Gait & Posture 30 (2009) 71–75

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Measurements of vertical displacement in running, a methodological comparison

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A R T I C L E I N F O

Article history:
Received 1 July 2008
Received in revised form 6 November 2008
Accepted 4 March 2009

Keywords:
Vertical displacement
Treadmill running
Running economy

A B S T R A C T

The aim was (1) to evaluate measurements of vertical displacements (V_{disp}) of a single point on sacrum as an estimate of the whole body centre of mass (CoM) V_{disp} during treadmill running and (2) to compare three methods for measuring this single point. These methods were based on a position transducer (PT), accelerometers (AMs) and an optoelectronic motion capture system. Criterion method was V_{disp} of the whole body CoM measured with the motion capture system. Thirteen subjects ran at 10, 12, 14, 16, 18, 20 and 22 km h^{-1} with synchronous recordings with the three methods. Four measurements of the (V_{disp}) were derived: (1) V_{disp} of CoM calculated from a segment model consisting of 13 segments tracked with 36 reflective markers, (2) V_{disp} of the sacrum recorded with the PT, (3) V_{disp} of the sacrum calculated from the AM, and (4) V_{disp} of the sacrum calculated as the mid point of two reflective markers (sacrum marker, SM) attached at the level of the sacral bone. The systematic discrepancy between the measurements of sacrum V_{disp} and CoM V_{disp} varied between 0 and 1.5 mm and decreased with increasing running velocity and decreasing step duration. PT and SM measurements showed strong correlation, whereas the AM showed a variability increasing with velocity. The random discrepancy within each subject was 7 mm for all three methods. In conclusion single-point recordings of the sacrum V_{disp} may be used to monitor changes in V_{disp} of CoM during treadmill running.

1. Introduction

Running economy (RE) is defined as total oxygen consumption in mL kg^{-1} min^{-1} during running at a given submaximal, steady state velocity [1]. Factors influencing running economy may be of physiological [2] and biomechanical [3] origin and is related to training adaptations [4]. Further investigations are needed to explain the effect of each sub-factor on RE. These effects appear to be both complex and individual [5]. It seems plausible, that all movements diverging from the running direction will affect the RE negatively, especially so in exaggerated vertical displacement (V_{disp}) of the centre of mass (CoM). Thorstensson et al. [6] showed that movements in the medio-lateral directions are smaller than in the vertical direction and probably have less influence on the RE. Williams and Cavanagh [7], reported that elite distance runners exhibited a somewhat lower (not significantly) V_{disp} compared to non-elite distance runners. Heise and Martin [8] found that total vertical force impulse correlate negatively with RE. The vertical impulse is proportional to the change in vertical velocity of CoM, and hence directly related to the V_{disp} of the CoM. The V_{disp} causes a demand in mechanical power, $P_v = \mathrm{sf}\cdot m\cdot g\cdot V_{disp}$, where sf is the step frequency, m is the mass of the body, and g is the gravitational acceleration. This is the power required to lift the CoM a distance V_{disp} at a certain rate. Part of this power may come from the release of potential energy stored in elastic components of the body (and shoes) [3,4]. In running there are energy transfers occurring in each cycle between kinetic and potential energy, both in the form of CoM height and stretched or compressed elastic components. The actual amount of energy that is dissipated during these transfers (and that hence must be compensated by work of the muscles) is not fully known. However, if we assume that the amount of energy dissipated correlates positively with the actual fluctuation of potential energy, it makes sense to focus on the V_{disp} of CoM as relevant for RE. As a numeric example, a reduction of V_{disp} with 1 cm at a step frequency of 200 min^{-1} reduces the mechanical power by 22 W and may improve RE with some -0.3 L min^{-1} for a person with a body mass of 67.3 kg. Consequently, methods to measure V_{disp} accurately and in a simple manner is relevant, in order to analyse and monitor P_v and relate this to RE.

In the case of level walking, measuring the V_{disp} of a single point on the sacrum has been shown to perform equally well as

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doi:10.1016/j.gaitpost.2009.03.001

a measure of CoM V_{disp} as more complex methods involving whole body motion capture or the integration of the ground reaction force [9]. Consequently, we wanted to evaluate the accuracy of single point measurements in running. We decided to use accelerometers (AMs), position transducer (PT) and photogrammetry (sacrum marker, SM) as simple and practical methods for measuring V_{disp} of the single point.

Accelerometers have shown to be useful in sports science as they are precise, reliable, small and relatively cheap. As such, they have become a widespread tool in ambulatory measurement systems [10,11]. A general problem with AMs is the low-frequency error, causing integration of AM data to be invalid very soon. This problem becomes less of an issue when studying cyclic motions, such as running, since the computation can be restarted at each iteration. For our purposes it is appealing to use an AM as a very unobtrusive mean to measure running economy inside as well as outside the laboratory, similar to the system presented by Wixted et al. [12].

The PT considered is a simple draw wire device that generates a signal proportional to the drawn length of the wire. By positioning the PT above the treadmill and attaching the wire to the runner, an obtainable direct measurement of the V_{disp} is given.

There were two aims of this study: to investigate the validity of sacrum V_{disp} as a measure of CoM V_{disp}, and to compare three methods for measuring sacrum V_{disp} (PT, AM, SM). The whole body CoM measured and calculated by means of a motion capture system and 36 reflective markers was taken as the criterion method. This method in itself is approximative and contains important simplifications. Our assumption is that the error caused by ignoring the contribution of legs and arms to the V_{disp} in the single point methods dominates over the errors in the criterion method.

