Title: Trunk-pelvis coordination during load carriage running

Article type: Short communications

Bernard X.W. Liew, PhD[a]

Susan Morris, PhD [b]

Kevin Netto, PhD [b]

[a] School of Sport, Rehabilitation and Exercise Sciences, University of Essex, Colchester, Essex, CO4 3SQ, United Kingdom

[b] School of Physiotherapy and Exercise Sciences, Curtin University, GPO Box U1987, Perth, WA 6845, Australia.

Address correspondence and reprint requests to Dr Bernard Liew, S School of Sport, Rehabilitation and Exercise Sciences, University of Essex, Colchester, Essex, CO4 3SQ, United Kingdom; E-mail: bl19622@essex.ac.uk, liew_xwb@hotmail.com

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.

Keywords: Load carriage, Dynamical Systems Theory, Motor control, Running, Coordination

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 are 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: 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 >45 minutes/week over the past year. Participants were excluded if they have 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 (± 10%) over two conditions: BW only and with a 20 %BW sandbag-loaded backpack (CAMELBAK, H.A.W.G.® NV,14 litre), 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 10kg 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 (± 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).

Table 1 Scheme used to categorize coordination patterns

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

2.3 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 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 was 3.51 (0.11) m/s; 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 Figure 1, coupling angle and coordination variability are reported in Figure 2 and 3, respectively.

