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Froude and Strouhal dimensionless numbers to study human gait: An experimental approach.

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1 Introduction

Issued from fluid mechanics, the dimensionless approach enables characterizing a mechanical phenomenon while discarding the effects of size, thereby establishing similarity between systems of different sizes. The inverted pendulum model (IP) has often been used to model human walking. In this line, Alexander [1] introduced a dimensionless speed as the Froude number ($N_{fr} = v^2/gl$, with v , the forward velocity; g , the acceleration due to gravity and l , the rigid leg length). The bouncing mass (BM, fig 1.2) is preferred to model running and introduces an elastic component that captures the athletes ability to bounce and to jump (fig 1.2). Considering the link between the stiffness and the natural oscillation frequency, Alexander [1] also considered the Strouhal number ($Str = f_0l/v$, with f_0 the natural frequency) as a dimensionless frequency.

The π theorem, developed by Vaschy and Buckingham [2], enounced that a physical equation using N_P physical variables, which are dependant of N_D base dimensions, necessitates $N_P - N_D$ dimensionless numbers (π) to completely describe the mechanical phenomenon of a system. The BM model consists of a point mass oscillating at the end of a massless spring. Applying π theorem, five physical variables: gravity (g), frequency (f), initial spring length (l), mass (m) and stiffness (k) refer to three basic dimensions: L (m), M (kg), T (s). Thus 2 π dimensionless numbers are necessary to characterize the system behavior. In that sense, Alexander suggested to take into account N_{fr} and Str .

Delattre et al. [3] showed that neither N_{fr} nor Str were sufficient to characterize running mechanics or to establish similarity between the subjects' dynamics. Each of the numbers makes its own contribution: N_{fr} contributing to predict antero-posterior kinetic events and Str , the temporal

organization. The authors suggested that a concomitant use of N_{fr} and Str would induce more accurate movement characterization.

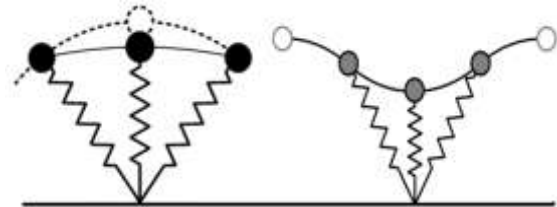


Figure 1: Compliant Inverted Pendulum (CIP) and Bouncing Mass (BM) models

During walking, a flattening of the trajectory of the body centre of mass (CoM) compared to IP has been demonstrated experimentally [4]. This finding suggests a compliant leg that flattens the vertical excursion of the CoM and promotes a compliant inverted pendulum model (CIP, fig 1.1). Applying π theorem to CIP, 2 π dimensionless numbers are necessary to characterize the system behavior. This implies that an elastic phenomenon operates during walking and points to Str and N_{fr} as indicators for studying walking too.

The aim of this study was to develop a concomitant consideration of Str and N_{fr} for an accurate dimensionless analysis of human walking and running.

2 Methods

Thirteen healthy subjects (mean \pm sd; age 23.5 \pm 2.7 years; height 1.78 \pm 0.07 m; Body mass 72.5 \pm 5 kg; leg length 0.93 \pm 0.05 m) took part in this study after signing an informed consent document.

Firstly, the spontaneously chosen walking velocity (V_{100}) of the subject was identified. Ten speeds were determined as extending from 80 to 280% of V_{100} by incremental step of 20% (ie V_{80} to V_{280}).

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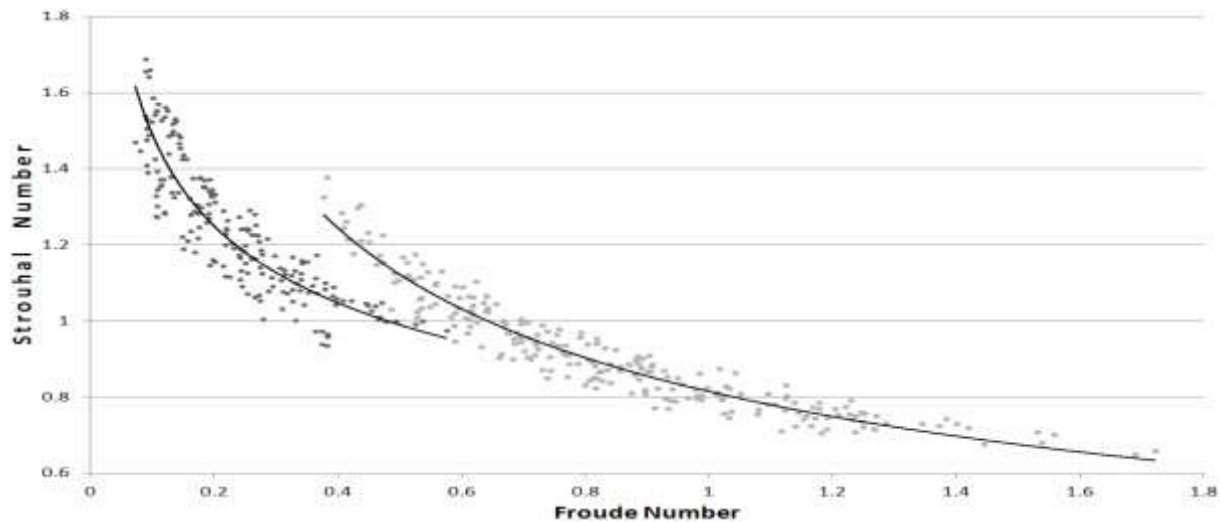


Figure2 : Relation between Nfr and Str according to locomotion mode.
Black circle: Walking gait; Gray square: Running gait.

These speeds were then imposed to the subject in a random order using a light running track. A Vicon motion analysis system and kistler forceplates integrated to a walkway enable one to record the kinematic and kinetic parameters during the walking and running trials. Nfr and Str were computed from the forward speed (v), the leg length (l) and the spontaneously chosen stride frequency (f_0).

3 Results and Discussion

According to Kram [5], our experimental data confirm that the walk-to-run transition occurs close to a 0,5 value of the Froude number (fig. 2.1).

A strong relation between Str and Nfr appears across walking and running trials. The relations are $Str=0.8296Nfr^{-0.254}$ ($r^2=0.8017$) and $Str=0.8144Nfr^{0.463}$ ($r^2=0.9266$), respectively.

CIP and BM models of human gait consider an elastic component and entails the use of Nfr and Str dimensionless numbers to describe human gait. The tight relations between both numbers revealed for walking and running confirm the adequacy of a dimensionless approach to experimental data on gait. The dimensionless numbers can be use to capture the dynamic similarities between different-sized subjects. According to Alexander, who suggested to associate Nfr and Str, these relations yield an experimental tool to establish dynamic similarities.

Groucho then Modela dimensionless numbers have been purposed for this purpose. They were justified from normal peak force study [6] and energy exchange at the centre of gravity of a BM [7]. Further studies are needed to devise a better way to reach dynamic similarities between different walking and running subjects.

4 Conclusions

The present study suggests a new means to associate Nfr and Str dimensionless numbers into the study of human gait. Based on models that introduce an elastic component into walking and running, they propose a new approach to study human gait and dynamic similarities between different-sized subjects.

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