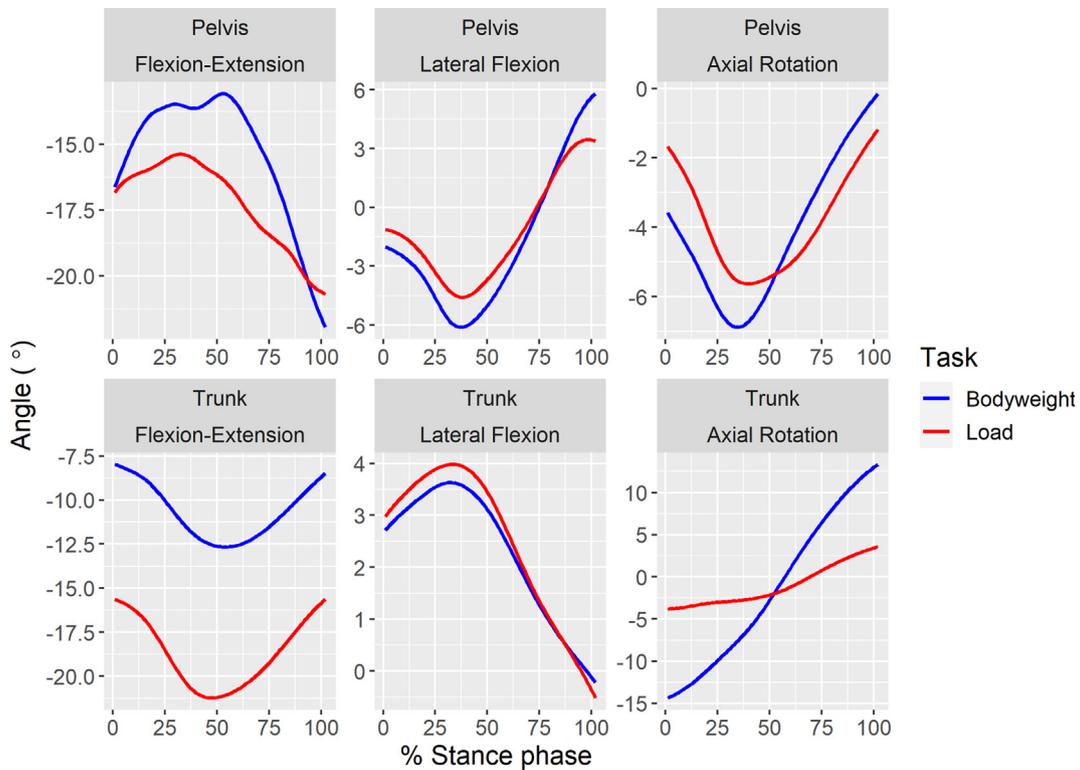


Fig. 1. Three-dimensional mean angular waveforms of the trunk and pelvic segments across the stance phase in running. (+) angle reflects extension, right lateral flexion, and left axial rotation.

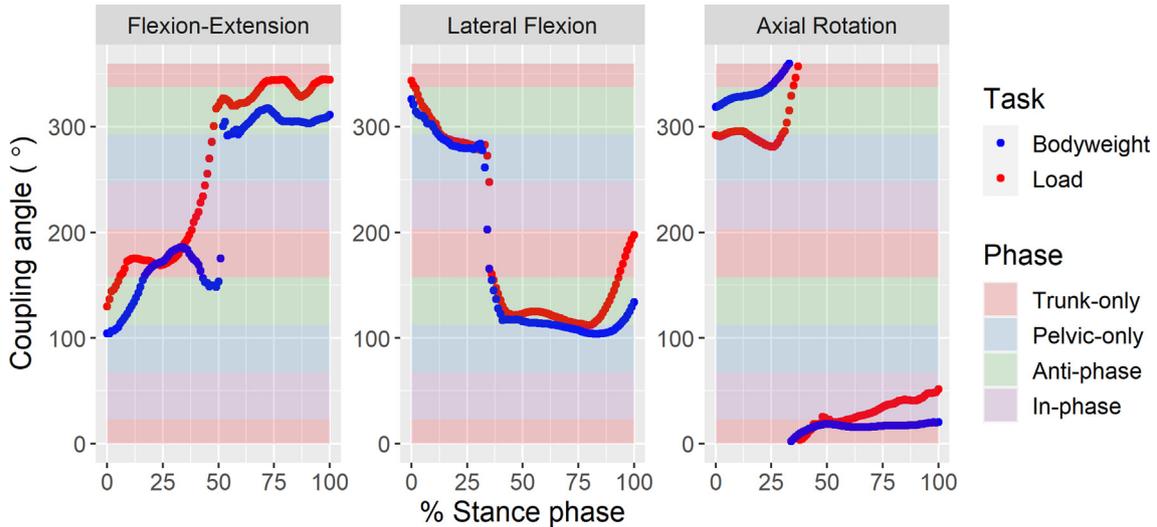


Fig. 2. Group averaged time varying coupling angle (°) across the stance phase in running. Shaded regions reflect the four coordination phases that data points across the stance phase lie in.

