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Gait phase varies over velocities

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ABSTRACT

We sought to characterize the percent (PT) of the phases of a gait cycle (GC) as velocity changes to establish norms for pathological gait characteristics with higher resolution technology. Ninety five healthy subjects (49 males and 46 females with age 34.9 ± 11.8 yrs, body weight 64.0 ± 11.7 kg and BMI 23.5 ± 3.6) were enrolled and walked comfortably on a 10-m walkway at self-selected slower, normal, and faster velocities. Walking was recorded with a high speed camera (250 frames per second) and the eight phases of a GC were determined by examination of individual frames for each subject. The correlation coefficients between the mean PT of the phases of the three velocities gaits and PT defined by previous publications were all greater than 0.99. The correlation coefficient between velocity and PT of gait phases is −0.83 for loading response (LR), −0.75 for mid stance (MSt), and −0.84 for pre-swing (PSw). While the PT of the phases of three velocities from this study are highly correlated with PT described by Dr. Jacquenlin Perry decades ago, actual PT of each phase varied amongst these individuals with the largest coefficient variation of 24.31% for IC with slower velocity. From slower to faster walk, the mean PT of MSt diminished from 35.30% to 25.33%. High resolution recording revealed ambiguity of some gait phase definitions, and these data may benefit GC characterization of normal and pathological gait in clinical practice. The study results indicate that one should consider individual variations and walking velocity when evaluating gaits of subjects using standard gait phase classification.

1. Introduction

As a key parameter for gait analysis, a gait cycle (GC), defined as the time from heel strike to the ipsilateral heel strike, is widely used for the evaluation of basic and clinical disorders [1–5]. The gait cycle (GC) is measured from heel strike to heel strike of the same leg. There are two major phases: stance and swing. The sub-phases of stance are initial contact (IC), loading response (LR), mid stance (MSt), terminal stance (TSt) and, pre-swing (PSw). The sub-phases of swing are initial swing (ISw), mid swing (MSw), and terminal swing (TSw) [6]. Precise measures of the sub-phases may be useful to characterize normal gait with variable velocities to improve clinical evaluation of altered ambulation evaluation.

The sub-phases during walking occur at IC 2%, LR 12%, MSt 31%, Tst 50%, PSw 62%, ISw 75%, MSw 87%, and TSw 100% of the GC. These measures were derived from gait results of more than 400 subjects (61 subjects with age 6–12 yrs, 53 subjects with age 13–19 years old, 236 subjects with age 20–69 yrs and 70 subjects with age with 70+ yrs) [6,7], and however, variations of duration of gait sub-phases with different genders, ages, BMI, and velocities are not well defined.

Murray et al. [8] reported the high correlation coefficients between the duration of GC and the durations of phase components (0.96 for stance, 0.75 for swing and 0.79 for double-limb stance) as speeds change. By using photography at a rate of 20 exposures per second with 7 subjects, another study [9] showed that as speeds decreased, the durations of heel rise and toe off were increased. Those studies have demonstrated the strong influences of the velocities on the durations of sub-phases.

The objective of this study was to characterize the sub-phase changes of the CG as a function of velocity in normal people by using high time resolution videography. This study was intended to enhance the usefulness of objective evaluation for orthopedic intervention techniques and characterize the GC changes associated with age, gender, BMI and variable velocities.

2. Methods

2.1. Subjects

Subjects were recruited through the university and neighborhood community. The subjects received a small monetary

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Table 1
Subject characteristics [mean ± SD (range)].

	Total	Female	Male
Number of subjects	95	46	49
Age (yr)	34.9 ± 11.8 (20–67)	36.27 ± 10.62	33.86 ± 12.66
Height (m)	1.65 ± 0.09 (1.47–1.84)	1.58 ± 0.06	1.71 ± 0.06
Body weight (kg)	64.0 ± 11.7 (42.4–103.5)	59.34 ± 10.93	68.06 ± 10.84
BMI (kg/m^2)	23.5 ± 3.6 (17.2–35.8)	23.72 ± 3.90	23.26 ± 3.32

compensation for their participation. Ninety-five subjects were enrolled in the study (Table 1). Based on the cutoff of BMI for Chinese population [10], there are 54 normal subjects with BMI< 24 (21.00 ± 1.89), 41 overweight/obese subjects with BMI ≥ 24 (26.74 ± 2.50). All subjects were free of any impairment of the locomotors system. Subjects wore comfortable tight clothes to facilitate viewing the lower extremities. The study was approved by the Institutional Review Board at Capital Medical University. All subjects signed written consent to participate.

2.2. Devices

A High-Speed Video Camera (FASTCAM-ultima 1024, Japan) with a 16 mm lens perpendicular to the walkway was used to record walking at a rate of 250 frames per second (fps). The distance from the camera to the walkway was 4.2 m The height of camera lens was 50 cm. The camera was activated by a manual trigger to capture at least one full GC. The trigger is a small device and researchers can hold it and tap the button to activate the camera when subject walked into the camera view. The sequence of measure was normal, slower and then faster velocities with a 30 s rest period between examinations.

