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Joint power and kinematics coordination in load carriage running: Implications for performance and injury

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ABSTRACT

Investigating the impact of incremental load magnitude on running joint power and kinematics is important for understanding the energy cost burden and potential injury-causative mechanisms associated with load carriage. It was hypothesized that incremental load magnitude would result in phase-specific, joint power and kinematic changes within the stance phase of running, and that these relationships would vary at different running velocities. Thirty-one participants performed running while carrying three load magnitudes (0%, 10%, 20% body weight), at three velocities (3, 4, 5 m/s). Lower limb trajectories and ground reaction forces were captured, and global optimization was used to derive the variables. The relationships between load magnitude and joint power and angle vectors, at each running velocity, were analyzed using Statistical Parametric Mapping Canonical Correlation Analysis. Incremental load magnitude was positively correlated to joint power in the second half of stance. Increasing load magnitude was also positively correlated with alterations in three dimensional ankle angles during mid-stance (4.0 and 5.0 m/s), knee angles at mid-stance (at 5.0 m/s), and hip angles during toe-off (at all velocities). Post hoc analyses indicated that at faster running velocities (4.0 and 5.0 m/s), increasing load magnitude appeared to alter power contribution in a distal-to-proximal (ankle → hip) joint sequence from mid-stance to toe-off. In addition, kinematic changes due to increasing load influenced both sagittal and non-sagittal plane lower limb joint angles. This study provides a list of plausible factors that may influence running energy cost and injury risk during load carriage running.

1. Introduction

Running related sports which require load carriage (e.g. ultra-marathon) have become increasingly popular over the past two decades [1,2]. However, compared with walking research into load carriage [3] running mechanics has received little attention [4,5], with prior investigations focusing mainly on military applications [5,6]. Within the military setting, overuse lower limb injuries are commonly associated with heavy load carriage which may involve both walking and running [7]. However, epidemiological evidence of a detrimental effect of load on non-military athletes is lacking. Research into loaded running in civilians is required to increase our understanding of the impact of load carriage on running energy cost [8] and injury risks [9].

The mechanics of running without external load (termed unloaded running) are well understood. Prior to mid-stance, the knee and ankle extensors absorb power to decelerate the body segments and support body weight (BW) [10,11]. During push-off, power to accelerate the body into flight is largely driven by the ankle extensors [10,11]. This temporal coordination in power flow likely reflects muscle coordination patterns which provide the required energy in running while minimizing metabolic cost [10,12]. Interestingly, it has been reported that increasing load magnitude in running does not alter the proportional contribution of hip, knee and ankle when considering average positive power [5]. However, when considering phase-specific gait effects, a previous study in walking reported that load carriage did influence joint power [3]. In running, it is yet unknown how each joint contributes to the total power across the stance phase, when load is carried. In addition, since previous studies have found different joint power contributions at different velocities [13], the effect of load on running joint power control may vary at different velocities.

An in-depth analysis of three dimensional (3D) joint angles is needed in this area, as changes to joint kinematics alter joint power contributions [14] and soft-tissue strain patterns [15,16]. For example, small alterations in knee flexion angle (e.g. 4°) has been shown to increase knee joint positive work by 2.5 J/kg [14] and

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increase the magnitude of knee joint load [17]. Current studies have only investigated the effects of load on sagittal plane kinematics in running at relatively slow velocities [4,5]. However, load carriage exerts significant non-sagittal plane torque on the body [18], which when coupled with insufficient muscle capacity, may result in deviations of non-sagittal plane kinematics and create asymmetrical soft-tissue stresses [15]. Since loaded running occurs across a range of velocities and joint internal loads increase at faster running velocities [19], investigating the effect of load in 3D whilst running at a range of velocities is needed.

With an increasing involvement of people in running sports requiring load carriage, detailed research into the effect load carriage has on running mechanics is warranted to facilitate the management of these athletes. Statistical Parametric Mapping (SPM) has been used to perform hypothesis testing on biomechanical time-series data [20], which provides a more robust statistical method for understanding the phase-specific effects of load on running mechanics. Thus, the aim of this study is to determine the phase-specific effect of running with three different loads across three different velocities on joint power and 3D kinematics over the stance phase.

2. Methods

2.1. Study design

A repeated measures design was adopted where participants performed a single testing session, which occurred in Curtin University's biomechanics laboratory.

2.2. Participants

16 male and 15 female participants enrolled [mean (standard deviation (SD)) age = 30.8 (5.9) years old; height = 1.70 (0.08) m; mass = 66.4 (10.8) kg; distance ran per week = 39.2 (26.4) km; hours ran per week = 3.73 (2.86) h]. Nine participants had at least one year experience in frequent load carriage (>10% BW, at least six separate occasions within a year) during sports and/or as a requirement of their occupation. Twenty-two participants had no prior experience in frequent load carriage. All participants provided signed informed consent prior to study enrolment. Ethical approval for this study was provided by Curtin University Human Research Ethics Committee (RD-41-14).

