A model for calculating the mechanical demands of overground running

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Abstract

An energy-based approach to quantifying the mechanical demands of overground, constant velocity and/or intermittent running patterns is presented. Total mechanical work done (W_{total}) is determined from the sum of the four sub components: work done to accelerate the centre of mass horizontally (W_{hor}), vertically (W_{vert}), to overcome air resistance (W_{air}) and to swing the limbs (W_{limbs}). These components are determined from established relationships between running velocity and running kinematics; and the application of work-energy theorem. The model was applied to constant velocity running (2 – 9 m·s^{-1}), a hard acceleration event and a hard deceleration event. The estimated W_{total} and each sub component were presented as mechanical demand (work per unit distance) and power (work per unit time), for each running pattern. The analyses demonstrate the model is able to produce estimates that: 1) are principally determined by the absolute running velocity and/or acceleration; and 2) can be attributed to different mechanical demands given the nature of the running bout. Notably, the proposed model is responsive to varied running patterns, producing data that are consistent with established human locomotion theory; demonstrating sound construct validity. Notwithstanding several assumptions, the model may be applied to quantify overground running demands on flat surfaces.

Keywords

energetics, power, external load, locomotion, match analysis

Introduction

Quantifying the loads athletes experience during training, competition and/or in research settings is routine practice, with several methods employed across settings (Lambert & Borresen, 2010). The value, utility, practicality, limitations and future directions of load quantification methods have been topics of discussion for several years (Aughey, 2011; Bourdon et al., 2017; Cummins, Orr, O'Connor & West, 2013; Gray, Shorter, Cummins, Murphy & Waldron, 2018; Lambert & Borresen, 2010). Where training theory is considered a simple 'dose-response' relationship, there is consensus that the exercise 'dose' experienced during training or competition can be described in two ways; through objective measures of the work performed by the athlete (external load) or as the relative biological (both physiological and psychological) stressors imposed on the athlete (internal load) (Bourdon et al., 2017). The 'response' may be described by changes in performance and/or adaptation, which notably, can be positive (e.g. performance increase, favourable physiological adaptation, readiness to train) or negative (e.g. symptoms of fatigue, overuse injury, reduced performance). Consistent with this understanding, several studies have implicated training load as having influence over performance outcomes (Jobson, Passfield, Atkinson, Barton & Scarf, 2009; Taha & Thomas, 2003), athlete wellbeing (Lathlean, Gastin, Newstead & Finch, 2019), fatigue/readiness to perform (Halson, 2014) and injury (Schwellnus et al., 2016; Soligard et al., 2016). To gain such insights, simultaneous monitoring of both external and internal load is recommended, as this permits the evaluation of psychophysiological stress relative to the work done. Indeed, reduced homeostatic disturbance to a given absolute work rate is a hallmark response to exercise training (Blomqvist & Saltin, 1983; Holloszy & Coyle, 1984). This speaks to the importance of adopting valid and reliable load monitoring methods (Lambert & Borresen, 2010).

The introduction of micro-technology devices (small units co-housing a global positioning system (GPS) receiver and various micro-electrical mechanical systems) designed for sporting applications has attracted considerable interest and discussion on how such data can and should be treated to understand performance, guide training design and inform player management decisions, particularly in field based team sports (Aughey, 2011; Cummins et al., 2013), where traditional load monitoring methods e.g. heart rate monitoring, are unsuitable given the intermittent nature of these sports (Bangsbo, Mohr & Krustrup, 2006). Notwithstanding the limitations of micro-technology devices (Malone, Lovell, Varley & Coutts, 2017), it would seem they continue to be used across many team sports as they readily provide kinematic summaries (time, distance, velocity, acceleration) of the gross locomotor patterns during field-based training and competition. Despite some microtechnology derived metrics demonstrating relationships with measures of acute internal load (Impellizzeri, Rampinini, Coutts, Sassi & Marcora, 2004) and/or readiness to perform (Young, Hepner & Robbins, 2012), the literature highlights several shortcomings and opportunities to improve common techniques (Bourdon et al., 2017; Furlan, Osgnach, Andrews & Gray, 2014; Gray et al., 2018). For example, Bourdon et al. (2017) identify that the manner in which commercial systems determine and report sprint and/or acceleration efforts, is often at odds with how a coaches view said efforts, leading to misinterpretation. Similarly, Gray et al. (2018) describe how the use of speed/acceleration zones (i.e. sample by sample binning of data according to speed or acceleration) fragment work bouts, rather than painting clear pictures of the work performed. Based on these discussions, the future of external load monitoring in team sports appears to destined for improved wearable sensors (with technological advancements) and advanced modelling techniques applied to present meaningful summary data to coaches and athletes (Bourdon et al., 2017).

In cycling, ergometers and power meters provide measures of mechanical work (total external load) and power-time curves that are readily analysed to describe the intensity and distribution of work. Whilst these technologies do not capture internal power (Brooks, Andrews, Gray & Osborne, 2013), it is arguably the gold standard method of measuring external load for cycling exercise. Intuitively, the work/power method summates rather than fragments data, and uses dimensionally appropriate units (as opposed to arbitrary units) for external load quantification. Measuring mechanical work and power during overground running is not nearly as simple, but is possible. Valuable insights such as the costly nature (both mechanically and metabolically) of accelerated and decelerated running (Osgnach, Poser, Bernardini, Rinaldo & di Prampero, 2010; Pavei et al., 2019; Zamparo et al., 2019) have resulted from energy-based analyses, as such, pursuing a field-based method of quantifying external load in terms of work and power seems advantageous from multiple perspectives. Gray et al. (2018) proposed that following sport-specific temporal classification of data sets into discrete movement categories e.g. walking, running, colliding, wrestling; a model specific to each movement category could be applied to provide a work-energy based description of each bout. Subsequent summation of all occurrences would yield the total 'load' of the bout.

The movement demands of field-based team sports are well documented (Bangsbo et al., 2006; Duthie, Pyne & Hooper, 2003; Gabbett, King & Jenkins, 2008; Wisbey, Montgomery, Pyne & Rattray, 2010), with many match analysis studies identifying that a large proportion of play is spent in low-intensity locomotor activities (walking and jogging or < 3.5 $m \cdot s^{-1}$) interspersed with brief (~3- 10 s) repeated bouts of high-intensity locomotor efforts (high speed running, explosive acceleration/deceleration). Given that the forward running gait is the predominant 'purposeful movement' in team sport match play (Bloomfield, Polman & O'Donoghue, 2007), a work-energy model for this specific movement category is likely to be an essential component of the external load profile of most field sports. Based on the Konig Theorem, Gray et al. (2018) conceptualised a model for the determination of mechanical work done during overground forward running. This study aims to apply this model to GPS derived velocity-time data to describe the mechanical power and mechanical demand during three conditions: 1) constant velocity running (simulated); 2) a maximal acceleration (simulated 40 m sprint); and 3) an intense deceleration (during on field training). This analysis serves to demonstrate how an energy-based approach can quantify the external load during over ground running of varied nature. It is hypothesised that the model will produce estimates of mechanical power for continuous and intermittent running bouts, that are appropriate for load monitoring applications.

Methods

Theory

The total mechanical work (W_{total}) done during running can be partitioned into external work (W_{ext}) and internal work (W_{int}) (Pavei et al., 2019a; Saibene & Minetti, 2003), where W_{ext} is the work done to accelerate the centre of mass (COM) with respect to the environment and W_{int} is the work associated with the acceleration of body segments with respect to the COM. Therefore, total mechanical work is given by:

$$W_{total} = W_{int} + W_{ext} \quad (1)$$

Furthermore, work done can be defined as either positive or negative. Positive work (W^+) is done when the kinetic (KE) and/or potential energies (PE) of a mass are increased. Conversely, negative work (W^-) is done when the kinetic (*KE*) and/or potential energies (*PE*) of a mass are decreased. These principles underpin all subsequent discussion.

