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Influence of contextual task constraints on preferred stride parameters and their variabilities during human walking

Lauro V. Ojeda[a], John R. Rebula[a,b], Arthur D. Kuo[a], Peter G. Adamczyk[b,*]

[a] Department of Mechanical Engineering, The University of Michigan, Ann Arbor, Michigan, USA
[b] Intelligent Prosthetic Systems, LLC, Ann Arbor, Michigan, USA

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ABSTRACT

Walking is not always a free and unencumbered task. Everyday activities such as walking in pairs, in groups, or on structured walkways can limit the acceptable gait patterns, leading to motor behavior that differs from that observed in more self-selected gait. Such different contexts may lead to gait performance different than observed in typical laboratory experiments, for example, during treadmill walking. We sought to systematically measure the impact of such task constraints by comparing gait parameters and their variability during walking in different conditions over-ground, and on a treadmill. We reconstructed foot motion from foot-mounted inertial sensors, and characterized forward, lateral and angular foot placement while subjects walked over-ground in a straight hallway and on a treadmill. Over-ground walking was performed in three variations: with no constraints (self-selected, SS); while deliberately varying walking speed (self-varied, SV); and while following a toy pace car programmed to vary speed (externally-varied, EV). We expected that these conditions would exhibit a statistically similar relationship between stride length and speed, and between stride length and stride period. We also expected treadmill walking (TM) would differ in two ways: first, that variability in stride length and stride period would conform to a constant-speed constraint opposite in slope from the normal relationship; and second, that stride length would decrease, leading to combinations of stride length and speed not observed in over-ground conditions. Results showed that all over-ground conditions used similar stride length-speed relationships, and that variability in treadmill walking conformed to a constant-speed constraint line, as expected. Decreased stride length was observed in both TM and EV conditions, suggesting adaptations due to heightened awareness or to prepare for unexpected changes or problems. We also evaluated stride variability in constrained and unconstrained tasks. We observed that in treadmill walking, lateral variability decreased while forward variability increased, and the normally-observed correlation between wider foot placement and external foot rotation was eliminated. Preferred stride parameters and their variability appear significantly influenced by the context and constraints of the walking task.

1. Introduction

Human walking can entail multiple goals such as regulation of speed, avoidance of excess energy expenditure, and maintenance of balance. In terms of gait parameters such as average stride length, frequency, and width, there are generally multiple combinations that can satisfy a single goal such as walking speed [1–3]. And for a given speed, it has long been observed that the preferred stride length coincides with minimum metabolic energy expenditure [4–6]. There are, however, a variety of contexts that may determine a person's walking speed. For example, speed may be governed intrinsically for a person walking solo, or extrinsically when one matches the speed of another person or group. The goal of matching speed could potentially conflict with or override the normal gait preference, on average or from stride to stride. We therefore seek to determine whether and how the context for walking speed may shape a person's gait preferences.

The preferred stride length normally increases with greater walking speed. This may be described through a nonlinear relationship [7,8], in which stride length s (defined between two same-side footfalls) increases with $a \cdot v^b$ where v is speed and a and b are subject-specific constants, or by a simpler linear approximation proportional to speed [8]. Either relationship also determines stride frequency f and period T (from $f = v/s$, $T = s/v$). This is not, however, a perfectly rigid constraint. The preferred relationship is different when humans walk to match a given stride length or frequency [9]. This behavior is consistent with minimization of energetic cost (which varies as a function of gait parameters), subject to a constraint. A broader

* Corresponding author. Tel.: 734 277 7043.
E-mail address: p.g.adamczyk@gmail.com, padamczyk2@wisc.edu (P.G. Adamczyk).

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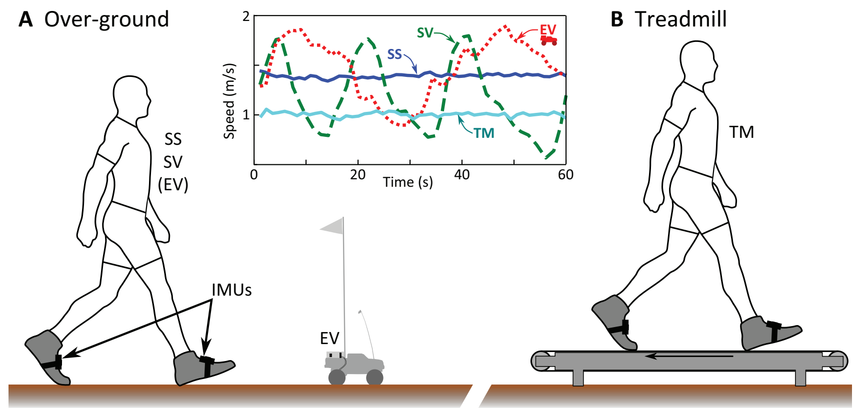

Fig. 1. Subjects wore synchronized, miniature inertial measurement units (IMUs) on both feet, and walked over-ground and on a treadmill. **(A)** Over-ground walking had three speed conditions: self-selected (SS), randomly self-varied (SV), and following a pace car with pseudo-random variation (externally-varied, EV). **(B)** Treadmill walking (TM) was at a single, constant speed. (Inset) Sample data for walking speed.

view is therefore that gait parameters depend on what variables are constrained, and therefore the context of the walking task.

