Medical Engineering and Physics 37 (2015) 892–897

Contents lists available at ScienceDirect

Medical Engineering and Physics

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

Technical note

Design and testing of a high-speed treadmill to measure ground reaction forces at the limit of human gait

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ARTICLE INFO

Article history:
Received 16 October 2014
Revised 27 January 2015
Accepted 25 April 2015

Keywords:
Instrumented treadmill
Human gait
Sprint running

ABSTRACT

Investigations focused on the gait and physiological limits of human speed have been on-going for more than a century. However, due to measurement limitation a kinetic understanding of the foot-ground collision and how these dynamics differ between individuals to confer speed and limit gait has only recently begun to come forth. Therefore, we designed and tested an instrumented high-speed force treadmill to measure the forces occurring at the limits of human performance. The treadmill was designed to maximize flexural stiffness and natural frequency by using a honeycomb sandwich panel as the bed surface and a flexible drive shaft between the drive roller and servo motor to reduce the mass of the supported elements which contribute to the system's response frequency. The functional performance of the force treadmill met or exceeded the measurement criteria established for ideal force plates: high natural frequency (z-axis = 113 Hz), low crosstalk between components of the force ($F_x/F_z = 0.0020$[SD = 0.0010]; $F_y/F_z = 0.0016$[SD = 0.0003]), a linear response ($R^2 > 0.999$) for loading with known weights (range: 44–3857 N), and an accuracy of 2.5[SD = 1.7] mm and 2.8[SD = 1.5] mm in the x and y-axes, respectively, for the point of force application. In dynamic testing at running speeds up to 10 m s^{-1}, the measured durations and magnitudes of force application were similar between the treadmill and over-ground running using a force platform. This design provides a precise instrumented treadmill capable of recording multi-axis ground reaction forces applied during the foot ground contacts of the fastest men and animals known to science.

1. Introduction

The use of instrumented treadmills to measure the ground reaction forces produced during the foot ground contacts of human walkers and runners has become wide spread in both clinical and scientific settings. These devices substantially enhance both the quality and quantity of kinetic data obtained from the assessment of steady-speed walking and running by reducing the variability of within stride parameters and by substantially reducing subject time commitments and the research personnel effort compared to the use of in-ground force platforms. Because the patterns of force application and the timing of foot ground collisions vary between walking and running, treadmills designed to study the different gaits require separate engineering solutions [e.g. 1,2]. Similarly, during high-speed running the brevity of the foot-strike and the magnitude of the forces applied also require distinct engineering considerations. As a result, multi-axis ground reaction force data, from high speed treadmill running has, at present, come forth from only one laboratory [3]. One other group [4] and the study reporting the fastest speed yet observed [11.1 m s^{-1}; 5] have reported the vertical waveforms during treadmill sprinting at speeds greater than 8.0 m s^{-1}. The response characteristics and mechanical properties of these instruments have not been described in the literature. Here, we provide the design and testing of a custom, instrumented, force treadmill that is capable of measuring the forces applied in the vertical and horizontal axes and of achieving belt speeds that are faster than the current human speed record; currently 12.3 m s^{-1} [6].

Studies focused on the gait mechanics used during high-speed running have observed foot ground contacts as brief as 0.080 s [7] and peak ground reaction forces up to 5 times the individual's body weight [3], corresponding to roughly 4000 N. These durations and forces are essentially one-third as brief and 100% greater, respectively, than those observed at the lesser running speeds that are typically used while studying human gait [e.g. 1,2,8,9]. Due to the substantial impulses, a high system fundamental frequency is needed in order to faithfully transmit the applied forces to the force transducers. The most rapid events within the ground reaction force waveform occur with an interval of 0.020 s, and these waveforms can be adequately reproduced ($R^2 > 0.99$) by a Fourier series incorporating terms up to

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http://dx.doi.org/10.1016/j.medengphy.2015.04.009
1350-4533/

75 Hz [5]. Generally, the natural frequency of a suspended structure such as a treadmill bed is enhanced by minimizing the mass of the supported material and by augmenting its intrinsic stiffness (Eq. (1)). A potential design strategy therefore, would be to reduce the dimensions of the supported surface, however, in order to test runners at the limits of human speed, the treadmill bed must be at least 1.7 m in length to accommodate the displacement of the foot during ground contact [10].

Existing instrumented force treadmills have been created by installing force platforms within the bed surface [11], mounting commercial or custom treadmills on top of in-ground force platforms [1,12,13] or force transducers [4,14,15,16,17], or have used proprietary techniques [3,5]. Force treadmills with an internal force platform are able to measure the vertical component of the ground reaction force only. Whereas, designs using the mount-on-top solution are able to detect the forces applied in multiple axes, because the internal frictional forces within the device cancel, only the forces applied by the leg contribute to the sum of forces that are measured by the transducers [17]. However, this design requires the mass of the entire apparatus to be supported by the transducers, otherwise an unknown amount of force may be dissipated through the non-instrumented support. In some designs the supported treadmill elements include a flywheel for belt-speed maintenance, the mass of which further reduces the response frequency of the system. On the basis of these findings and the recognition of the considerably more difficult instrumentation challenge present in a high speed application we excluded existing designs due to concerns of measurement capability.