In overground running on a level surface the COM is accelerated in the horizontal and vertical planes (Cavagna, Saibene & Margaria, 1964). Additionally, even in the absence of wind, air poses a resistive force to the motion of the COM (di Prampero, 1986). Therefore, W_{ext} can be considered a function of the work done on the COM in the horizontal plane (W_{hor}), vertical plane (W_{vert}) and to overcome air resistance (W_{air}). Therefore, external work is given by:

$$W_{ext} = W_{hor} + W_{vert} + W_{air} \quad (2)$$

Internal work (W_{int}) is typically determined from changes in segment energies derived from motion analysis (Pavei et al., 2019; Zamparo et al., 2019). However, Minetti (1998) provides a model equation to predict W_{int} from velocity, stride frequency, duty factor (the percentage of the stride cycle in which a single limb is in the support phase) and a constant reflecting the inertial properties of the limbs. In the absence of uneven terrain, varying loads or changes in wind direction and speed, body mechanics are tightly coupled with forward velocity in running (Gray, Price, & Jenkins, In Press; Lee & Farley, 1998; Mann & Hagy, 1980; Nilsson, Thorstensson & Halbertsma, 1985; Saito, Kobayashi, Myashita & Hoshikawa, 1974; Zatsiorsky, Werner & Kaimin, 1994). As such, stride frequency and duty factor are readily modelled from running velocity (Gray et al., In Press), enabling the subsequent determination of W_{int} (Minetti, 1998). As W_{int} is primarily determined by limb kinematics, W_{limbs} is used in the present study to denote this partition.

Model Calculations

The velocity-time curve used in the modelling process is assumed to represent the horizontal motion of the COM during forward, overground running on a hard (not able to be deformed), horizontal surface orthogonal to the earth's gravitational field; the runner's sagittal plane (the plane upon which the runner's limbs tend to have their greatest angular motion) assumes a fixed vertical orientation i.e. perpendicular to the running surface.

The following sections describe a method of determining W_{total} during an overground running bout, from the velocity-time curve of a GPS receiver. Common to all systems will be a finite sampling frequency, as such the velocity-time curve of any running bout to be analysed will include a finite number of samples (n), a fixed time interval (t_i) between samples. The formulae presented herein are written for the j^{th} sample, over a period of n, GPS samples.

Determination of mechanical work and power from GPS velocity data according to the above theoretical framework was completed in four steps:

1. Predicting COM and limb kinematics from GPS velocity
2. Determining external work from GPS Velocity
3. Determining internal work from GPS Velocity
4. Summation to determine total mechanical work and power

1. Predicting COM & Limb Kinematics from GPS Velocity

The kinematics of the COM and the limbs are tightly coupled to running speed. The motion of the COM in running is likened to a bouncing ball, where it is lowest during mid support and highest in mid-flight (Farley & Ferris, 1998). Therefore, with each step (half stride) there is a vertical oscillation of the COM, the vertical displacement (Δh, from lowest to highest point) of which, has been shown to vary linearly with movement velocity ($r^2 = 0.444$, $p = 0.034$, $n = 90$) (Ito, Komi, Sjodin, Bosco & Karlsson, 1983; Lee & Farley, 1998) according to:

$$\Delta h = -0.008 + 0.004 \cdot v \quad (3)$$

where Δh is in m, and v in $m \cdot s^{-1}$.

Similarly, temporal limb kinematics have been shown to vary with ‘steady state’ running velocity. Support duration decreases whilst swing duration is maintained or only modestly decreased at high speeds (Nilsson et al., 1985). The percentage of the stride cycle in which a single limb is in the support phase is termed the duty factor. Consequently, with increasing ‘steady state’ running velocity, stride frequency (f) increases whilst duty factor (d) decreases. Given f and d are notable determinants of mechanical power in locomotion (Minetti, 1998; Nardello, Ardigo & Minetti, 2011), Gray et al. (In Press) have previously established regression equations relating stride frequency and duty factor to running velocity in a sample of male football (soccer) players. The regression equations determined were:

$$f = 0.026 \times v^2 - 0.111 \times v + 1.398 \quad (4)$$

$$d = 0.004 \times v^2 - 0.061 \times v + 0.50 \quad (5)$$

where f is in Hz, d is % (in decimal form), and v in $m \cdot s^{-1}$. The application of equations 3, 4 and 5 will soon be explained.

2. Determining External Work from GPS Velocity

External work done can be determined from changes in the kinetic (*KE*) and potential energy (*PE*) of the COM (Cavagna et al., 1964). The *KE* of the COM is the vectorial sum of its horizontal (KE_{hor}) and vertical (KE_{vert}) components, thus W_{hor} is given by the change in KE_{hor}. The horizontal velocity of the COM may be approximated by velocity-time data from a micro-technology device. The resolution and sampling frequency of this technology is unlikely to detect within stride fluctuations in COM motion, therefore this data can only be assumed to represent the gross forward velocity, which is important nonetheless. On this basis, W_{hor} can be expressed as:

$$W_{hor}^{j} = \sum_{j=1}^{n} 0.5\left(v_{j+1}^{2} - v_{j-1}^{2}\right) \qquad (6)$$

Importantly, where $v_{j+1} > v_{j-1}$ (as for acceleration), positive horizontal work (W_{hor}^{+}) is done by the body. Where $v_{j+1} < v_{j-1}$ (as for deceleration), negative horizontal work (W_{hor}^{-}) is done by the body. Furthermore, when determining work done from changes in KE, mass is a scaling factor and has therefore been excluded such that units are $J \cdot kg^{-1}$.

With each step taken, the COM rises and falls by a height, Δh (Lee & Farley, 1998). The vertical oscillation of the COM suggests the KE_{vert} and *PE* of the COM are in continual flux. Additionally, the first law of thermodynamics implies $\Delta PE = \Delta KE_{vert}$, therefore either may be used to approximate W_{vert}. In this approach, ΔPE will be used given Δh can be predicted from velocity using equation 3. ΔPE of the COM from its lowest to highest position and vice versa, equate to the positive vertical work (W_{vert}^{+}) and negative vertical work (W_{vert}^{-}) done by the body, respectively. Assuming, the COM rises and falls the same height in a step, it holds that $|W_{vert}^{+}| = |W_{vert}^{-}|$. Thus, either can be expressed as:

$$\left|W_{vert^{+}}^{j}\right| = \left|W_{vert^{-}}^{j}\right| = \sum_{j=1}^{n}\left(2 \cdot g \cdot \Delta h_{j} \cdot f_{j}\right) \qquad (7)$$

where Δh_j and f_j are predicted from v_j using equations 3 and 4, respectively. Similar to equation 6, when determining work done from changes in PE, mass is a scaling factor and has again been excluded such that units are J·kg^{-1}.

Air resistance (F_{air}) is an external force applied by the volume of air that meets and passes around the surface of a body. It can be mathematically expressed as a function of ambient air density (ρ), projected frontal surface area (A_p), the square of the relative air speed (S) and a drag coefficient (C_d) according to:

$$F_{air} = 0.5 \times r \times A_r \times S^2 \times C_d \qquad (8)$$

Air density varies with T and BP, therefore with knowledge of these values, ambient air density (ρ) can be estimated according to:

$$r = \frac{273 \times r_o \times BP}{760 \times T} \qquad (9)$$

with the unit kg·m^{-3}, where BP is in mmHg, T is in ˚C and ρ_o = 1.293 kg·m^{-3} (air density at sea level and 273 K).

Projected frontal surface area of a human running is ~26 % of total body surface area (BSA) (Davies, 1980; Pugh, 1971, 1976; Shanebrook & Jaszczak, 1976), which can be determined using established prediction equations (DuBois & DuBois, 1916; Shuter & Aslani, 2000). Applying a BSA prediction equation (Shuter & Aslani, 2000), A_p can be determined according to:

$$A_r = 0.26\left(94.9 \times ht^{0.655} \times M^{0.441}\right) \qquad (10)$$

with the unit m^2, where ht = standing height in m and M = body mass in kg.

Using varied methodological approaches, the C_d for humans running ranges from 0.7 to 1.1 (Davies, 1980; Pugh, 1971; Shanebrook & Jaszczak, 1976; Walpert & Kyle, 1989). In the present model, $C_d = 1$ will be adopted.

In calm air, the movement velocity (v) of a runner determines the relative air speed, thus $v = S$ (di Prampero, 1986). Under these conditions, the mechanical work done to overcome air resistance (W_{air}) is proportional to the cube of the runners forward velocity i.e. v^3 and can be expressed as:

$$W_{air}^{j} = \sum_{j=1}^{n}\left(\frac{0.5 \cdot r \cdot A_r \cdot v_j^3 \cdot C_{d_j} \cdot t_i}{M}\right) \tag{11}$$

with the unit J·kg^{-1}, where ρ, A_ρ, v, C_d , t_i and M are substituted as previously defined.