2.3. Experimental protocols

In order to eliminate the effect of acceleration and deceleration at the beginning and end of the examination, the 6-m middle part of a 10-m walkway was designated for data collection. The walkway was covered with wear resistant paper marked by lines at intervals of 2 cm. A standard 1 m scale was placed along the walkway as the reference. Before the test, each subject walked barefoot on the walkway at a comfortable velocity to familiarize themselves with the laboratory environment. Totally, three trials with three velocities were recorded and each trial contained one full gait cycle at least. First, the subjects walked at their self-selected comfortable velocity (normal velocity) on the walkway, and one researcher activated high speed camera with a trigger when the subject step into the camera view. After a short break for saving video, with the same protocols, the subject was asked to walk freely at a slower velocity than normal, and then at a faster velocity than normal back and forth for gait recording.

3. Data analysis

Phtron FASTCAM Viewer software was used to analyze the video images. All video images were analyzed frame by frame by two research staff to divide all gait cycles into eight sub-phases independently. Then two researchers examined their results together until agreed. It took two months to analyze all video images for sub-phases analysis. Intraclass correlation coefficient (ICC) was used to evaluate reliability of measurements of PT of gait sub-phases.

The definitions of eight sub-phases were based on the classical gait analysis methods of Perry [6,7]. IC (0–2%): the foot contacts the ground and a subtle heel soft tissue deformation can be seen; LR (2–12%): a very rapid ankle plantar flexion, until the frame when the opposite limb has preswing; MSt (12–31%): begins as the opposite foot enters preswing; TSt (31–50%): begins with heel rise and the opposite foot heel strike; PSw (50–62%): begins with IC of the opposite limb and ends with ipsilateral; ISw (62–75%): begins as the foot is lifted from the floor and ends when the swing foot is opposite the stance foot; MSw (75–87%): begins as the swing forefoot is opposite the stance limb and ends when the tibia is vertical with the foot parallel to the floor; TSw (87–100%): begins with a vertical tibia and ends when the foot strikes the floor again.

The durations of sub-phases were calculated by (the number of frames of sub-phases) × 4 ms. The cumulative PT of each sub-phase was calculated by [(the number of frames from the ending frame of the sub-phase to first frame of IC)/the total number of frames of the GC)] × 100%. The walkway was covered with wear resistant paper marked by lines at intervals of 2 cm. Average of stride length in this study was 100 cm, so error could be controlled within 2%. A standard 1 m scale plate was placed along the walkway as the reference. The stride length is calculated by using the ShiXun motion analysis software (Beijing Sport University, Beijing, China) based on pixel ratio of the scale plate. Velocity was calculated as stride length/GC duration. If the difference between stride lengths measured by two researchers is more than 1 cm, then two researchers had to measure the stride length again until the difference is less than 1 cm.

Data were analyzed by SPSS 17.0. The distribution and homogeneity of variance of age, height, BMI, PT of gait sub-phases, and other kinematic parameters were calculated. One way ANOVA was performed to compare PT of each sub-phase and the kinematic parameters between different velocities. Correlations between PT of gait sub-phases and age, height, body weight, BMI, gait velocities were performed with Pearson's test respectively. Significance is defined as $p < 0.05$.

4. Results

Two hundred eighty five cycles from 95 subjects were analyzed. Mean percents of ending periods of the eight sub-phases at normal, slower and faster velocities are given in Table 2. IC initiated at 0% of GC and TSw ended at 100% of GC. Correlation coefficients between the mean PT at normal, faster and slower gait velocities and the PT defined by Perry and Burnfield [6] are 0.9978, 0.9983 and 0.9991 respectively (Fig. 1). The mean PT of IC (1.78, 1.81 and 1.89%) for normal, faster and slower velocities are smaller than the result (2%) from Perry and Burnfield [6]. Overall, the mean PT of eight sub-phases at the normal velocity is closer to Perry's results compared with faster and slower velocities. Intraclass correlation coefficients between measurements of PT of eight sub-phases by two researchers are 0.953, 0971, 0.945, 0. 983, 0.978, 0.986, 0.956 and 1.00 respectively.

PT of the stance sub-phases changes largely with velocities. With normal velocity, the mean PT of IC is 1.81% with the range of 1.08–2.59%, 12.89% (8.33–15.73%) for LR and 31.56% (19.05–40.47%) for MSt; with faster velocity, the mean PT of IC is 1.78% with the range of 0.85–2.55%, 10.32% (5.39–13.77%) for LR and 25.39% (15.48–34.78%) for MSt; with slower velocity the mean PT of IC for is 1.89% with the range of 0.67–2.95%, 14.55% (10.73–19.29%) for LR and 35.30% (18.75–44.48%) for MSt. When the gait velocity is increased from slower to normal, then to faster, the duration of TSt is increased from 14.94% to 18.67%, then to 24.81% of a GC, the duration of MSt is decreased from 20.75% to 18.66%, then to 15.01% of a GC, and the duration of LR is decreased from 12.66% to 11.08%, then to 8.54% of a GC.

Correlation coefficients between velocities and PT of gait phases are given in Table 3. PT of LR, MSt and PSw are highly correlated