2.3. Running protocol

Participants wore their personal running shoes and completed a warm-up before the experiment. Participants ran across a 20 m runway, embedded with three consecutive force platforms (3 m lengthwise) (AMTI, Watertown, MA), while carrying three load conditions (0%, 10%, 20% BW) across three velocities (3.0 m/s, 4.0 m/s, 5.0 m/s). Timing gates (SMARTSPEED Pro, Fusion Sport Pty Ltd, Australia) were placed five metres apart on either side of the force plates, whilst a 15 m run up was given to enable each participant to achieve the desired velocity before running across the force plates. Thirty-one sequences of load-velocity condition were generated using a random sequence generator (https://www.randomizer.org/), to minimize the influence of testing order on our dependent variables. Load carriage was achieved through varying the volume of sand (in sandbags) carried in a backpack (CAMELBAK, H.A.W.G.® NV, 14 l). The backpack was fitted snugly to the participants' trunk with waist and chest straps. Each condition required five successful running attempts, each within a ±10% variation of the prescribed velocity and with no visible alteration in running gait pattern to target the force plate. At least 30 s rest was provided between each running attempt and a 5 min rest between each running condition.

2.4. Biomechanical modelling and processing

The position and orientation of the right lower limb segments was calculated using an inverse kinematic (IK) lower limb model created in Visual 3D (C-motion, Germantown, MD), using the Levenberg–Marquardt algorithm [21]. A standard lower limb marker set protocol was used, which had been previously described [22]. The hip joint centre was defined using a regression equation [23], whilst the knee and ankle joint centres were defined as the mid-point of the femoral epicondyles and malleoli [22], respectively. For the IK model, the hip, knee, and ankle joints were constrained to have three rotational degrees of freedom (DOF), whilst that of the pelvis segment had six DOF. A segmental weight of two was given to the thigh, three to the shank, and four to the pelvic and foot segments [21].

Marker trajectories were captured at 250 Hz using an 18 camera motion analysis system (Vicon T-series, Oxford Metrics, UK), while ground reaction force (GRF) was recorded at 2000 Hz using the force platforms. Gap filling was performed in Vicon Nexus (v2.1.1, Oxford Metrics, UK). Raw marker trajectories and force data were filtered using a low pass, zero-lag, 4th order Butterworth filter at 18 Hz [21] for inverse dynamics. Trajectories were filtered at a higher frequency for inverse dynamics, to match the force data filtering frequency in order to avoid joint moment artefacts [24]. However, this frequency of 18 Hz resulted in excessive 'noise' in the kinematic waveforms. Hence, raw trajectories data was filtered at 12 Hz for kinematic analysis [25]. A Cardan XYZ rotation sequence was used to calculate 3D joint angles [26]. Joint angles were expressed in an orthogonal frame in the proximal segment using the right hand rule [22]. This meant that positive values along the x-axis (medio-lateral axis) represented hip flexion, knee extension, and ankle dorsiflexion; positive values along the y-axis (postero-anterior axis) represented hip adduction, knee adduction, and ankle inversion; and positive values along the z-axis (vertical axis) represented hip and knee internal rotation, and ankle adduction. Instantaneous joint angles and power trajectories of the right hip, knee, and ankle were computed only during the stance phase of running. A threshold of 20 N in ground reaction force was used to determine initial foot contact and toe-off. Joint power was normalized by the scaling factor of $ML^{0.5}g^{1.5}$ (mean (SD)) scaling factor = 1845.10 (338.36), with base factors of gravitational constant g (9.81 m/s^2), leg length, L (m), and body mass, M (kg) [3].

2.5. Statistical analysis

All analyses were performed using spm1d package (v0.3) (www.spm1d.org), installed in Python 2.7, and implemented in Enthought Canopy 1.5.4 (Enthought Inc., Austin, USA) [27]. Canonical correlation analysis was performed to determine the magnitude of the correlation between the predictor variable (load magnitude), and the dependent vector variables [20]. As the current implementation of SPM in spm1d only allows for a univariate predictor variable [27], Canonical correlation analyses was performed at each running velocity. In order to determine significance, field smoothness was derived from time-varying gradients of the residuals [28]. Next, given the calculated smoothness, Random Field Theory (RFT) was used to determine a critical threshold that maintained an alpha rate of 0.05 [27]. Hence, a critical threshold of 0.05 was set for joint power, and a Bonferroni corrected threshold of 0.0167 (0.05/3) was set for each of the three joint angles. Post hoc scalar field analysis was performed on each vector component, only when significance was achieved at the vector-field level. For scalar field analysis, SPM linear regression t-statistic was performed on each vector components. A Bonferroni corrected threshold of 0.0167 (0.05/3)