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Temporal-spatial gait parameter models of very slow walking

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ABSTRACT

This study assessed the relationship between walking speed and common temporal-spatial stride-parameters to determine if a change in gait strategy occurs at extremely slow walking speeds. Stride-parameter models that represent slow walking can act as a reference for lower extremity exoskeleton and powered orthosis controls since these devices typically operate at walking speeds less than 0.4 m/s. Full-body motion capture data were collected from 30 health adults while walking on a self-paced treadmill, within a CAREN-Extended virtual reality environment. Kinematic data were collected for 0.2–0.8 m/s, and self-selected walking speed. Eight temporal stride-parameters were determined and their relationship to walking speed was assessed using linear and quadratic regression. Stride-length, step-length, and step-frequency were linearly related to walking speed, even at speeds below 0.4 m/s. An inflection point at 0.5 m/s was found for stride-time, step-time, stance-time, and double support time. Equations were defined for each stride-parameter, with equation outputs producing correlations greater than 0.91 with the test data. This inflection point suggests a change in gait strategy at very slow walking speeds favouring greater ground contact time.

1. Introduction

Humans naturally walk at different velocities, effortlessly increasing or decreasing step-frequency and stride-length to speed up or slow down [1]. Several investigations at slow, comfortable, and fast walking speeds have been conducted to characterise temporal-spatial stride-parameters [2–6]. From these studies, simple linear relationships have been found between walking speed and stride-length and between walking speed and step-frequency. Curvilinear relationships were found between walking speed and stance-time, swing-time, and stride-time. Studies that modelled temporal-spatial parameters and walking speed provided simple linear regression equations that predicted step-length and frequency, and approximated swing and stance-time, using quadratic polynomials or logarithmic formulas [4,5,7]. These results and seminal works investigating walking speed [8] have led to a general assumption that stride-parameters follow a consistent pattern of change in response to speed, and that stride-parameter values can be predicted at a given walking velocity.

Numerous studies have characterised the relationship between temporal-spatial parameters at slow, comfortable, and fast walking speeds. However, few studies have investigated these relationships with very slow walking speeds, below 0.4 m/s [9,10], and no study has applied regression analyses to determine if very slow speeds follow a predictable pattern of change. Therefore a complete characterisation of stride-parameters at very slow speeds has yet to be realised.

At their preferred walking speeds, persons with lower limb pathology walk with visibly altered gait patterns compared to able-bodied people. Direct comparisons between these populations failed to identify stride-parameter differences independent of walking speed, where walking speed can differ by two to 10 times depending on the severity of pathology [11]. In this regard, clinicians should make allowances for walking speed when basing clinical decisions on stride-parameters. To do so, clinicians must know stride-parameter reference values across a wide range of walking velocities, including very slow walking (< 0.4 m/s).

Slow walking is especially relevant for new lower extremity powered exoskeletons (LEPE), where users walk at speeds between 0.1 m/s and 0.55 m/s, with an average speed of 0.26 m/s [12]. LEPE joint trajectories are from able-bodied individuals walking at speeds unattainable in use, including studies specifically conducted to provide slow walking joint trajectory data for exoskeleton development [13].

Since individuals walking slowly use different locomotor and postural control strategies [9,14], the relationship between speed and temporal spatial parameters may change at slowing walking speed due to reduced underlying locomotor task demands on speed dependent muscle activation amplitude [15], time spent in double support [16], and altered neuromuscular control of the swing limb [17]. An improved

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understanding of stride-parameters at speeds achievable by device users would provide a biomimetic basis for developers when designing LEPE gait trajectories. This data would provide a clearer picture of device parameters required to support users in the early stages of recovery following neurological injury, as well as those achievable within device parameter limitations (strength and speed of motors, number of joints, etc.).

This research extended temporal spatial parameters models to very slow speeds that are common for exoskeleton users and those with incomplete spinal cord injury. Based on the assumption in the literature that parameters associated with walking speed follow a predictable pattern of change, we hypothesized that stride-parameters would fit simple linear and quadratic formulas at walking seeds below 0.4 m/s, but that these patterns may change predictably at very slow speeds. This analysis provides a more complete characterisation of stride-parameters at very slow speeds, a valuable tool for both clinicians and lower extremity powered orthosis developers.

2. Methods

2.1. Participants

A convenience sample of thirty able-bodied (AB) volunteers was recruited from staff, students, and volunteers at The Ottawa Hospital Rehabilitation Centre and University of Ottawa. (15 males, 15 females; mass = 75.8 ± 13.2 kg, height = 1.73 ± 0.12 m; age = 30 ± 10 years). Participants did not have gait or health issues that affected walking on level ground. Participant's leg length was recorded for normalisation purposes. This study was approved by The Ottawa Hospital Research Ethics Board and all participants provided informed consent.