3. Determining Internal Work from GPS Velocity

Internal work primarily describes the work done to swing the limbs (W_{limbs}) and is typically determined from changes in segment energies derived from motion analysis. However, Minetti (1998) provides a model equation to predict the mechanical work done to swing the limbs, per unit distance travelled (D_{limbs}), in walking and running from velocity, stride frequency and duty factor as follows:

$$D_{limbs} = q \cdot v^2 \cdot f\left(1+\left(\frac{d}{1-d}\right)^2\right) \tag{12}$$

where $q = 0.1$, and is a constant reflecting the inertial properties of the limbs and the mass partitioning between the limbs and the rest of the body (Minetti, 1998) (units are J·kg^{-1}·m^{-1}). This equation allows within and between segment energy transfer and takes the absolute sum of positive and negative work performed by the limbs (Minetti, 1998; Nardello et al., 2011). On this understanding, W_{limbs} can be expressed as:

$$W_{limbs}^{j} = \sum_{j=1}^{n} \left(q \cdot v_j^3 \cdot f_j \left(1 + \left(\frac{d_j}{1 - d_j} \right)^2 \right) \cdot t_i \right) \quad (13)$$

where f_j and d_j are predicted from v_j using equations 4 and 5, respectively (units are $J \cdot kg^{-1}$).

4. Summation to Determine Total Mechanical Work, Power and Demand

Equations 6, 7, 11 and 13 define components (W_{hor}^{+}, W_{hor}^{-}, W_{vert}^{+}, W_{vert}^{-}, W_{air} and W_{limbs}) of the total mechanical work done (W_{total}) for running at a given velocity. As such, W_{total} can be expressed as:

$$W_{total}^{j} = \sum_{j=1}^{n} \left(\left| W_{vert^{+}}^{j} \right| + \left| W_{vert^{-}}^{j} \right| + \left| W_{horiz}^{j} \right| + W_{limbs}^{j} + W_{air}^{j} \right) \quad (14)$$

where W_{total} is in $J \cdot kg^{-1}$.

The total mechanical power (P_{total}) can be determined by dividing by the time interval according to:

$$P_{total}^{j} = \frac{W_{total}^{j}}{t_i} \quad (15)$$

units are $W \cdot kg^{-1}$. To determine the mechanical power of any sub component in the model e.g. P_{hor}^{+} from W_{hor}^{+}, the same approach can be applied.

The total mechanical demand (D_{total}) can be determined by dividing mechanical power (P_{total}) by the running velocity according to:

$$D^{j}_{total} = \frac{P^{j}_{total}}{v^{j}} \quad (16)$$

units are $J \cdot kg^{-1} \cdot m^{-1}$, a customary unit for the mechanical and metabolic cost of locomotion (Minetti, 1998). To determine the mechanical demand of any sub component in the model e.g. D_{hor}^{+} from P_{hor}^{+}, the same approach can be applied.

Participants

For condition 1), data that simulated constant velocity running were manually developed therefore no participants were required. For conditions 2) and 3), ten elite Australian football players were recruited from an Australian Football League (AFL) club to participate. The participants represented a cross section of age, size, and running ability of elite Australian football players (mean ± SD age: 25.4 ± 4.1 years, body mass: 89.3 ± 11.4 kg, stature: 188.9 ± 7.1 cm). Informed consent was gained prior to participation and the study was approved by an ethics committee of The University of Queensland.

Procedures

Data sets simulating constant velocity running at 2, 3, 4, 5, 6, 7, 8, 9 and 10 $m \cdot s^{-1}$ were prepared for analysis in R (R, Vienna, Austria), which determined mechanical work done based on the model described above. Environmental conditions were standardised (BP= 760 mmHg, T= 23°C and no wind) and mean stature (189 cm) and body mass (89.3 kg) of the participants were used in the calculations. The relationships between constant velocity running and mechanical power are presented.

GPS data (SPIpro, GPSports, Canberra, Australia) collected at 5 Hz during a pre-season sprint testing session (3 x 40 m sprints on an outdoor tartan athletics track) were downloaded (GPSports, Team AMS, Canberra, Australia) and reviewed to set parameters for an exponential function (Chelly & Denis, 2001; P. E. di Prampero et al., 2005) that represented the group's sprint performance. This was:

$$v_t = v_{max} \times \left(1 - e^{\frac{-t}{\tau}}\right) \quad (17)$$

where v_t is the modelled running velocity in m·s^{-1}, v_{max} is the maximal velocity reached during the sprint in m·s^{-1}, and τ is the time constant in s. The mean ± SD v_{max} of the participant group was 9.16 ± 0.42 m·s^{-1}, which was substituted into equation 17, along with τ = 1.4. The modelled velocity-time curve (reproduced at 5 Hz) was visually inspected and considered to adequately represent the sprint performance of the participant group (Figure 1). This velocity-time data was then imported for analysis in R, as described above. The modelled changes in mechanical work and power over the duration of the simulated sprint are presented.

****Figure 1 near here****

GPS data recorded during a regular season, field-based training session were downloaded and reviewed to identify each participant's peak deceleration not attributed to a collision or fall. This discrete deceleration event was exported to Microsoft Excel (Microsoft Corp., Redmond, USA) where kinematic variables used to describe the nature of deceleration events were determined; duration (s), initial velocity (m·s^{-1}), final velocity (m·s^{-1}) and peak deceleration (m·s^{-2}). These events were then opened for analysis in R. The application used the raw, exported 5 Hz velocity-time curves to determine the mechanical work done based on the model described above. Participant characteristics (stature, body mass and maximum running velocity) were individualised in this deceleration analysis. The modelled changes in mechanical work and power during the participant's decelerations are presented. The data of Participant 6 are presented graphically to illustrate how the model operates. Participant 6 was selected on the basis of mass, stature and sprint ability, which are consistent with mean values for elite Australian football players (Buttifant, 1999; Young et al., 2005).

Results

Consistent with the units defined in equations 14, 15 and 16, all presented estimates of mechanical work, power and demand are expressed relative to body mass for comparative purposes.

Constant Velocity Running

During simulated constant velocity running W_{hor}^{+} and W_{hor}^{-}, are equal to zero. Figure 2 shows the changes in D_{vert}^{+}, D_{vert}^{-}, D_{air} and D_{limbs} (components of mechanical demand) for constant velocity running from 2 - 10 m·s^{-1}. D_{total} was minimised at ~4 m·s^{-1} before increasing curvilinearly with running velocity (Figure 3). P_{total} (total mechanical power) increased in an exponential manner from ~4.4 W·kg^{-1} at 2 m·s^{-1}, up to ~42 W·kg^{-1} at 10 m·s^{-1}. At a low running speed of 3 m·s^{-1}, the mechanical work done to raise and lower the COM (W_{vert}^{+} & W_{vert}^{-}) accounted for ~68% of the total mechanical work done, followed by W_{limbs} and W_{air}, with ~30% and 2% respectively. At 9 m·s^{-1}, W_{limbs} was the primary contributor to mechanical demand (~77%), followed by W_{vert}^{+} & W_{vert}^{-} (~15%) and W_{air} (~8%). The relative contributions from each component in the model for running velocities between 2 and 10 m·s^{-1} are shown in Figure 4.

**** Figure 2, 3 & 4 near here***

Acceleration

Mechanical demand reached a peak of 6.8 J·kg^{-1}·m^{-1} just 0.4 s into the maximal 40 m sprint (~6 s in total), at a horizontal velocity of 2.3 m·s^{-1} and an acceleration of 9.87 m·s^{-2}, before reducing to almost half of this value (3.45 $J \cdot kg^{-1} \cdot m^{-1}$) as v_{max} was attained (Figure 5b). Mechanical power increased rapidly over the first second, followed by a slow progression toward a peak value of ~31 $W \cdot kg^{-1}$ at a horizontal velocity and acceleration of ~9 $m \cdot s^{-1}$ and 0.24 $m \cdot s^{-2}$, respectively (Figure 5c). The total work done over the whole sprint was estimated to be 160.6 $J \cdot kg^{-1}$. Of this, 54.2% was attributed to swinging the limbs back and forth (W_{limbs}), 25.1% to accelerate the COM horizontally (W_{hor}^{+}), 14.7% to accelerate and decelerate (W_{vert}^{+} & W_{vert}^{-}) the COM vertically and 5.8% to overcome air resistance (W_{air}). Figure 7a shows the mechanical power curves for each component of the model during the simulated sprint.