Therefore, we modified the mount-on-top strategy, and used a sandwich structured composite with a honeycomb core to achieve high strength per unit weight for the bed surface, and reduced the mass of the supported treadmill elements by using a flexible drive shaft to prevent the servo motor's mass from contributing to the natural frequency of the system. In addition, we minimized system mass wherever possible in the design stage by using light weight components in the fabrication and drive system. We established as a target a fundamental frequency of 90 Hz, thereby providing a small margin of error in order to ensure the actual fundamental frequency exceeded the 75 Hz minimum [5] required for the system to faithfully transmit the applied dynamic forces to the load cells for direct measure. We evaluated the functional performance of the treadmill in accordance with the objective measurement criteria established previously [18,19] for ideal force plates namely, low crosstalk between the measured components of the force and a linear response with sufficient sensitivity over the range of anticipated dynamic forces. Finally, we evaluated the precision of the treadmill's ability to determine the point of force application across the bed's surface.

2. Materials and methods

2.1. Design

To achieve our goal of a 90 Hz natural frequency for the treadmill system, we undertook the following modeling procedure. We approximated the natural frequency in accordance with:

$$\text{Natural frequency (Hz)} = \frac{1}{2\pi}\sqrt{\frac{P}{\delta m}}, \quad (1)$$

where P is the maximum force we expected to observe during sprint running, δ is the vertical deflection resulting from P, and m is the mass of the supported equipment. We anticipated that peak ground reaction forces would remain less than 5000 N. These are roughly the forces that would allow a 100 kg runner to apply elite sprinter levels of peak force. This overestimates the likely observed forces because this body mass is roughly 25% greater than the typical elite level sprinter [20].

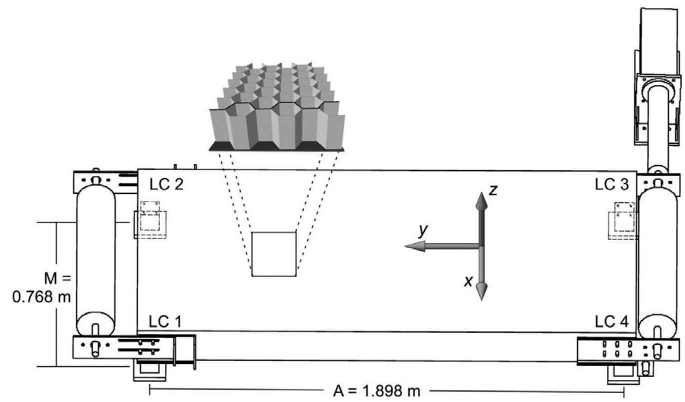

Fig. 1. A component diagram of the high-speed force treadmill and the locations of the load cells (LC). The *M* and *A* constants are used to determine the point of force application in accordance with Eqs. (3) and (4). The flexible line shaft connecting the motor to the rear axle permits the removal of the motor's mass from the elements contributing to the treadmill system's natural frequency. Inset illustrates the corrugated foil (black line), or ribbon, within the sandwich panel, this orientation produces a 2-fold higher stiffness in the *y* vs *x* axis. For clarity, the decking surrounding the treadmill and the safety harness worn by the subjects are not shown.

To estimate the vertical deflection under load we used simply-supported, centrally-loaded, beam theory equations designed for sandwich structures, as described by Hexcel [21]:

$$\delta = \frac{2k_b P l^3}{E_f t_f h^2 b} + \frac{k_s P l}{b h G_c} \quad (2)$$

where k_b is the beam-bending deflection coefficient ($k_b = \frac{1}{48}$), l is the length of the treadmill bed, k_s is the beam-shear deflection coefficient ($k_s = \frac{1}{4}$), E_f is the modulus of elasticity of the facing skin, h is the height of the honeycomb core, t_f is the thickness of the facing skin, b is the width of the treadmill bed, and G_c is the shear modulus of the core in the direction of the applied load. We selected a bed length of 2.00 m to provide 0.30 m of additional space for foot placement and be able to accommodate an expected 1.7 m of travel by the foot during ground contacts at speeds approaching the current human limit [6,10].

We used an iterative optimization approach that maximized vertical stiffness to determine the internal properties of the honeycomb panel. Finite element analysis (Autodesk Inventor, CA, USA) provided estimates of the response of the honeycomb laminate to loading by a virtual model that matched the dimensions of the human forefoot (63 mm × 77 mm). An aluminum (alloy 3003) honeycomb core with 6.35 mm cell sizes, and a density of 83.3 kg m^{-3}, permanently bonded to a 3.175 mm thick aluminum (alloy 5052) facing skin and loaded as above provided a compression safety factor of 3, and a single cell dimpling safety factor of 15. Increased distance between the facing skins acts to reduce the vertical deflection of a panel (Eq. (2)), however in North America non-custom orders of honeycomb are limited to the 15.24 cm height we used. Finally, within the plane of a honeycomb panel, the panel is 2-fold stiffer [21] in the axis parallel to the direction of the ribbons of material forming the core, here the ribbon direction is parallel to the *y*-axis (Fig. 1).

To further reduce the supported mass we used a flexible line shaft (R+W Coupling Technology, IL, USA—ZA 150) to remove the motor from the total supported mass of the bed system. The purpose of the coupling was to permit a rigid mounting of the motor to the floor and allow the instrumented bed to move independently, thus preventing the motor from dissipating loads applied to the bed. According to the manufacturer the load cells (AMTI, MC3A; MA, USA) have a stiffness of 3.0 × 10^{8} N m^{-1} providing an expected maximum deflection of 0.017 mm for the specifics of our assembly (Fig. 1); well within the 5.8 mm of misalignment tolerated by the line shaft without resistive forces.