Gait & Posture 46 (2016) 118–125

Contents lists available at ScienceDirect

Gait & Posture

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

From normal to fast walking: Impact of cadence and stride length on lower extremity joint moments

Marzieh M. Ardestani [a,*], Christopher Ferrigno [a,b], Mehran Moazen [c], Markus A. Wimmer [a]

[a] Department of Orthopedic Surgery, Rush University Medical Center, Chicago, IL, USA
[b] Department of Anatomy and Cell Biology, Rush University Medical Center, Chicago, IL, USA
[c] Department of Mechanical Engineering, University College London, Torrington Place, London, WC1E 7JE, UK

ARTICLE INFO

Article history:
Received 27 October 2015
Received in revised form 13 January 2016
Accepted 4 February 2016

Keywords:
Gait
Speed
Cadence
Stride length
External joint moments

ABSTRACT

This study aimed to clarify the influence of various speeding strategies (i.e. adjustments of cadence and stride length) on external joint moments. This study investigated the gait of 52 healthy subjects who performed self-selected normal and fast speed walking trials in a motion analysis laboratory. Subjects were classified into three separate groups based on how they increased their speed from normal to fast walking: (i) subjects who increased their cadence, (ii) subjects who increased their stride length and (iii) subjects who simultaneously increased both stride length and cadence. Joint moments were calculated using inverse dynamics and then compared between normal and fast speed trials within and between three groups using spatial parameter mapping.

Individuals who increased cadence, but not stride length, to walk faster did not experience a significant increase in the lower limb joint moments. Conversely, subjects who increased their stride length or both stride length and cadence, experienced a significant increase in all joint moments. Additionally, our findings revealed that increasing the stride length had a higher impact on joint moments in the sagittal plane than those in the frontal plane. However, both sagittal and frontal plane moments were still more responsive to the gait speed change than transverse plane moments. This study suggests that the role of speed in altering the joint moment patterns depends on the individual's speed-regulating strategy, i.e. an increase in cadence or stride length. Since the confounding effect of walking speed is a major consideration in human gait research, future studies may investigate whether stride length is the confounding variable of interest.

1. Introduction

The existing body of literature is rich with studies analyzing how walking speed, an important consideration in gait analysis, may impact human gait biomechanics [1–6]. Significant associations have been found between gait speed and joint kinematics [7–10], joint kinetics [11,12], muscle activities [13–15] and gait stability [16–19] in both healthy people and subjects with pathology. Cadence (number of steps per minute) and stride length are the key determinants of gait speed which describe important spatio-temporal aspects of human gait pattern [20]. The cadence and stride length relationship has been investigated as an indicator of gait control [21], gait abnormalities and fall risk [22]. Healthy subjects can regulate their gait speed by singularly adjusting the cadence, stride length or a combination of both strategies[23], with each strategy imparting excessive demands on different kinematics [24,25]. Since the gait kinetic pattern is directly dictated through the interaction of joint kinematics [26], it is likely that different speeding strategies impact gait differently. To the best of our knowledge, a systematic evaluation of different speeding strategies (i.e. adjustments of cadence and stride length) and their role in altering the lower extremity joint moments has not been investigated in the literature. In addition, the speed-mediated effects have been studied only for discrete features of gait patterns such as "magnitudes" of joint moments defined at specific time points. In fact, available statistical analyses, such as t-test or analysis of variance (ANOVA) can only provide scalar-based hypotheses testing. Hence, many studies ignore the temporal information and dynamic patterns of gait by summarizing the complex waveforms with only a few scalars, and consequently fail to provide a more holistic understanding of the speed-mediated effects throughout the entire gait cycle.

* Corresponding author. Tel.: +1 3129422789.
E-mail address: Marzieh_M_Ardestani@rush.edu (M.M. Ardestani).

http://dx.doi.org/10.1016/j.gaitpost.2016.02.005
0966-6362/

This study used Spatial Parameter Mapping (SPM) to evaluate the waveforms for each gait parameter. SPM is a well-established technique for image comparison [27] that has recently been utilized in the field of biomechanics enabling the comparison of measurements at a vector level and over the entire gait waveform [28–32]. The primary aim of this study was to understand how changes in cadence and stride length affect the external joint moments once a person switches from normal to fast walking speed. As a secondary aim, it was investigated which moments in what plane were affected the most. While this study does not directly aim to address the debate on the best technique for alleviating the confounding effects of speed in gait tests, it may provide additional insights on this matter.

2. Materials and methods

2.1. Subjects

Gait data from a total of 55 healthy asymptomatic adults were obtained from an IRB approved data repository at Rush University Medical Center. Since age has been shown to influence gait speed [33], subjects were chosen from a certain age ranging from 40 to 60 years. This age range is of interest in gait studies on lower extremity joint pathologies and was chosen to facilitate future comparison of the results. Inclusion criteria were: no clinical and structural (K/L grade < 2) evidence of complications such as osteoarthritis or rheumatoid arthritis in ankle, knee and hip joints, no significant lower limb pain over that past 2 months and no recent history of fracture or surgery in the lower limbs. Subjects needed to be pain-free at the day of testing with $<$10 mm on the visual analog 100 mm score of the Western Ontario and McMaster Universities Arthritis Index (WOMAC) [34]. Since the external joint moments and other variables of interest had to be reprocessed, exclusion criteria included difficulties in data processing such as marker dislocation, missing trials, etc.