****Figure 5 near here****

Deceleration

The mean ± SD duration (s), initial velocity ($m \cdot s^{-1}$), final velocity ($m \cdot s^{-1}$) and peak deceleration ($m \cdot s^{-2}$) of the deceleration curves collected from the team training session were 2.1 ± 0.2 s, 6.4 ± 1.1 $m \cdot s^{-1}$, 1.2 ± 0.8 $m \cdot s^{-1}$and -5.3 ± -0.6 $m \cdot s^{-2}$, respectively. Figure 6a shows the velocity-time curve of Participant 6 during hard voluntary deceleration. All other participants had similar shaped curves despite some variation in the initial and final velocities. The mechanical demand reached a peak of 8.1 $J \cdot kg^{-1} \cdot m^{-1}$ just 1.5 s into the 2.4 s deceleration event, at a horizontal velocity of 4.0 $m \cdot s^{-1}$ (Figure 6b). This occurred at the same time as the peak deceleration (-6.6 $m \cdot s^{-2}$). Mechanical power typically began relatively high (dependent on the initial velocity), increased to a peak under intense deceleration and reduced to a minimum once velocity tended towards a constant, low value. For Participant 6, mechanical power was initially high, but stable at ~22 $W \cdot kg^{-1}$, before peaking at 43.5 $W \cdot kg^{-1}$, then returning to zero (Figure 6c). This peak occurred just prior to the peak deceleration. Moreover, for Participant 6, the total work done over the whole 2.4 s deceleration was estimated to be 58 $J \cdot kg^{-1}$. Of this, ~52% was attributed to decelerating the COM horizontally

(W_{hor}^-), ~32% to swinging the limbs back and forth (W_{limbs}), ~14% to accelerate and decelerate (W_{vert}^+ & W_{vert}^-) the COM vertically and 1% to overcome air resistance (W_{air}). Figure 7b shows the mechanical power curves for each component of the model during Participant 6's deceleration event.

****Figure 6 near here****

****Figure 7 near here****

Discussion and Implications

This study describes and applies a new energetic approach to model the demands of non-steady state overground running from GPS data, that offers insights into the mechanical demands of running. Application of the model to constant velocity, accelerated and decelerated running has demonstrated the manner by which the model quantifies the mechanical demands of varied running patterns. Specifically, the analysis highlights that the model is able to produce estimates of mechanical demand that: 1) are principally determined by the absolute running velocity and/or acceleration; and 2) can be attributed to different mechanical loads on the runner given the nature of the running bout.

There is a tenfold variation (1.81- 18.3 $W \cdot kg^{-1}$) in estimates of total mechanical power for running at 3.6-3.9 $m \cdot s^{-1}$; largely attributable to whether within and between-segment energy transfer is permitted in the model (Arampatzis, Knicker, Metzler & Bruggemann, 2000). By allowing within and between segment energy transfer when deriving W_{limbs} and taking the absolute sum of positive and negative work throughout, the present analysis yields a mechanical power of ~6 $W \cdot kg^{-1}$ for running at 3.75 $m \cdot s^{-1}$. This approach was adopted to permit derivation of metabolic power in future analyses (Zatsiorsky, 1997). Despite the values in this analysis falling neatly within those reported in the literature, the general lack of consensus regarding methodological approach (Arampatzis et al., 2000), makes it difficult to comment on the validity of the mechanical power estimates produced. Nonetheless, applying the model to constant velocity running clearly showed that the mechanical demands of running increased with velocity, independent of acceleration (Figure 3). As W_{int} is intuitively related to stride frequency, it is not surprising that W_{int} tends to increase with speed for both walking and running (Nardello et al., 2011). In contrast, W_{ext} tends to decrease with constant velocity running (Cavagna & Kaneko, 1977). The greater increases in W_{int} compared to W_{ext} result in overall increases in W_{total} with velocity. Figure 4 reflects these well-accepted concepts in the human locomotion literature, with P_{total} primarily attributed to P_{vert} at low running velocities and P_{limbs} at high running velocities.

Collectively, the model suggests continual shifts in the primary mechanical demands of the energy expended during intermittent running. The model describes accelerating the COM vertically as the greatest mechanical demand during low velocity, low acceleration running efforts (Figure 4); swinging the limbs as the greatest mechanical demand during high velocity, low acceleration running efforts (Figure 7); and accelerating/decelerating the COM horizontally as the greatest mechanical demand during low-moderate velocity, high acceleration/deceleration running efforts (Figure 7). These general outcomes of the model are consistent with our understanding of human locomotion (Cavagna & Kaneko, 1977; Doke, Donelan & Kuo, 2005; Farley & Ferris, 1998) and the findings of recent experimental work on the sprint acceleration (Pavei et al., 2019) and shuttle running (Zamparo et al., 2019) mechanics/energetics. Indeed, a mechanical power analysis of maximal 20 m sprints using a 35-camera motion capture system reports peak power values of ~30 $W \cdot kg^{-1}$, with the forward (horizontal) acceleration of the COM, vertical acceleration of the COM and acceleration of the limbs relative to the COM, accounting for 50%, 9% and 41% of the total power, respectively. To enable comparison, by removing the W_{air} component from the present model and applying it to the velocity-time curve produced by equation 17 over a 3-second period (to simulate a 20 m sprint), W_{hor}, W_{vert} and W_{limbs} were found to account for 49%, 16% and 35%, respectively. Thus, the present model provides field-based estimates of mechanical power partitions in similar proportions to gold standard laboratory measurements. Similarly, the acceleration/deceleration data presented are consistent with the findings of Zamparo et al. (2019); which demonstrates athletic males produce greater mechanical power during maximal deceleration than maximal acceleration.

It is now commonly accepted that acceleration and deceleration are energetically costly running patterns (Polglaze & Hoppe, 2019). The model estimates D_{total} during constant velocity running at 9 $m \cdot s^{-1}$ (approximate peak running velocity of elite field sport athletes) to be 3.3 $J \cdot kg^{-1} \cdot m^{-1}$ (Figure 3). Notably, this falls short of the D_{total} values observed during maximal accelerations (6.8 $J \cdot kg^{-1} \cdot m^{-1}$) and decelerations (8.1 $J \cdot kg^{-1} \cdot m^{-1}$). Moreover, Figures 5 and 6 clearly demonstrate the mechanical demand reaches a peak when the rate of change in velocity is greatest. Figure 7 confirms it is indeed the W_{hor}^{+} and W_{hor}^{-} components of the model that are responsible for raising the mechanical demand of such running events. These comparisons highlight the model readily captures the ‘costly’ nature of acceleration and deceleration events. In contrast, the model suggests that in calm conditions overcoming air resistance presents a very minor contribution to the overall mechanical demand of running. Indeed, despite increasing with running velocity, at 10 $m \cdot s^{-1}$, D_{air} accounts for less than 10% of D_{total} (Figure 4), which is also consistent with previous research (di Prampero, 1986; Pugh, 1971; Ward Smith, 1984).

Limitations

The model proposed herein and its applications are based on the following assumptions:

1) The vertical displacement of the COM, stride frequency and duty factor are predicted from forward velocity according to equations 3, 4 and 5. Firstly, these relationships have been derived from constant velocity overground running in sub-elite athletes (Gray, et al., In Press; Lee & Farley, 1998). Pavei et al. (2019) report stride frequency and duty factor during maximal 20 m sprints in a laboratory setting, showing stride frequency is almost constant at ~2 Hz throughout the accelerated running bout; whilst duty factor quickly declined from ~0.38 to plateau at ~ 0.2 after ~10 m. Applying these values to the first 3 seconds of the 40 m sprint data in this study (to evaluate the error introduced by applying constant speed kinematics to accelerated running) resulted in a mean change in P_{total} of 1.3%, however this was the net effect of up to ~8% underestimation in the initial stages of the sprint and up to ~10% overestimation in the latter stages. To the authors knowledge, no data exists that allows for similar comparisons during deceleration and/or change of direction, as such the magnitude of error introduced for these running patterns is unknown. Secondly, effects of fatigue (Brueckner et al., 1991), size (Saibene & Minetti, 2003), running surface (Lejune, Willems & Heglund, 1998), running ability (Paradisis et al., 2019) and other contextual factors on these kinematic variables are not taken into consideration. With improvements in wearable technology, direct measurement of these variables may replace these prediction equations, however until such time, this serves as a first approximation.