2.2. Equipment

The CAREN-Extended virtual environment (Motekforce Link, Amsterdam, NL) was used in this study. This system includes Vicon 3D motion capture (Vicon, Oxford, UK), 180° screen for 3D virtual world projection, and a six degree of freedom (6-DOF) moving platform with an embedded dual-track treadmill (Bertec Corp., Columbus, OH), with force plates under each track sampling at 1000 Hz. Full-body kinematics were tracked at 100 Hz, using a 6-DOF, 57 marker set [18]. Platform position was tracked using three markers on the platform surface.

Participants were provided time to acclimate to the seven slow walking speeds (0.2-0.8 m/s, incremented by 0.1) and to self-paced treadmill walking. The self-paced (SP) algorithm used pelvis markers to determine the participant's anterior-posterior treadmill position, velocity, and acceleration, in relation to the participant's initial standing position (middle of the treadmill). As the participants walked, the system automatically changed treadmill speed to keep the person in the middle of the treadmill. Acclimation is required to ensure that the person does not try to walk at the front of the treadmill, where the treadmill would continue to speed up to bring the person back to their middle position. Following the acclimation period, at least 10 strides of level walking were collected for each speed while participants walked on a path through a virtual park scene [19] that provided realistic optic flow. Speeds were randomised to avoid learning bias. Total walking distance varied depending on acclimation period and time to complete 10 left and right strides with the left and right leg landing on their respective force plates.

2.3. Data analysis

Marker data were filtered with a 4th order, low pass Butterworth filter (10 Hz). Visual3D (C-Motion) was then used to define a 13-segment model. Foot on and foot off were determined using ground reaction force data, calculated at the first frame the vertical ground reaction force exceeded or dropped below 20 N respectively. Ground reaction force data was filtered with a zero phase shift 4th order Butterworth low pass filter with a cut off frequency of 20 Hz. Treadmill speed was determined from anterior-posterior foot marker velocity during midstance. Custom Matlab software (2010a, Mathworks, Matwick, MA) was used to calculate stride-time, step-time, stance-time, swing-time, double support time (DST), stride-length, step-length, and step-frequency (Table 1). These parameters were summarised for each person using mean, standard deviation, max, min, coefficients of variability, and 95% confidence interval. Repeated measures analysis of variance (ANOVA) was performed to determine the effect walking speed and leg dominance, with $p < 0.05$ considered statistically significant.

Table 1
Temporal-spatial stride parameter definitions.

Stride-time	Time (s) between successive foot contacts of the same foot
Step-time	Time (s) between successive contacts of each foot
Stance-time	Time (s) when the foot is in contact with the ground
Swing-time	Time (s) when the foot is not in contact with the ground
Double support time	Time between foot-off on one limb and foot contact on the opposite limb
Stride length	Anterior-posterior distance (m) between the same heel marker over successive foot contacts
Step-length	Anterior-posterior distance (m) between heel markers at foot stride
Step-frequency	Number of steps per second (steps/s)

Group means for each parameter were calculated at each speed. Linear and quadratic regressions were performed to determine the relationship between walking speed and mean stride-parameter values. Pearson correlations were applied to determine the strength of association between speed and each stride-parameter. Correlation coefficients (r^2) greater than 0.90 were considered strong.

For parameters without a strong correlation, linear regressions were used to test for inflection points between faster and slower walking speeds. For each participant, linear regressions were performed across multiple walking speed sets, with data from the next slowest speed added to subsequent sets. Linear regression r^2 were determined for each speed set and a non-liner change was identified if r^2 dropped below 0.90 and remained so for subsequent sets. An inflection point was identified if a non-linear change occurred consistently at the same speed for the majority of participants. If an inflection point was found, linear and quadratic equations were fit to data before and after the defined point. To investigate leg length effects, linear and quadratic curves were also calculated with speed normalised to leg length.

Equations for parameters with strong linear and quadratic correlations were applied to each participant's data to assess how well the equations represented the participant's temporal-spatial gait. All statistics were calculated using Malab's Statistics and Machine Learning Toolbox.

3. Results

Temporal-spatial results for all speeds are shown in supplemental material. No significant main effect was observed between limbs ($p = 0.247$), across all parameters. Linear and quadratic equations and r^2 values are presented in Table 2. As expected, stride-length ($r^2 = 0.98 \pm 0.03$), step-length ($r^2 = 0.98 \pm 0.02$), and step-frequency ($r^2 = 0.94 \pm 0.04$) had strong positive linear relationships with effect of walking speed. Correlations were marginally improved using a quadratic equation ($r^2 = 0.99 \pm 0.02$; $r^2 = 0.99 \pm 0.02$; $r^2 = 0.95 \pm 0.05$).

Stride, step, stance, and double support times all had a consistent inflection point at 0.5 m/s. Swing-time did not have a strongly linear relationship to speed and a consistent inflection point was not

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