Figure 1

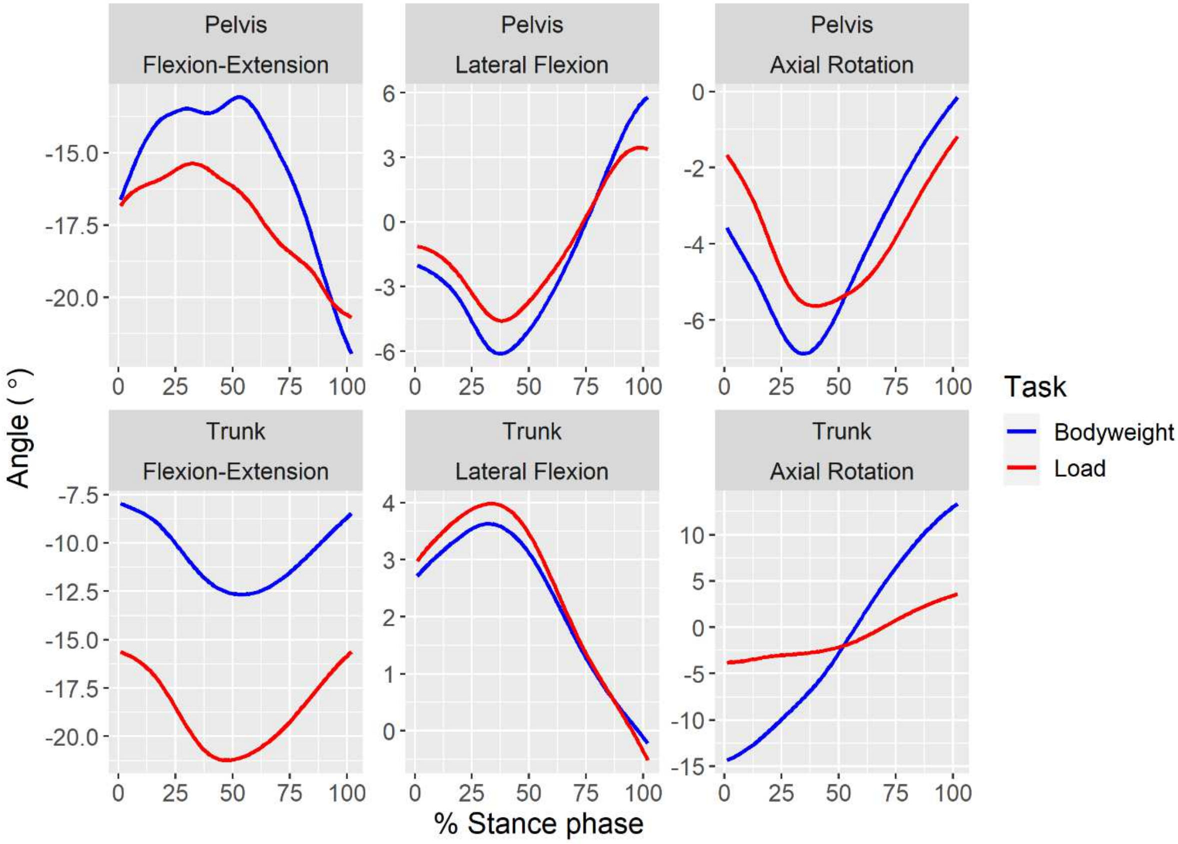

Figure 1Three-dimensional mean angular waveforms of the trunk and pelvic segments across the stance phase in running. (+) angle reflects extension, right lateral flexion, and left axial rotation.

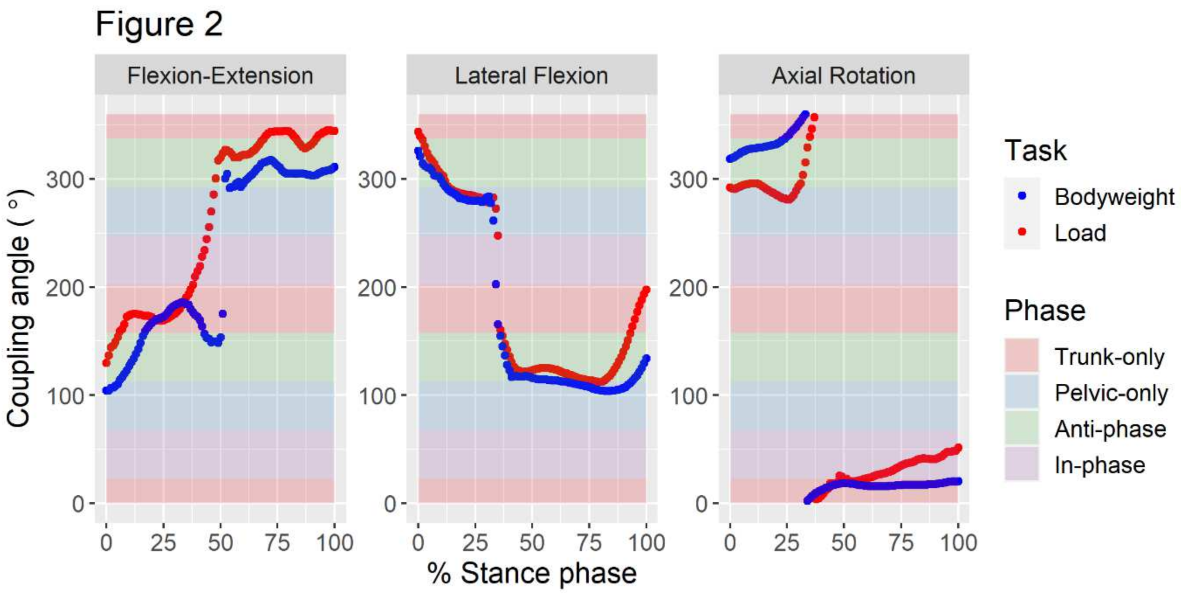

Figure 2Group averaged time varying coupling angle (°) across the stance phase in running. Shaded regions reflect the four coordination phases that data points across the stance phase lie in.