2) Vertical work done by the COM is determined, on the understanding that the COM rises and falls to the same height in a step. Studies suggest this is a simplification of the ‘true’ trajectory of the COM during running (Cavagna, 2006; Ito et al., 1983; Lee & Farley, 1998). Furthermore, the

model assumes the runner's sagittal plane is always vertical, such that the oscillation of the COM can be quantified by changes in PE. This assumption, does not consider the observation that runner's lean (change the orientation of the sagittal plane) during 'bend running' and markedly lower their COM during more abrupt changes of running direction. Movement in the coronal plane is assumed to be negligible and given that GPS receivers have insufficient resolution to detect within-stride fluctuations in forward velocity, the positive and negative work associated with the propulsive and braking forces during stance are also negated. These assumptions appear to result in overestimations, based on comparisons with recent experimental works (Pavei et al., 2019), however it is not possible to quantify the magnitude of error this introduces based on current literature.

3) Mechanical internal work was predicted using the prediction equation of Minetti (1998), which is based on several assumptions itself, namely the four limbs are straight segments with constant inertial properties at all running speeds. This is clearly a simplification of the 'true' limb structure and human gait and it may have led to an overestimation of the mechanical demand of swinging the limbs. The equation has proven a robust alternative to direct measurement during constant speed (Nardello et al., 2011) and short sprint running (Pavei et al., 2019). However, during accelerated running where limb configurations are changing on a step-by-step basis (Nagahara, Matsubayashi, Matsuo & Zushi, 2014; Pavei et al., 2019), the compound factor 'q' decays exponentially from ~0.22 to reach an asymptote of ~0.1 (as in constant speed running). Where q is appropriately defined, it seems this prediction equation provides values within 1 $W \cdot kg^{-1}$ of gold standard measures (Pavei et al., 2019), however more work is needed to describe how q varies

during deceleration and change of direction at varied intensities. Until these data are available it seems reasonable to fix q between 0.1 and 0.2 for intermittent running bouts.

4) The model is presently described to apply to an environmental state where there is strictly ‘no wind’ (equation 11). As such the additional mechanical demand of overcoming a head-wind (added resistive force) or reduced mechanical demand in the presence of a tail-wind is not considered. Where wind direction and speed are able to be measured, equation 11 can be modified to accommodate these effects. Using the participant characteristics in this analysis, a 5 $m \cdot s^{-1}$ head wind when running at 10 $m \cdot s^{-1}$ increases mechanical power by 1.37 $W \cdot kg^{-1}$, reducing to just 0.15 $W \cdot kg^{-1}$ when running at 3 $m \cdot s^{-1}$. The practical significance of this assumption is therefore context specific.

5) The mechanical work done to ventilate, circulate blood and other functions within the trunk and limbs is not accounted for, which is often the case in biomechanical modelling.

Practical Implications

Gray et al. (2018) recently proposed temporal classification of movement events e.g. walking bouts, running bouts, contact events etc. and subsequent energy-based quantification of these movement events in field-based games. The model presented and evaluated is proposed as a method to quantify the mechanical demands of identified running events. The present analyses have demonstrated how the model serves to account for the demands of constant low- and high-speed running events, acceleration events and deceleration events, so that applied researchers and practitioners understand how global load metrics such as mechanical work done ($J \cdot kg^{-1}$) in a running based session may be derived; in this case, from the well described relationships between running velocity and running kinematics (Gray et al., In Press; Pavei et al., 2019; Saibene & Minetti, 2003).

Users applying the model must remain cognisant of the assumptions outlined previously. The authors readily acknowledge these limitations and consider the model to provide reasonable estimates of mechanical demand and power outside a laboratory setting. Work estimates produced by the model are also subject to the quality of velocity-time data from which it is based. As such users, must also familiarise themselves with the validity and reliability of commercial GPS receivers and data collection factors that impact data quality (Scott, Scott & Kelly, 2016). Furthermore, general application of the model to entire GPS field-sport match files is not appropriate, as the model assumes forward running is the only gait adopted. Separate models should be used to discretely evaluate other gaits and match events (Gray et al., 2018).

Given the proposed application of the model, and the low mechanical demand attributable to air resistance during running (Pugh, 1971, 1976), the importance of including air resistance as a load during team-sport training and competition, is questionable. Particularly, as players spend a majority of time during team sport match play at low speeds (i.e. $< 3\ m \cdot s^{-1}$) (Bangsbo et al., 2006; Duthie et al., 2003; Gray & Jenkins, 2010), where air resistance is negligible (Figure 2). As such the authors note that whilst the inclusion of W_{air} provides a more complete description, its inclusion in applied practice may not be necessitated. Indeed, others readily omit this component (di Prampero, Botter & Osgnach, 2015) to simplify the analysis.

Conclusions

This study presents a new approach to quantify the mechanical demands of intermittent running, as measured using GPS technology. The running model presented and evaluated is proposed as part of a broader energy-based solution to the quantification of field sport match demands via micro-technology (Gray et al., 2018). The model uses established relationships between forward running velocity and running kinematics to model the work done during a running bout. Whilst this is based on several assumptions, the model provides reasonable approximations of mechanical demand and power, that are responsive to varied running patterns, as evidenced in this analysis. The present model may be considered an initial step toward achieving an optimal energy-based method of quantifying load through micro-technology. Indeed, many attributes of this model could be refined and improved upon through direct measurement rather than prediction e.g. stride frequency, and/or experimental work to improve various components e.g. W_{limbs}. Modelled mechanical power during extended overground running may also open new avenues for research and possibly strengthen our understanding of running performance, just as power-based concepts have done for cycling (Shearman, Dwyer, Skiba & Townsend, 2016; Waldron, Gray, Furlan & Murphy, 2016).

Acknowledgments

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Declaration of Interest Statement

The authors report no conflict of interest

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Tables

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Figures

Figure 1.