the metabolic cost of running. For example in walking, carrying a 31.75 kg load resulted in greater oxygen uptake when the load was carried in a rucksack, compared to a weighted vest (Gerhart et al., 2020). A rucksack would have greater axial moment of inertia than a weighted vest. To avoid high trunk axial torque when running with a backpack, participants could increase axial trunk stiffness (LaFiandra et al., 2002). Greater axial stiffness would reduce axial trunk-only coordination.

The greater trunk-pelvic coordination variability in loaded compared to BW running could be due to the relative inexperience of our participants in load carriage, and/or individuals having to con-

trol an extra degree of freedom (DOF), in the form of a backpack. There is little consensus in the literature that greater task experience increases (Hafer et al., 2019), or reduces (Floria et al., 2018) coordination variability. However, whilst adding a 40% BW backpack load increased trunk-pelvic coordination variability compared to BW walking, when the load was fixed to the trunk by a hip belt, variability was reduced (Sharpe et al., 2008). Speculatively, it is possible that greater trunk-pelvic coordination variability may serve to minimize COM displacement variability, which would optimize the energetic cost of running with load (Williams and Cavanagh, 1987). The functional relationship

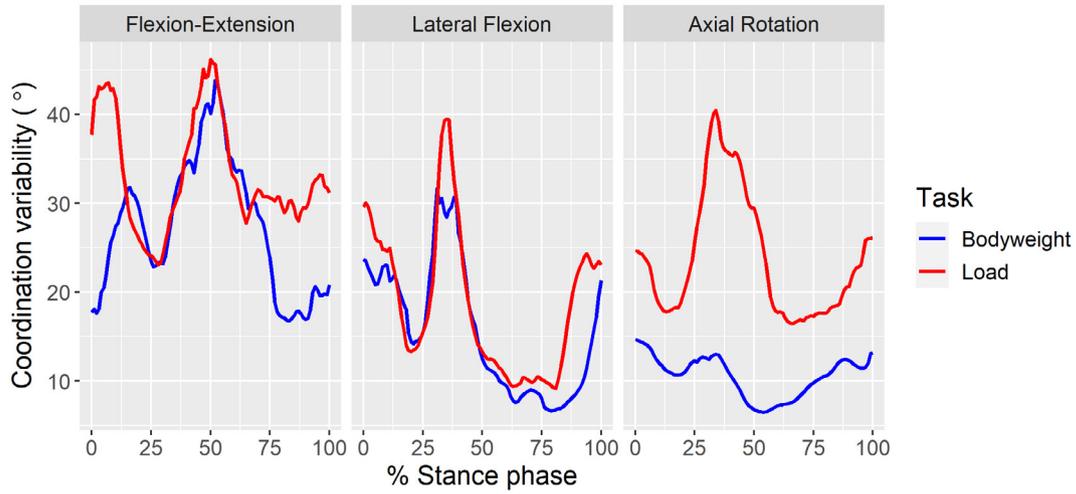


Fig. 3. Group averaged time varying coordination variability (°) across the stance phase in running.

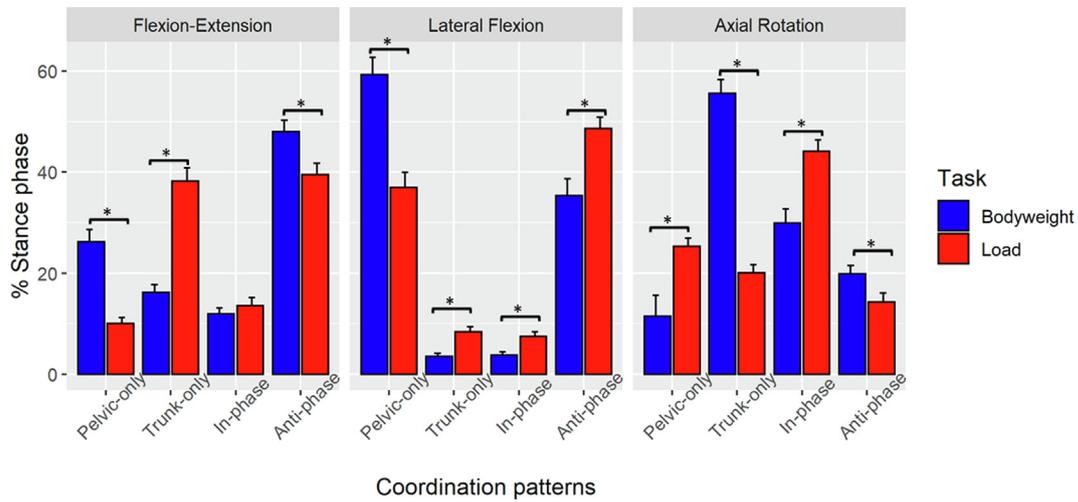


Fig. 4. Group mean (error bars as 95% confidence interval) of the percentage of stance phase spent in each coordination pattern during running. * indicate statistical significance difference between load conditions.

