Available online at www.sciencedirect.com
ScienceDirect
Gait & Posture 25 (2007) 40–48
GAIT & POSTURE
www.elsevier.com/locate/gaitpost

Froude number fractions to increase walking pattern dynamic similarities: Application to plantar pressure study in healthy subjects

P. Moretto [a,*], M. Bisiaux [a], M.A. Lafortune [b]

[a] *Laboratoire d'Etudes de la Motricité Humaine (EA 3608), Faculté des Sciences du Sport et de l'Education Physique, 59790 Ronchin, France*
[b] *Nike Sport Research Laboratory, Beaverton, OR, USA*

Received 20 July 2005; received in revised form 17 December 2005; accepted 22 December 2005

Abstract

The purpose of this study was to determine if using similar walking velocities obtained from fractions of the Froude number (N_{Fr}) and leg length can lead to kinematic and kinetic similarities and lower variability. Fifteen male subjects walked on a treadmill at 0.83 (VS_1) and 1.16 m s^{-1} (VS_2) and then at two similar velocities (V_{Sim27} and V_{Sim37}) determined from two fractions of the N_{Fr} (0.27 and 0.37) so that the average group velocity remained unchanged in both conditions ($VS_1 = \bar{V}_{Sim27}$ and $VS_2 = \bar{V}_{Sim37}$). N_{Fr} can theoretically be used to determine walking velocities proportional to leg lengths and to establish dynamic similarities between subjects. This study represents the first attempt at using this approach to examine plantar pressure. The ankle and knee joint angles were studied in the sagittal plane and the plantar pressure distribution was assessed with an in-shoe measurement device. The similarity ratios were computed from anthropometric parameters and plantar pressure peaks. Dynamically similar conditions caused a 25% reduction in leg joint angles variation and a 10% significant decrease in dimensionless pressure peak variability on average of five footprint locations. It also lead to heel and under-midfoot pressure peaks proportional to body mass and to an increase in the number of under-forefoot plantar pressure peaks proportional to body mass and/or leg length. The use of walking velocities derived from N_{Fr} allows kinematic and plantar pressure similarities between subjects to be observed and leads to a lower inter-subject variability.

In-shoe pressure measurements have proven to be valuable for the understanding of lower extremity function. Set walking velocities used for clinical assessment mask the effects of body size and individual gait mechanics. The anthropometric scaling of walking velocities (fraction of N_{Fr}) should improve identification of unique walking strategies and pathological foot functions.

Keywords: Walking; Froude number; Dynamic similarity; Joint angles; Plantar pressure

1. Introduction

Previous studies [1,2] reported inter-subject dynamic similarities during the transition from walking to running. The pendulum model was applied to set similar velocities between subjects (Fig. 1). The mass of the body at the centre of gravity (Cg) oscillates at the end of a rigid segment length L representing the leg [3,4]. At the time of a step, Cg of the subject describes an arc of a circle of radius L. At the linear velocity (V), Cg undergoes an acceleration ($\ddot{a}$) equal to V^2/L. When the leg is vertical, $\ddot{a}$ is directed upwards and perpendicular to the ground. This acceleration cannot be higher in intensity than gravitational acceleration (g) because the model would take-off. The take-off of the subject illustrates the disappearance of the double support phase and the transition from walking to running. The ratio (V^2/gL) enabled the authors to estimate a theoretical Froude

* Corresponding author at: Laboratoire d'Etudes de la Motricité Humaine (EA 3608), Faculté des Sciences du Sport et de l'Education Physique, 9, rue de l'Université, 59790 Ronchin, France. Tel.: +33 3 20 88 73 76; fax: +33 3 20 88 73 63.
E-mail address: pierre.moretto@univ-lille2.fr (P. Moretto).

0966-6362/$ – see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.gaitpost.2005.12.010

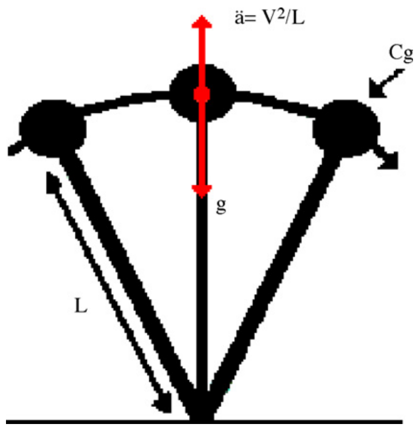

Fig. 1. Modeling of the transition between walking and running according to Alexander (1992). With $\ddot{a}$, acceleration; g, gravitational acceleration; Cg, centre of gravity; V, linear velocity; L, length of the leg.

number ($N_{Fr} = V/\sqrt{gL}$) equal to 1 [3,5] at the transition between walking and running.

Using Thorstensson and Roberthson's [6] experimental data, Alexander [2] and Donelan and Kram [7] estimated that this transition occurred at a N_{Fr} of approximately 0.6. Wagenaar and Beek [8] and Zatsiorsky et al. [9] went even further by saying that fractions of N_{Fr} below 1 can be used to determine similar walking velocities between different subjects. A recent review by Vaughan and O'Malley [10] presented studies which used the Froude number in naval architecture, for locomotion analysis and advancements in robotic science. From Alexander [5] to Zijlstra et al. [11], many studies have used the Froude number to differentiate between the effects of walking velocity and anthropometry.