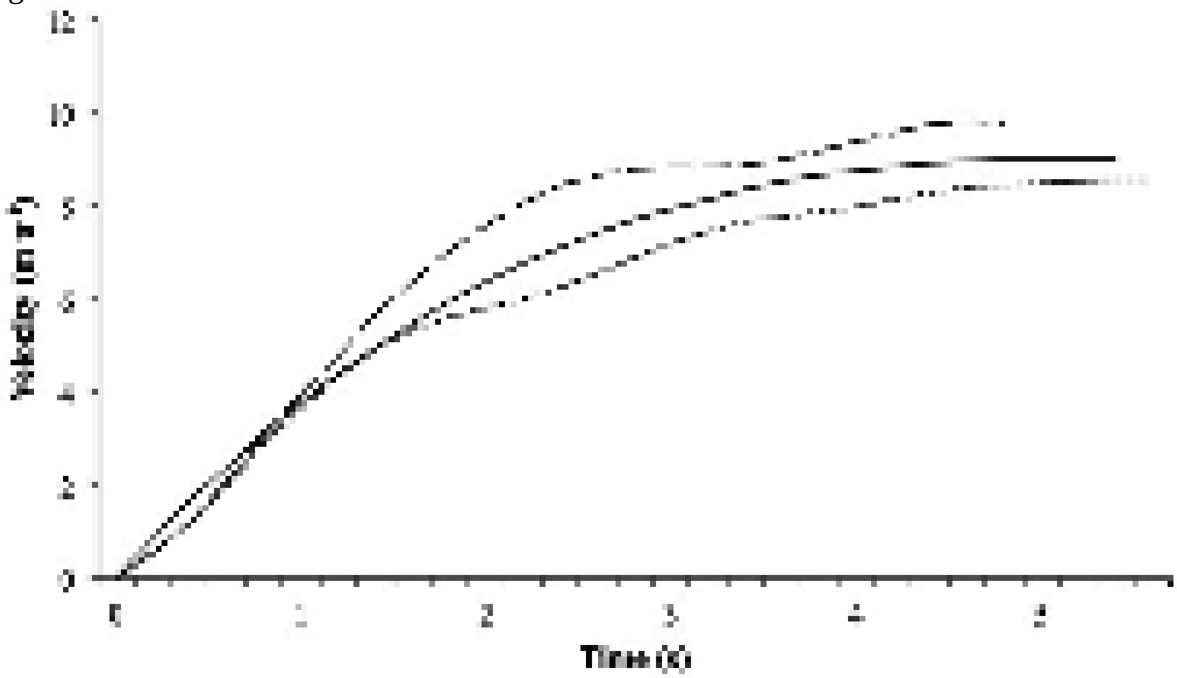
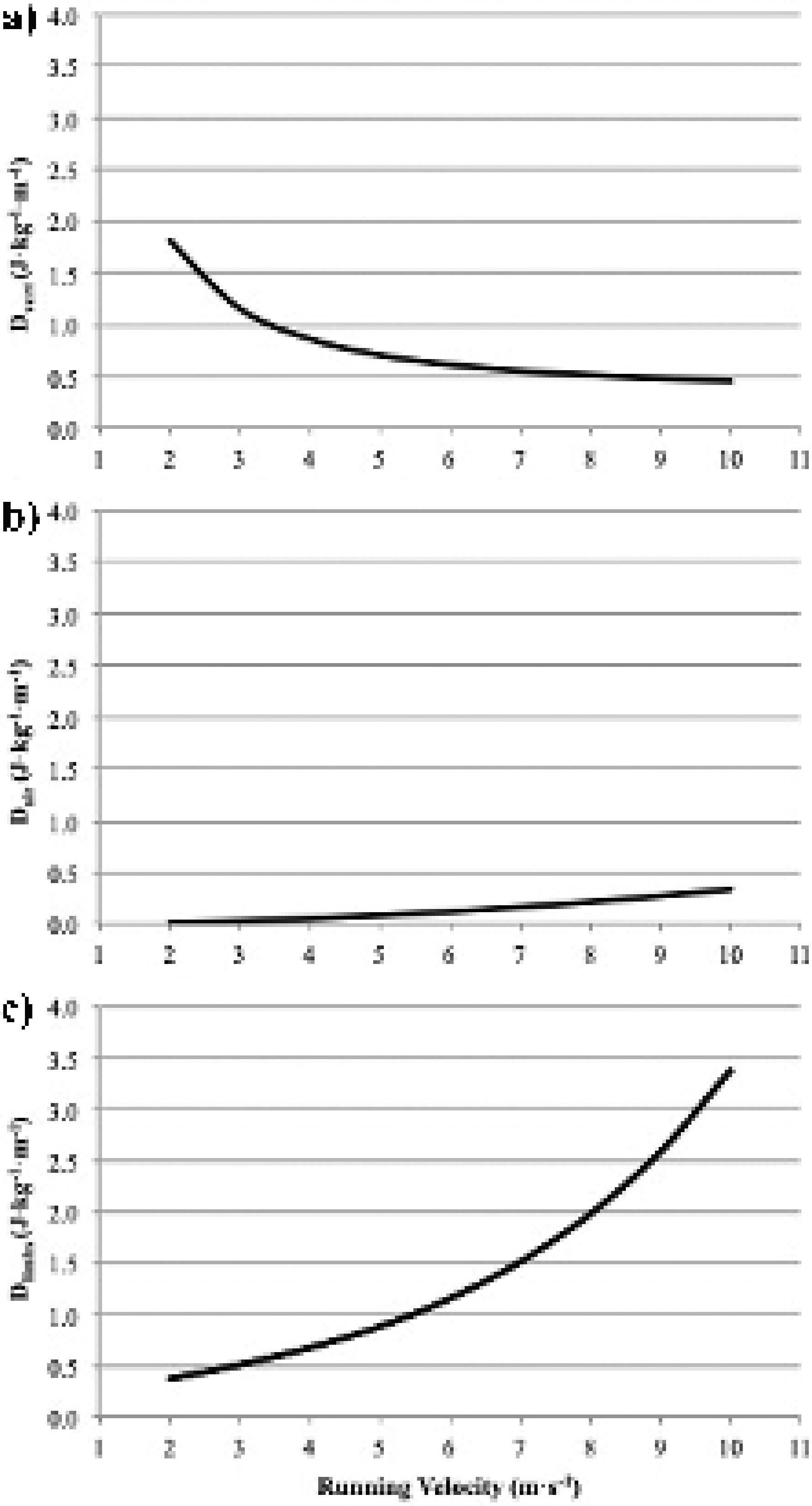


Figure 2.


a)
b)
c)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
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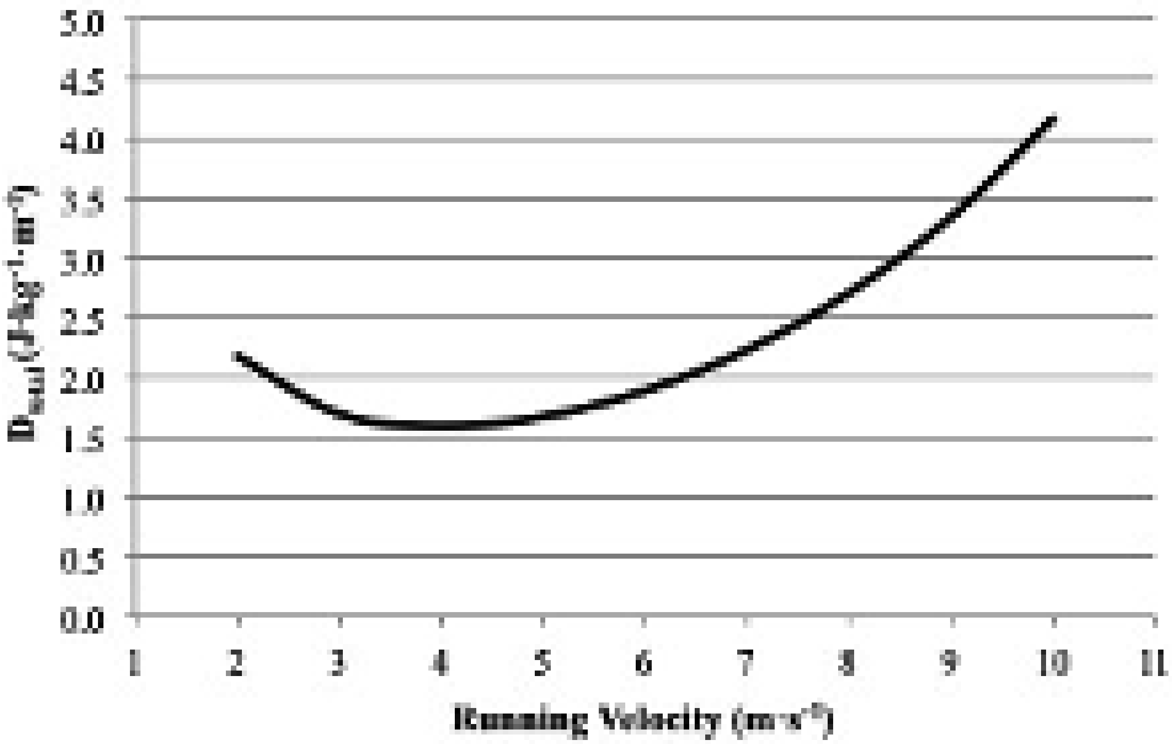
11
Running Velocity (m·s⁻¹)

Figure 3.