There are many possible contexts for walking. Stride frequency may occasionally be constrained, for example if one walks to the beat of music. Stride length may be constrained for walking over stepping stones or to avoid obstacles, and both length and frequency may be constrained when marching in formation. Alternatively, walking speed may be determined externally, for example when one person wishes to match the speed of another. Less natural, but common in the laboratory, is for speed to be controlled by a treadmill or by the time between photo-gates overground. These contexts may be subtly different, because each case provides different cues and allowances regarding speed. The speed of a group of people can potentially vary, and so any single individual may be tracking a changing speed, perhaps with some subjective allowance for momentarily deviating from the group. If that allowance is small, the strategy for tracking a changing speed may favor relatively short and brief strides to facilitate faster speed corrections. A treadmill usually imposes fixed reference speed, and its length imposes limits on allowable deviations in the person's speed, both of which may affect the preferred stride parameters. And if a treadmill's speed is not fixed, that may also result in altered stride parameters [10]. The context that is perhaps most difficult to define is normal walking, which may entail an intrinsic goal such as reaching a particular destination within a desired time frame. Depending on such a goal, the minimization of energy expenditure generally results in different sets of optimal gait parameters [3]. It is unknown whether or how an imposed speed constraint, such as those used in laboratory experiments, will differ from unconstrained walking in situ.

An additional feature of gait parameters is their variation relative to mean. Each stride parameter exhibits variability depending in part on the average stride parameters and walking speed [11,12]. Some variabilities are also correlated, with manifestations such as covariance between stride length and width [13], stride length and speed [14], or stride width and foot angle [15]. Here, context also plays an important role, because a treadmill constrains allowable variations, resulting in a particular stride covariance pattern that limits fluctuations in speed due to the treadmill's restricted length [16,17]. Overground walking is almost certainly different, especially when there is no explicit speed reference. In fact, humans exhibit relatively larger fluctuations in speed than in stride length, width, or frequency, suggesting that intrinsic speed regulation may be quite relaxed compared to the desire to optimize stride length [14]. However, lacking a specific comparison of stride covariances under different contexts such as treadmill versus overground, it remains to be proven whether stride variations are also context dependent.

The purpose of the present study was to compare how contexts such as self-selecting speed versus tracking a reference speed, or walking over ground versus on a treadmill, affect human gait parameters and their variability. We directly compared stride parameters and their variability among free and constrained over-ground walking tasks and treadmill walking using the same instrumentation and computational techniques. We hypothesized that tracking tasks might cause small shifts in the preferred stride relationship toward shorter strides, to accommodate stride corrections made for tracking. We also expected that a treadmill's constant-speed constraint would reduce variability in stride length and speed, compared to free overground walking. Furthermore, those fluctuations should co-vary according to the speed constraint, with fluctuations violating the constraint resulting in relatively fast corrective responses. We tested for such effects to explore how even subtle differences in the context of walking can affect parameters that are normally considered indicative of biomechanical or neural control function.

2. Methods

2.1. Subjects and conditions

We measured gait parameters of healthy adult human subjects walking in free and speed-controlled conditions over-ground, and at constant speed on a treadmill. We estimated forward, lateral and angular foot placement and stride period using inertial sensors worn on each foot. We computed metrics to describe these parameters and their variabilities as a function of contexts such as self-selected speed, an external reference requiring tracking of speed, or treadmill-fixed speed. A total of 23 subjects participated, 12 Young (22.4 ± 4.2 years (mean ± S.D.), 4 male, 8 female; leg length 0.91 ± 0.06 m) and 11 Elderly (65.7 ± 3.0 years (one not reported), 5 male, 6 female; leg length 0.89 ± 0.07 m), treated as a single group for analysis. Overground conditions were tested in an indoor hallway, approximately 112 m long in a straight line and 2.4 m wide, with a smooth tile floor and fluorescent lighting. The treadmill was a split-belt instrumented research treadmill (Bertec Corp., Columbus, Ohio, USA; 1.83 m long, 0.83 m wide) with computer-controlled speed, and a centerline gap of about 20 mm. Subjects wore their customary walking shoes, to which inertial sensors (APDM Inc., Portland, OR, USA) were mounted on the upper forefoot outside the shoe using elastic polyurethane tape (Fig. 1). The sensors sampled three-axis angular velocity (range 2000 deg/s) and linear acceleration (range 6 g's) continuously at 128 Hz. Subjects gave their written informed consent according to University of Michigan Institutional Review Board policies.