2.2. Three dimensional gait analysis

All tests were conducted between 2007 and 2008 by the same trained clinician and technical staff of the laboratory while an identical marker set and similar experimental condition were applied to all subjects. A total of six passive retroreflective markers were placed on the most lateral point of the superior iliac crest, the aspect of the greater trochanter, the lateral knee joint line, the lateral malleolus, the lateral most point on the calcaneus, and the head of the fifth metatarsal of the dominant limb. Markers were tracked with a sampling rate of 120 Hz using a gait analysis software system (CFTC - Computerized Functional Testing Corporation, Chicago, IL) with four optoelectronic cameras (Qualisys, Gothenburg, Sweden) [35]. Ground reaction forces (GRF) were measured using a multicomponent force plate (Bertec, Columbus, OH- sampling rate of 120 Hz). Each subject completed a total of six barefoot walking trials including three trials at self-selected normal speed and three trials at self-selected fast speed. Walking trials were deemed successful when the subject had a clean force plate strike on the indexed limb (the dominant leg). For every subject, the self-selected fast walking speed with an increase of at least one standard deviation higher than normal was accepted as self-selected fast speed. This criterion yielded a $>$10% increase in the subjects' normal walking speed. Three-dimensional hip, knee and ankle joint moments were calculated using CFTC software. The software was based on a rigid link model of the lower extremities with no instantaneous rotation about the long axis of each segment and basic inverse dynamics. Details of the model have been described earlier[36]. External joint moments were then normalized to bodyweight times height (%BW*HT) [37] and averaged over normal and fast walking trials for each subject. Sample frequency was normalized to 100 samples per gait cycle from 0% (heel strike) to 100% (the following heel strike of the same leg). Using a custom MATLAB script (version 2009, The Mathworks, Natick, MA, USA), the spatiotemporal variables (i.e. speed, stride length and cadence) were extracted from force plate measurements.

2.3. Subject Clustering

For each subject, the average of cadence ($\overline{Cadence}$) and stride length ($\overline{Stride}$) were computed over the normal and fast walking trials. For each subject, the increments of cadence ($\Delta Cadence$) and stride ($\Delta Stride$) were then defined as follows:

$$\Delta Cadence_i = \frac{\overline{Cadence_i^{fast}} - \overline{Cadence_i^{normal}}}{\overline{Cadence_i^{normal}}} \times 100\%$$

$$i = \text{number of subject}$$

$$\Delta Stride_i = \frac{\overline{Stride_i^{fast}} - \overline{Stride_i^{normal}}}{\overline{Stride_i^{normal}}} \times 100\%$$

Comparing the $\Delta Cadence$ and $\Delta Stride$ for each subject, participants were classified into one of the following groups:

I. Subjects who mainly increased their cadence to execute fast speed trials as $\left(\frac{\Delta Cadence}{\Delta Stride}\right) > 1$.
II. Subjects who mainly increased their stride length to execute fast speed trials as $\left(\frac{\Delta Cadence}{\Delta Stride}\right) < 1$
III. Subjects who increased both cadence and stride length to the same extent to increase their gait speed as $\left(\frac{\Delta Cadence}{\Delta Stride}\right) \cong 1$

2.4. Statistical analysis

One-way ANOVA with a significance level of $p = 0.05$ was used to compare subjects in terms of age, height, speed cadence and stride length. Spatial parameter mapping (SPM) was used to compare the waveforms of the external joint moments. SPM is a vector-field analog for traditional statistical analyses such as t-test or ANOVA which provides a framework for continues-level statistical comparison of biomechanical waveforms [28]. For a detailed description of SPM, see Pataky et al., 2010. In brief, for each vector (i.e. joint moment) a critical threshold was determined based on the smoothness and temporal increment of that vector over the gait cycle [32]. For each joint moment, t-statistics or F-statistics were calculated as a (100×1) continuum, referred as SPM(t) or SPM(F). If SPM exceeded the threshold, a significant difference is recognized. Using Random Field Theory [38], the probability with which this difference has occurred by chance was then calculated (p-value). Presented in this study, the vector-field equivalent of a paired t-test, SPM(t), was implemented to compare the joint moments between normal and fast speeds within each group, while the vector-field equivalent of a one-way ANOVA, SPM(F), was used to compare joint moments between groups at normal and fast speed trials. All of the aforementioned computations were conducted using "SPM1D", a free and open source software package for SPM, written in MATLAB software code [29].

3. Results

Three subjects were excluded due to difficulties in data processing, leaving 13 males and 39 females for inclusion with an average age of 54.2 ± 6.0 (years), body weight of 74.2 ± 11.3 (kg) and a height of 1.60 ± 0.07 (m). Overall, subjects increased their