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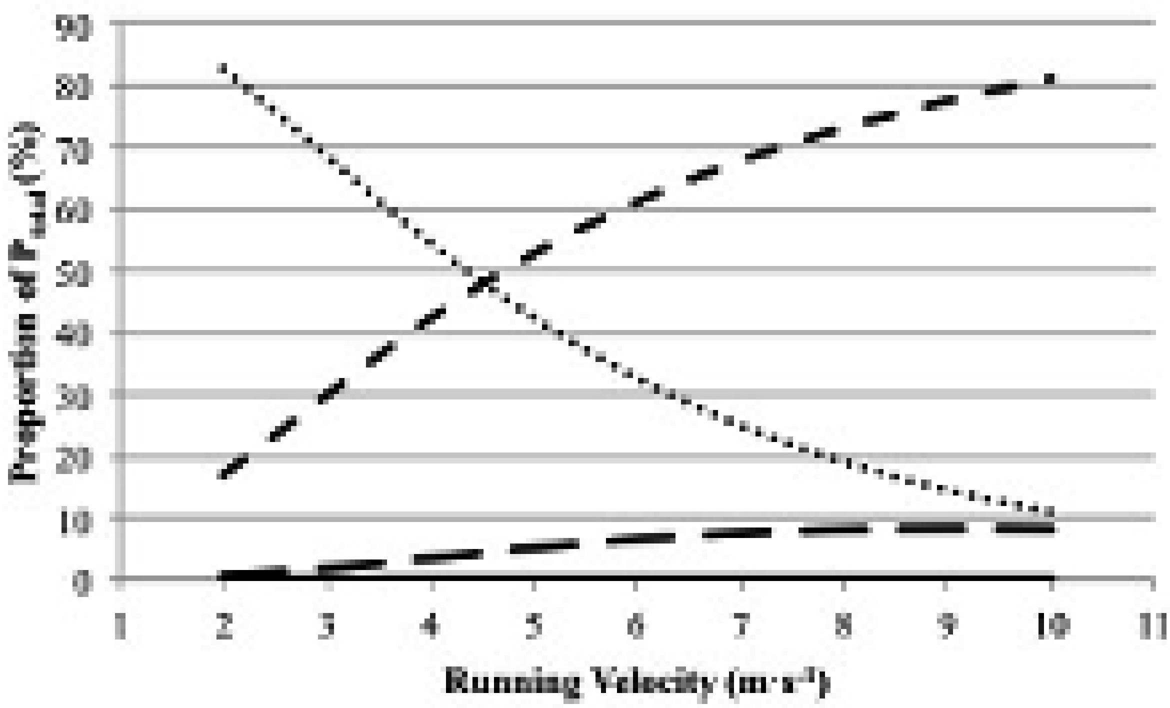

Figure 5.

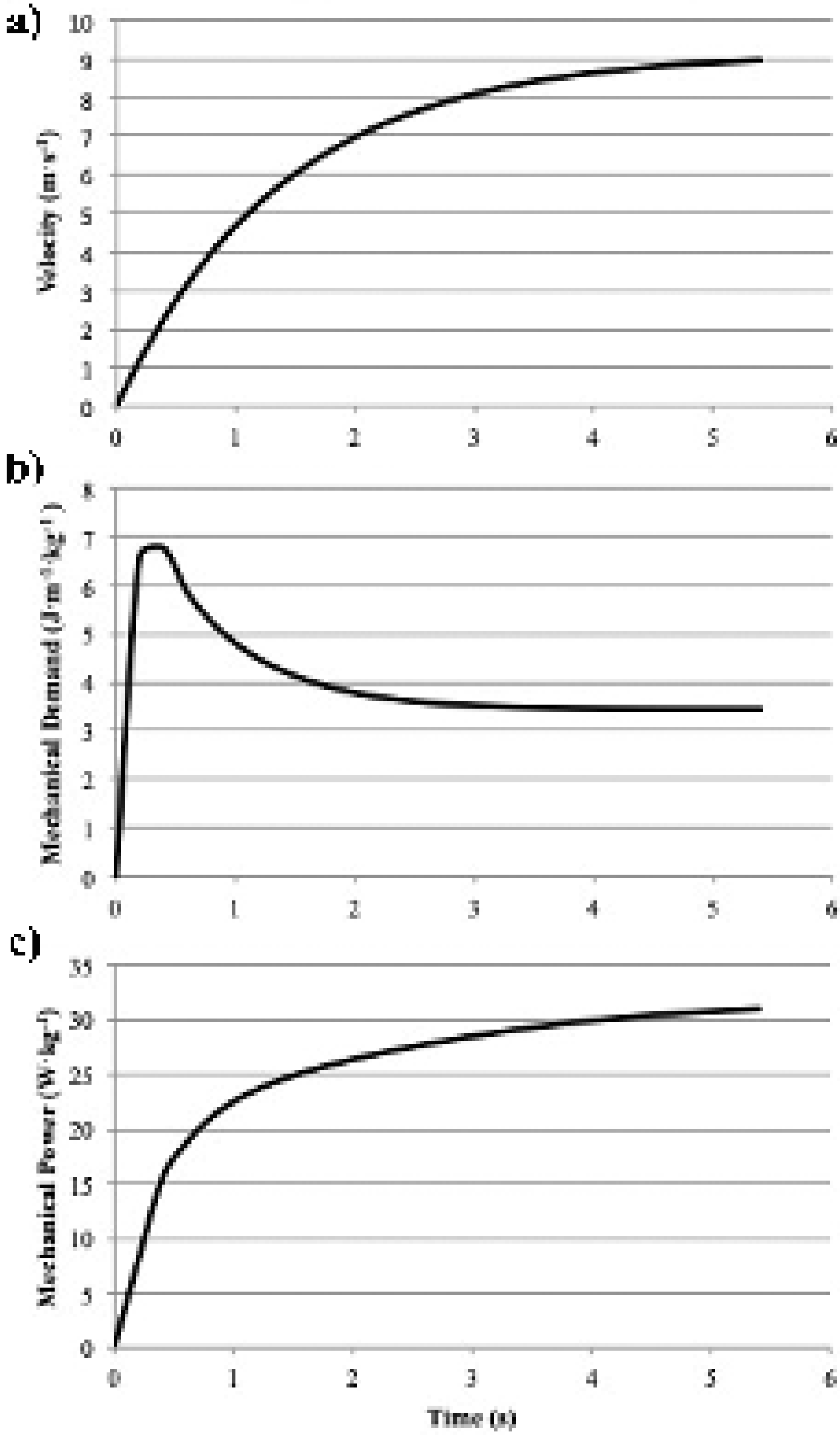
a)
Velocity (m·s⁻¹)
b)
Mechanical Demand (J·m⁻¹·kg⁻¹)
c)
Mechanical Power (W·kg⁻¹)
Time (s)

Figure 6.

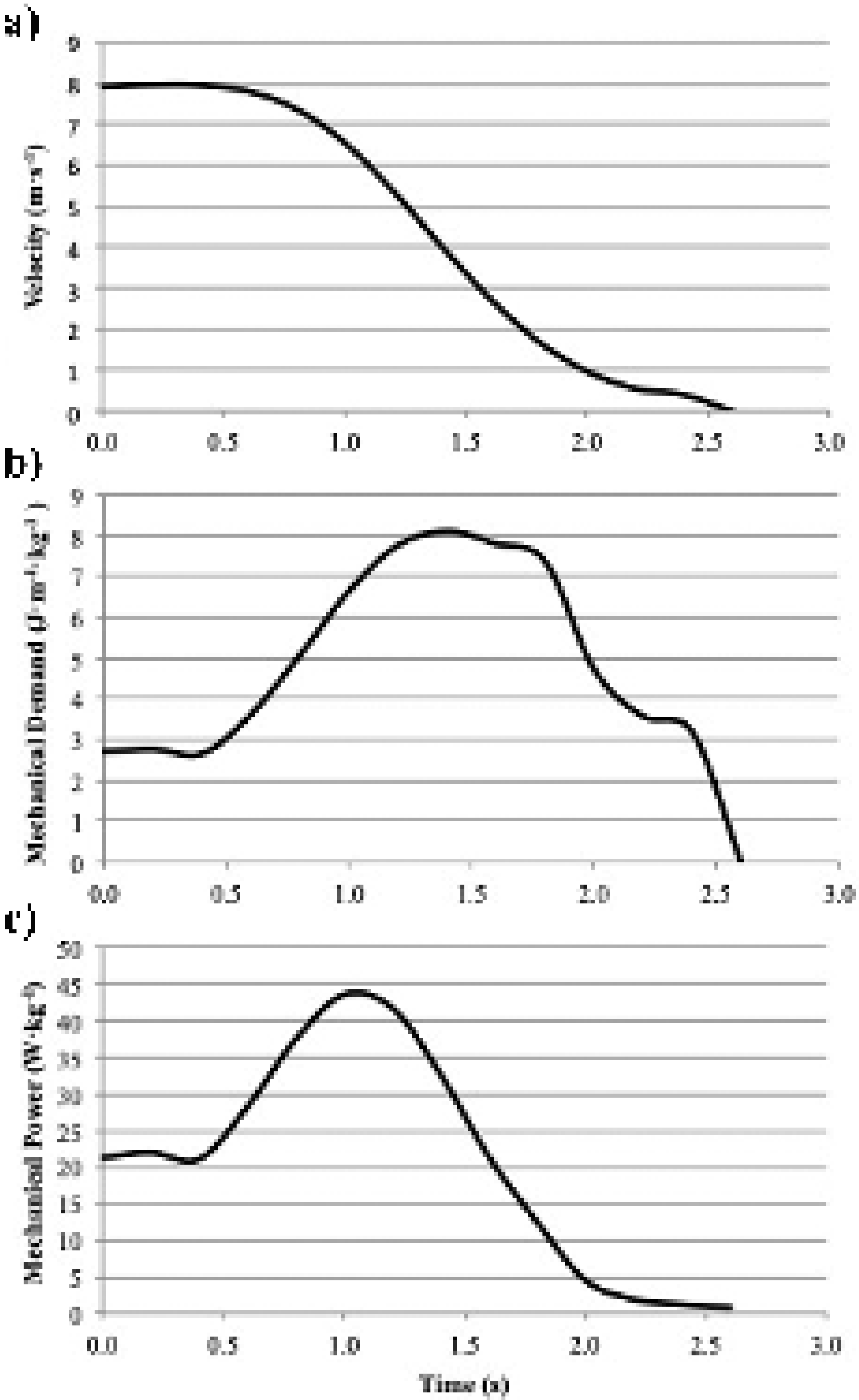
a)
Velocity (m·s-1)
0 1 2 3 4 5 6 7 8 9
0.0 0.5 1.0 1.5 2.0 2.5 3.0
b)
Mechanical Demand (J·m-1·kg-1)
0 1 2 3 4 5 6 7 8 9
0.0 0.5 1.0 1.5 2.0 2.5 3.0
c)
Mechanical Power (W·kg-1)
0 5 10 15 20 25 30 35 40 45 50
0.0 0.5 1.0 1.5 2.0 2.5 3.0
Time (s)