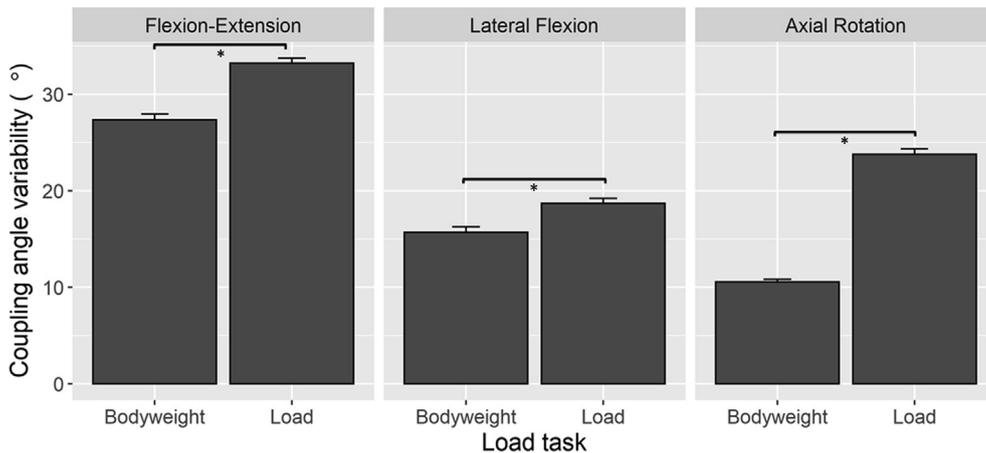


Fig. 5. Group mean (error bars as 95% confidence interval) of the coordination variability averaged across the stance phase in running. * indicate statistical significance difference between load conditions.

between joint-level and “end-point”, whole-body, variability was previously proposed (Hamill et al., 2012). This relationship was also supported by a study in BW walking which demonstrated

how inter-segmental variability in angular momentum was harnessed to reduce whole-body angular momentum (Robert et al., 2009). Future research is warranted to understand if the observed

increase in trunk-pelvis coordination variability with load, was attributed to task novelty and/or reflected a strategy to minimize whole-body variability.

One possible limitation of the present study was the analysis of trunk-pelvis coordination from trials of both limbs. A previous study reported similar trunk-pelvis kinematics when walking and turning 90° whilst pivoting on the right or left limb (Smith and Kulig, 2016). The influence of laterality on coordination and variability may be similar between loaded conditions, given that we included identical number of trials from both limbs for all participants and conditions. Second, although greater than 10 trials have been recommended for vector coding (Hafer and Boyer, 2017), this threshold was recommended based on lower limb, not spinal, coordination variability. Previous studies investigating trunk-pelvis coordination variability have used five (Needham et al., 2014) and six trials (Seay et al., 2014). Future research should investigate a threshold number of trials needed to attain consistent trunk-pelvis coordination variability. Third, participants in the present study were novice load carriers. It may be that regular running with load may reduce some of the coordination variability associated with load carriage, which should be further investigated. Lastly, the significant main effect of sex suggests that load effects on trunk-pelvic variability may differ between males and females. However, the literature has been equivocal if biomechanical adaptations to load differs between sex (Lobb et al., 2019; Silder et al., 2013). Further analysis into possible load and sex interaction on running coordination was not presently pursued given the focus was to understand the main effect of load, but would be a fruitful line of future investigations.

The present findings could inform exercise interventions and sports apparel design to optimize load running energetics. For example, neuromuscular exercises to enhance trunk stiffness may enable runners to better manage high trunk axial torque associated with load carriage. Greater frontal plane anti-phase coordination during loaded running may serve to minimize COM medial-lateral displacement and optimize postural control. Such knowledge may be integrated into the design of oscillating load carriage systems for energy conservation. One example is a medial-lateral oscillating system that provides a medial-lateral force on the trunk opposite to the trunk's translation direction during walking (Martin and Li, 2018).

Carrying a load while running altered trunk-pelvis coordination and its variability. This change may reflect a mechanical strategy that optimizes the metabolic cost of running. Future studies should investigate how trunk-pelvis coordination and its variability alters COM variability, and ultimately the metabolic cost, during load carriage running.

Declaration of Competing Interest

The authors declared that there is no conflict of interest.

Acknowledgments

None

Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jbiomech.2020.109949>.

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