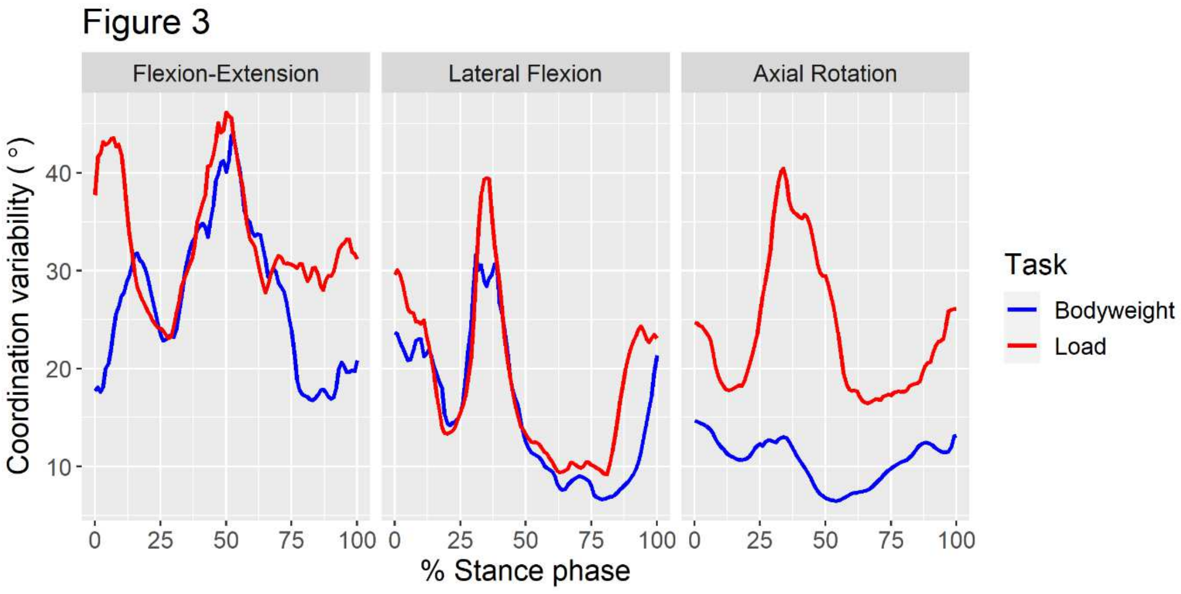

Figure 3Group averaged time varying coordination variability (°) across the stance phase in running.

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 (Figure 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 (Figure 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) (Figure 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) (Figure 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).

Figure 4

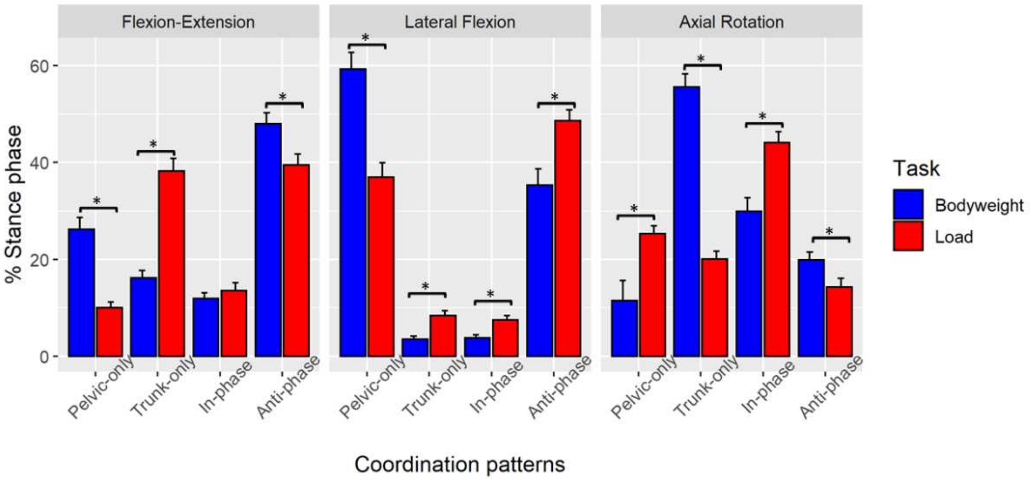

*Figure 4Group mean (error bars as 95% confidence interval) of the percentage of stance phase spent in each coordination pattern during running. * indicate statistical significance difference between load conditions.*