However, many of these studies considered the Froude number (N_{Fr}) as the dimensionless walking speed and focussed on N_{Fr} as a means to normalise (set or spontaneously adopted) walking velocities. The use of the Froude number to determine similar dynamic conditions of walking has not been assessed.

Similar dynamic conditions suppose geometric similarities between different subjects. The first idea is to consider that two subjects are anthropometrically proportional. Two subjects (S_1 and S_2) being proportional, the ratios computed from the leg length (l_2/l_1) and body mass (m_2/m_1) are defined as k and k^3, respectively [9]. In a wider sense, these ratios defined the length (L) and mass (M) basic dimension ratios.

Under similar dynamic conditions, the determining of similar velocities from N_{Fr} enables us to establish a time ratio (λ). Velocity is distance divided by time. The ratio of velocities is therefore equal to $k\lambda^{-1}$. To express the ratio of similar velocities (V_{Sim1} and V_{Sim2}) of the same two subjects, the constant N_{Fr} and g (gravitational acceleration) must be simplified. The velocity ratio is therefore equal to the square root of leg length ratio (Eq. (1)):

$$\frac{V_{\mathrm{Sim2}}}{V_{\mathrm{Sim1}}} = \frac{N_{Fr}\sqrt{gl_2}}{N_{Fr}\sqrt{gl_1}} = \sqrt{\frac{l_2}{l_1}} = k^{0.5} \tag{1}$$

Determining similar velocities between subjects means determining a time scale which is dependent on the distance scale. As the ratio of velocities ($k\,\lambda^{-1}$) is equal to $k^{0.5}$, consequently, the time ratio (λ) is equal to $k^{0.5}$.

Under similar conditions, the ratios of the basic dimensions, length (L), mass (M) and time (T) are k, k^3 and $k^{0.5}$, respectively. All the kinematic and kinetic ratios can be determined as a combination of the ratios of the basic dimensions. For example, the product of similarity ratios corresponding to each of the physical dimensions involved in pressure ($\mathrm{ML^{-1}T^{-2}}$) expresses the pressure similarity ratio (Eq. (2)):

$$\mathrm{ML^{-1}T^{-2}} \Rightarrow k^3 k^{-1}(k^{0.5})^{-2} = k \tag{2}$$

Therefore, ratio "k" can be computed from the ratio of the pressure peaks (PP_1 and PP_2) of two different subjects (S_1 and S_2), i.e. $k = PP_2/PP_1$.

If the dynamic conditions associated with walking velocity are similar, then the kinematic and kinetic parameters should be proportional from one subject to another. An exception exists, as the angles cannot be directly expressed from basic dimensions and the trigonometric functions are necessary to establish the link between lengths and angles. However, the effect of dynamic similarities on angles can be developed thus.

According to the inverted pendulum model, linear velocity (V_{Sim}) of body mass at the centre of gravity swinging at the extremity of a leg of length (l) can be expressed in relation to the angular velocity (ω) (Eq. (3)). Angular velocity (ω) is the ratio of an angle (θ) and time (Δt):

$$V_{\mathrm{Sim}} = l\omega = l\theta\Delta t^{-1} \tag{3}$$

The ratio of similar velocities, V_{Sim1} and V_{Sim2}, of the two subjects, S_1 and S_2, is equal to $k^{0.5}$ and can be expressed in terms of leg lengths (l_2 and l_1), angles (θ_2 and θ_1) and times (Δt_1 and Δt_2) (Eq. (4)):

$$\frac{V_{\mathrm{Sim2}}}{V_{\mathrm{Sim1}}} = \frac{l_2\theta_2\Delta t_2^{-1}}{l_1\theta_1\Delta t_1^{-1}} = k\alpha k^{-0.5} = k^{0.5} \Rightarrow \alpha = 1 \tag{4}$$

Since the angle ratio (α) is equal to 1 if the angles θ_2 and θ_1 are identical (Eq. (4)), it follows that kinematic similarities should yield identical joint angles between one subject and another at "Similar" velocities.

Being normalised with respect to L, M, T dimensions, the peak of pressure (corresponding to a force ($\mathrm{kg\,m\,s^{-2}}$) distributed over a surface ($\mathrm{m^2}$)) can be expressed in a dimensionless form as: Dim(PP) = PP SL^2/mg (PP, peak of pressure (kPa); SL, step length (m); m, body mass (kg) and g, acceleration due to gravity ($\mathrm{m\,s^{-2}}$)). The dimension of Dim(PP) is 1 $\left(\frac{\mathrm{kg\,m\,s^{-2}}}{\mathrm{m^2}}\frac{\mathrm{m^2}}{\mathrm{kg\,m\,s^{-2}}}\right)$.

According to Stansfield et al. [12], the step length rather than leg length is used to introduce a 'velocity-dependent' parameter in the dimensionless expression of a pressure