2. Methods

2.1. Subjects

Thirteen males, trained in running participated in the study (Table 1). The group represents a number of different sports and each subject had to be comfortable with running speeds up to 22 km h^{-1}. A written informed consent was obtained after information of purposes and potential risks of the investigation. The study was approved by the regional Ethics committee of Karolinska Institute and performed according to the Helsinki declaration. All participants were accustomed to treadmill running.

Table 1
Basic data about the subjects.

Subject no.	Age (years)	Height (cm)	Weight (kg)	Sport	Level
1	26	185	72.0	Running	National
2	23	188	72.5	Running	District
3	23	181	67.3	Running	National
4	22	183	68.0	Orienteering	National
5	20	186	79.4	Soccer	District
6	24	179	69.9	Orienteering	International
7	25	185	75.1	Orienteering	International
8	25	169	58.7	Orienteering	International
9	20	170	64.5	Orienteering	District
10	24	181	90.8	Decathlon	National
11	21	178	72.9	Soccer	District
12	20	178	70.1	Soccer	District
13	22	180	65.0	Running	National

Running refers to mid- and long-distance running.

2.2. Instrumentation

2.2.1. Optoelectronic motion capture system

An optoelectronic 3D motion analysis system with eight infrared cameras (ProReflex MCU1000 System, Qualisys AB, Gothenburg, Sweden), operating at 150 Hz, was used to collect trajectories of spherical reflective markers (12 mm diameter). The cameras, having a field of view of 43° horizontally and 33° vertically, were mounted on brackets secured to the wall or ceiling in the setup, in average 2.4 m (2.1–2.6 m) above the running surface. The system calibration, performed according to the manufacturer's manual and with a 0.750 m wand, displayed a wand length standard deviation of 0.64 mm within the measurement volume (approximately 11.2 m × 7.0 m × 2.4 m). A single PC was used to synchronously record data from the infrared cameras and from the two analog sources (AM and PT). The analog data were acquired at 1500 Hz through an A/D convertor with 16-bit resolution.

2.2.2. Position transducer

A position transducer (Mod. 1850-050, HIS-Houston Scientific International Inc., Houston, US) was mounted 2.5 m above the running surface. It is equipped with a variable electrical resistor and a thin inextensible wire connected to the axis of the resistor, allowing the voltage output to vary proportionally to the change in wire length. To measure V_{disp} the spring-loaded wire of the PT was connected to the back of the strap around the subjects' waist (Fig. 1b). The strap was tightened just below crista iliaca anterior superior and was secured with surgical tape. Calibration of the PT was done in a separate experiment using the optoelectronic system and a single reflective marker at the end of the wire and with a measuring tape.

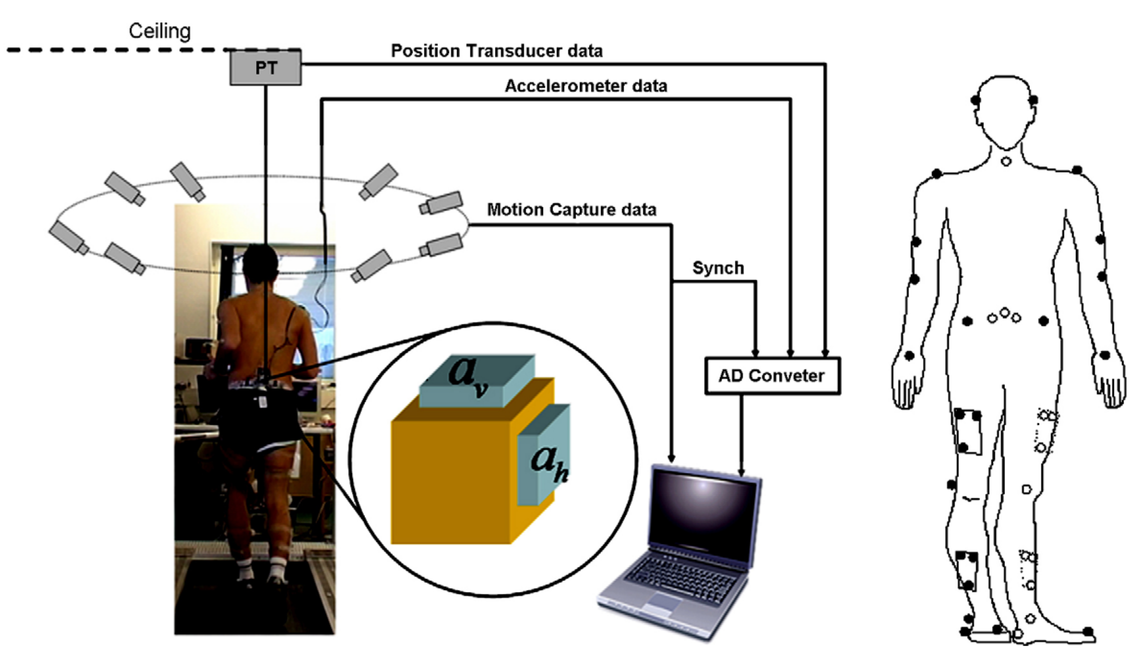

Fig. 1. (a) Experimental setup showing placement of accelerometers, position transducer, endpoint of position transducer wire, motion capture system and (b) placement of the 36 reflective markers for the motion capture. Filled circles indicate visible markers, open circles indicate markers on the back side of the body or segment.