Figure 5

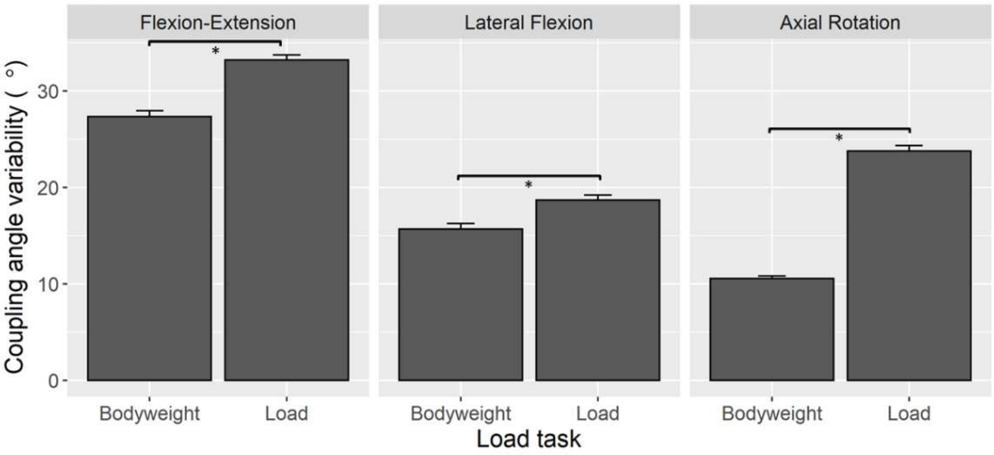

*Figure 5Group mean (error bars as 95% confidence interval) of the coordination variability averaged across the stance phase in running. * indicate statistical significance difference between load conditions.*

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 the metabolic cost of running. For example in walking, carrying a 31.75kg 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 control 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 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 > 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.

Acknowledgments: None

Conflict of Interest and Source of Funding: No benefits in any form have been or will be received from a commercial party related directly or indirectly to the subject of this manuscript. No authors have a conflict of interest.

References.

Ahmadyar, B., Rüst, C.A., Rosemann, T., Knechtle, B., 2015. Participation and performance trends in elderly marathoners in four of the world's largest marathons during 2004-2011. Springerplus 4, 465-465.

Alger, K., 2014. The marathon Des Sables kit list. Runner’s World. [http://www.runnersworld.co.uk/events/a772690/man-v-marathon-des-sables-the-marathon-des-sables-kit-list/.]

Baggaley, M., Esposito, M., Xu, C., Unnikrishnan, G., Reifman, J., Edwards, W.B., 2020. Effects of load carriage on biomechanical variables associated with tibial stress fractures in running. Gait & Posture 77, 190-194.

Baker, R., 2001. Pelvic angles: A mathematically rigorous definition which is consistent with a conventional clinical understanding of the terms. Gait & Posture 13, 1-6.

Bertram, J.E., Hasaneini, S.J., 2013. Neglected losses and key costs: tracking the energetics of walking and running. The Journal of Experimental Biology 216, 933-938.

Brown, T.N., O’Donovan, M., Hasselquist, L., Corner, B.D., Schiffman, J.M., 2014. Body borne loads impact walk-to-run and running biomechanics. Gait & Posture 40, 237-242.

Chang, R., Van Emmerik, R., Hamill, J., 2008. Quantifying rearfoot–forefoot coordination in human walking. Journal of Biomechanics 41, 3101-3105.

Dempster, W., 1955. Space requirements of the seated operator: Geometrical, kinematic, and mechanical aspects of the body with special reference to the limbs. Wright-Patterson Air Force Based, OH.

Fagundes, A.d.O., Monteiro, E.P., Franzoni, L.T., Fraga, B.S., Pantoja, P.D., Fischer, G., Peyré-Tartaruga, L.A., 2017. Effects of load carriage on physiological determinants in adventure racers. PLoS ONE 12, e0189516.

Floria, P., Sanchez-Sixto, A., Ferber, R., Harrison, A.J., 2018. Effects of running experience on coordination and its variability in runners. Journal of Sports Sciences 36, 272-278.

Gerhart, H.D., Pressl, R., Storti, K.L., Bayles, M.P., Seo, Y., 2020. The effects of a loaded rucksack and weighted vest on metabolic cost and stride frequency in female adults. Ergonomics 63, 145-151.

Hafer, J.F., Boyer, K.A., 2017. Variability of segment coordination using a vector coding technique: Reliability analysis for treadmill walking and running. Gait & Posture 51, 222-227.

