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Are variations in running economy in humans associated with ground reaction force characteristics?

Accepted: 11 January 2001 / Published online: 15 March 2001 © Springer-Verlag 2001

Abstract It was hypothesized that certain ground reaction force (GRF) variables are positively correlated with running economy (RE; the aerobic demand at a single speed of running). Excessive momentum changes, quantified by linear impulse measures, as well the free moment applied to the running surface could be considered potentially wasteful efforts in terms of metabolic energy requirements. Recreational runners (n = 16) ran on a treadmill at 3.35 m s⁻¹ for physiological measurements and overground for biomechanical measurements. Correlation coefficients were calculated between RE and total vertical impulse (TVI), net impulses in three orthogonal directions, and descriptors of the free moment. The TVI and the net vertical impulse were the only GRF characteristics significantly correlated to RE (r = 0.62, r = 0.60, respectively). Greater overall muscle support requirements during ground contact, as represented by TVI, may have been responsible for greater aerobic demand.

Keywords Aerobic demand · Free moment · Impulse

Introduction

For a given aerobic activity, such as distance running, some individuals are more economical than others. Researchers have reported a 20%–30% range in the aerobic demand for a given submaximal running speed (i.e., running economy, RE, expressed in milliliters of oxygen per kilogram per minute) among age-, gender-, and performance-matched groups of trained distance runners (Conley and Krahenbuhl 1980; Daniels 1985; Morgan and Craib 1992). This inter-individual variability in RE has been the focus of exercise scientists from different disciplines such as biomechanics, exercise physiology, and sport psychology (for reviews of these areas see Anderson 1996; Crews 1992; Martin and Morgan 1992; Morgan and Craib 1992). Biomechanists have identified several variables describing structural characteristics and running mechanics which are related to RE (Martin and Morgan 1992; Williams and Cavanagh 1987); however, many of the relationships are weak and inconsistent from one study to the next regardless of the level of complexity used in the biomechanical models (Martin and Morgan 1992). For example, when several modeling schemes for calculating overall mechanical power output were examined, no single approach was found to be superior in explaining inter-individual variability in RE (Martin et al. 1993).

Fresh insight into the relationships between economy and biomechanics may come from the viewpoint of comparative biologists. Kram and Taylor (1990) examined the aerobic demand of running, hopping, and trotting in a variety of animal species ranging from 32-g kangaroo rats to 141-kg horses. They presented a simple inverse relationship between aerobic demand and stance time regardless of an animal’s size. Specifically, they suggested that “it is primarily the cost of supporting the animal’s weight and the time course of generating this force that determines the cost of running” (Kram and Taylor 1990, p 265).

During ground contact, a runner activates muscles for purposes of stability and for the maintenance of forward momentum. These functional and mechanical requirements during stance are reflected in the characteristics of the ground reaction force (GRF). Excessive changes in momentum produced by runners in the vertical, anterior-posterior and medial-lateral directions could be considered wasteful motions in terms of the metabolic energy requirements. Linear impulse, the time integral of a force, measures the change in momentum.
and quantifies the time course of the GRF. By quantifying the support requirements during ground contact and the potentially wasteful ground contact forces, the variability in RE among humans of comparable fitness levels could be better explained. In a comprehensive study of running mechanics and economy, Williams and Cavanagh (1987) included several GRF measures. A factor analysis applied to a large number of kinematic and kinetic measures yielded ten variables with high loadings for each factor. These included two impulse measures: the net impulse in the medial-lateral direction and the total vertical impulse (TVI).

Another representation of potentially wasteful motion during ground contact is the free moment (\(M_z\)). This characteristic has been described as “a force couple about a vertical axis (assuming a horizontal running surface) which results from shear forces between the foot and the ground” (Holden and Cavanagh 1991, p 887). Similar to excessive linear momentum produced during ground contact, the \(M_z\) may reflect unnecessary and uneconomical muscle forces produced during ground contact. It may explain, therefore, some of the intersubject variability in RE.

In the present study, it was hypothesized that less economical runners [i.e. those with a higher oxygen uptake (\(\dot{V}O_2\)) for a given speed of running] would exhibit greater support requirements during foot contact, as indicated by higher TVI values. It also was hypothesized that higher magnitudes of the net vertical impulse, absolute medial-lateral impulse (MLI), and \(M_z\) characteristics, would be associated with less economical running (i.e. higher aerobic demand).