Figure 7.

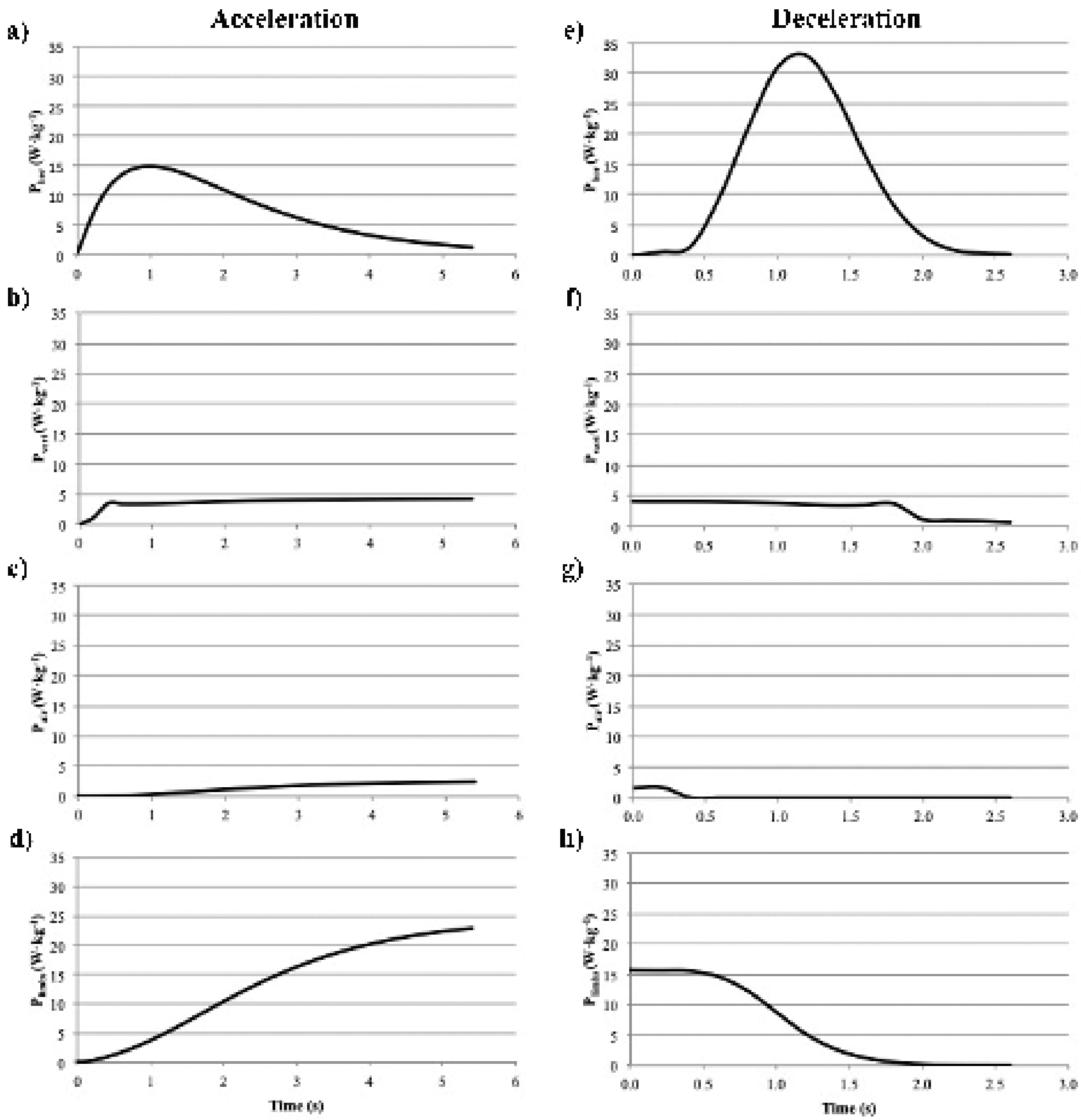

Figure Captions

Fig 1. Velocity curves from the fastest (long dashed line) and slowest (short dashed line) participants' 40 m sprints. The solid line is the exponential model $v_t = 9.16 \times \left(1\text{-}e^{\frac{-t}{1.4}}\right)$, which approximates the group's sprint performance, where *v* is in m·s^{-1} and *t* is in s.

Fig 2. The modelled mechanical demand (*D*) i.e. work done per unit distance to a) raise and lower the COM (D_{vert}^+ and D_{vert}^- combined); b) overcome air resistance; and c) swing the limbs during constant velocity, overground running. Note: As horizontal acceleration and deceleration are zero, no horizontal work is done; therefore, D_{hor}^+ and D_{hor}^- are not included.

Fig 3. The modelled total mechanical demand (D_{total}) i.e. work done per unit distance during constant velocity, overground running. This relationship is well described by the 4th order polynomial: $D_{total} = 0.0015v^4 – 0.0384v^3 + 0.4282v^2 – 1.975v + 4.7003$, where D_{total} is in J·kg^{-1}·m^{-1} and *v* is in m·s^{-1}.

Fig 4. The modelled relative contributions (%) of P_{hor} (solid line), P_{vert} (dotted line), P_{air} (long dashed line) and P_{limbs} (short dashed line) to P_{total} during constant velocity, overground running.

Fig 5. A kinematic and energetic description of a simulated 40 m sprint, including a) the velocity-time curve; b) the time-course of the modelled total mechanical demand (D_{total}); and c) the time-course of the modelled mechanical power (P_{total}) of the running bout.

Fig 6. A kinematic and energetic description of a hard, voluntary deceleration performed by Participant 6, including a) the velocity-time curve; b) the time-course of the modelled total mechanical demand (D_{total}); and c) the time-course of the modelled mechanical power (P_{total}) of the running bout.

Fig 7. The time-course of the mechanical power curves for P_{hor}, P_{vert}, P_{air} and P_{limbs} during the simulated 40 m sprint [panels a), b), c) and d), respectively]; and the hard, voluntary deceleration performed by Participant 6 [panels e), f), g) and h), respectively]. Note: the peak acceleration during the 40 m sprint was 5.7 $m \cdot s^{-2}$, whilst the peak deceleration by Participant 6 was -6.6 $m \cdot s^{-2}$.