Hafer, J.F., Peacock, J., Zernicke, R.F., Agresta, C.E., 2019. Segment Coordination Variability Differs by Years of Running Experience. Medicine & Science in Sports & Exercise 51, 1438-1443.

Hamill, J., Palmer, C., Van Emmerik, R.E.A., 2012. Coordinative variability and overuse injury. Sports Medicine, Arthroscopy, Rehabilitation, Therapy & Technology 4, 45.

LaFiandra, M., Holt, K., Wagenaar, R., Obusek, J., 2002. Transverse plane kinetics during treadmill walking with and without a load. Clinical Bomechanics (Bristol, Avon) 17, 116-122.

LaFiandra, M., Wagenaar, R., Holt, K., Obusek, J., 2003. How do load carriage and walking speed influence trunk coordination and stride parameters? Journal of Biomechanics 36, 87-95.

Liew, B.X., Morris, S., Netto, K., 2016. The effects of load carriage on joint work at different running velocities. Journal of Biomechanics 49, 3275-3280.

Lobb, N.J., Fain, A.C., Seymore, K.D., Brown, T.N., 2019. Sex and stride length impact leg stiffness and ground reaction forces when running with body borne load. Journal of Biomechanics 86, 96-101.

Martin, J.P., Li, Q., 2018. Altering Compliance of a Load Carriage Device in the Medial-Lateral Direction Reduces Peak Forces While Walking. Scientific Reports 8, 13775.

Needham, R., Naemi, R., Chockalingam, N., 2014. Quantifying lumbar–pelvis coordination during gait using a modified vector coding technique. Journal of Biomechanics 47, 1020-1026.

Pontzer, H., Holloway, J.H.t., Raichlen, D.A., Lieberman, D.E., 2009. Control and function of arm swing in human walking and running. The Journal of Experimental Biology 212, 523-534.

Preece, S.J., Mason, D., Bramah, C., 2016. The coordinated movement of the spine and pelvis during running. Human Movement Science 45, 110-118.

Robert, T., Bennett, B.C., Russell, S.D., Zirker, C.A., Abel, M.F., 2009. Angular momentum synergies during walking. Experimental Brain Research 197, 185-197.

Rosa, R.G.D., Gomenuka, N.A., Oliveira, H.B., Peyre-Tartaruga, L.A., 2018. Inclined Weight-Loaded Walking at Different Speeds: Pelvis-Shoulder Coordination, Trunk Movements and Cost of Transport. Journal of Motor Behavior 50, 73-79.

Scheer, V., Vieluf, S., Schröder, M., Lappe, P., Heitkamp, H.-C., 2020. A comparison of economy between two different backpack designs for runners. Applied Ergonomics 84, 103038.

Seay, J.F., Van Emmerik, R.E., Hamill, J., 2014. Trunk bend and twist coordination is affected by low back pain status during running. European Journal of Sport Science 14, 563-568.

Sharpe, S.R., Holt, K.G., Saltzman, E., Wagenaar, R.C., 2008. Effects of a hip belt on transverse plane trunk coordination and stability during load carriage. Journal of Biomechanics 41, 968-976.

Silder, A., Delp, S.L., Besier, T., 2013. Men and women adopt similar walking mechanics and muscle activation patterns during load carriage. Journal of Biomechanics 46, 2522-2528.

Smith, J.A., Kulig, K., 2016. Trunk-pelvis coordination during turning: A cross sectional study of young adults with and without a history of low back pain. Clinical Bomechanics (Bristol, Avon) 36, 58-64.

Teunissen, L.P., Grabowski, A., Kram, R., 2007. Effects of independently altering body weight and body mass on the metabolic cost of running. The Journal of Experimental Biology 210, 4418-4427.

Williams, K.R., Cavanagh, P.R., 1987. Relationship between distance running mechanics, running economy, and performance. Journal of Applied Physiology 63, 1236-1245.

Yen, S.C., Gutierrez, G.M., Ling, W., Magill, R., McDonough, A., 2012. Coordination variability during load carriage walking: can it contribute to low back pain? Human Movement Science 31, 1286-1301.