### Methods

#### Subjects

A group of 16 men [mean age 27.3 (SD 4.8) years, mean body mass 75.0 (SD 8.3) kg, mean body height 178.7 (SD 7.4) cm] with recent 10-km run times between 38 and 45 min volunteered as subjects. All subjects participated in two test sessions. In the first, procedures were explained and informed consent was obtained from each subject. This experiment complied with current laws in the United States regarding the testing of human subjects.

#### Data collection

Running shoes were provided for each subject to standardize any possible influences related to footwear design. After a series of treadmill accommodation trials totaling 30 min and a brief rest, peak oxygen uptake (\(\dot{V}O_2peak\)) was determined using the open circuit method and a continuous running protocol. Treadmill speed initially was set at 2.69 m s\(^{-1}\) for 3 min of warm-up on the level. Speed was then increased to 3.14 m s\(^{-1}\) and kept constant for all the remaining stages. Every 2 min thereafter, the treadmill gradient was increased 2.5% until the subject signaled that he had reached exhaustion. The highest value attained for the final exercise intensity was considered as \(\dot{V}O_2peak\). This measurement was used for sample description purposes only.

The \(\dot{V}O_2\) data were measured using a VISTA on-line data acquisition system (Vacumed). Inspired ventilation was measured using a ventilation measurement module (VMM; Alpha Technologics) and converted to a rate function (liters per minute). The VMM was calibrated prior to each test using a 3-l calibration syringe (Calibringe). Expired gas was sampled continuously from a mixing chamber, passed through a drying tube, and analyzed for carbon dioxide and oxygen concentration using an Applied Electrochemistry analyzer (model CD-3A) and a Beckman analyzer (model OM-11), respectively. The gas analyzers were calibrated before and after each test using certified commercial gas preparations.

During the second session, subjects completed a 5-min warm-up run followed by a 5-min rest and a 6-min run at 3.35 m s\(^{-1}\) on the treadmill. The \(\dot{V}O_2\) data were measured continuously during the 6 min run using the VISTA system described previously. The average of four 30 s measurements over the final 2 min was taken as the subject’s RE, which was normalized to body mass (milliliters per kilogram per minute).

Each subject then completed overground running trials across a force platform (Advanced Mechanical Technology, Inc., Watertown, Mass., USA) positioned in the middle of a 15-m runway. Speed was monitored using two photocells spaced approximately 3 m apart, the first of which triggered a timer and collection of force platform data immediately before the subject contacted the force platform and the second which stopped the timer. Force platform sampling was performed using a 12-bit A-D converter at 480 Hz for 0.65 s ensuring that the entire contact phase was recorded. Acceptable trials were those in which average speed was within \(\pm 3\%\) of the criterion speed, and there was no visible indication of stride modification within the measurement zone. Measurements collected from the force platform included the medial-lateral (\(F_{ml}\)), the anterior-posterior (\(F_{ap}\)), and the vertical (\(F_z\)) components of the GRF and the moments about the same axes (\(M_{ml}, M_{ap}, M_z\)).

#### Data analysis

Five successful right foot contacts were chosen for analysis for each subject. Zero offset values were calculated when the force platform was unloaded and each sampled channel was adjusted by its respective offset. After force and moment values were scaled to N and N m, respectively, the data were treated using a low-pass digital filter (\(f_{cutoff} = 50\) Hz). Mean values of GRF dependent variables were then calculated.

The TVI was calculated as:

\[
TVI = \int_0^{t_c} \left\{ \frac{F_z}{BW} \right\} dt
\]

where \(BW\) is subject’s body weight, and \(t_c\) is the time of ground contact.

The net vertical impulse (NVI) was calculated as:

\[
NVI = \int_0^{t_c} \left\{ \frac{F_z - BW}{BW} \right\} dt
\]

Impulses in the anterior-posterior (API) and medial-lateral (MLI) directions were calculated as absolute impulses because both \(F_{ap}\) and \(F_{ml}\) display positive and negative values.

\[
API = \int_0^{t_c} \left\{ \frac{F_{ap}}{BW} \right\} dt
\]

\[
MLI = \int_0^{t_c} \left\{ \frac{F_{ml}}{BW} \right\} dt
\]

The unit of measurement for all impulse variables was BW ms.

The \(M_z\) was calculated for the duration of ground contact as follows:

\[
M_z = M_x - (F_{ml} \times a_{ap}) + (F_{ap} \times a_{ml})
\]

where \(a_{ap}\) and \(a_{ml}\) are moment arms, with respect to the axis system of the force platform, of the medial-lateral and anterior-posterior GRF, respectively. Maximal and minimal values of the \(M_z\) applied