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Variability analysis of lower extremity joint kinematics during walking in healthy young adults

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ABSTRACT

The first objective of this study was to determine the kinematic variability of the lower extremity joints using methods from the mathematical chaos theory in a normal walking environment in conjunction with a large population of healthy young adults. The second objective was to test the hypothesis that variability characteristics are different between joints and to further investigate differences between male and female and right and left subgroups. A total of forty young healthy subjects (20 males: 24.1 ± 3.1 years; 20 females: 22.5 ± 3.2 years) volunteered, and their joint motions were captured while walking on a treadmill for 90 s in order to estimate Lyapunov Exponent (LE) values. Means and standard deviations of the LEs ranged from 0.035 ± 0.016 (right ankle) to 0.073 ± 0.023 (left knee) for the male subjects and from 0.028 ± 0.014 (left ankle) to 0.065 ± 0.028 (right hip) for the female subjects. Between the males and females, differences in LEs were observed to be statistically significant only for the left knee. There were no statistically significant differences between the right and left sides of the joints. However, differences between joints were statistically significant except between the hip and knee. These results are the first such comparison of the variability in the lower extremity without the confounding effect of walking speed on the variability of joint motions, and can serve as a normative database.

1. Introduction

Walking requires great coordination and the combined movements of the upper extremity (shoulder, elbow and wrist) and the lower extremity (hip, knee, ankle and toe) in order to move in a certain direction with a desired speed. It has been reported that people show different walking patterns depending upon their cultural traits as well as psychological and physical characteristics [1,2]. Even for the same person, each joint motion is observed to be different between one gait cycle and another during normal walking, although joint motion is continuous and repetitive as one limb typically provides support in the stance phase while the other limb moves forward in the swing phase [3]. Furthermore, the involvement of the musculoskeletal and nervous systems makes joint motions much more complicated resulting in a greater difference between joint motions and thus increased difficulties in their analyses (i.e., development of reference parameters and analytical methods). Despite these difficulties, identifiable walking patterns and joint motions under various walking conditions have been reported in the literature, mainly focusing on comparisons between healthy subjects and joint patients [4–9] and between young and old subjects [10–14]. Moreover, quantifications of joint motions have been performed to evaluate their variability by calculating diverse parameters such as stride-to-stride variations [15–17], entropy [14,18–20] and the Lyapunov Exponent (LE) [21–26].

In recent studies, it has been reported that measures of Lyapunov Exponent values (LEs) derived from the mathematical theory of chaos [21,23,25,27–29] and long-range correlations of stride interval fluctuations from nonlinear fractal dynamics [7,30,31] can find subtle differences between healthy and diseased joints; the method of long range correlations has been used as a tool to observe the variability of heart rate oscillations [30,32,33]. Patients with Anterior Cruciate Ligament (ACL) reconstruction exhibit an increase in LEs as compared with subjects with an intact knee [21]. Buzzi et al. have investigated the effect of age on the variability of the knee reporting larger values of LEs for the elderly [29]. Stergiou et al. have reported that knee joints with ACL injuries exhibit larger LEs than the contralateral intact knee [23]. Therefore, the LE estimates of joint movements from a large population of young healthy subjects would provide the normative values needed in the literature [23,28,29]. Moreover, these normative LE values could be clinically applied to the development of rehabilitation strategies by evaluating recovery progress in comparison of healthy subjects. For instance, the knee joints experience a broad range of flexion–extension angles requiring guaranteed stabilization which can be lost by damage to the components of the knee joints. The functional stages of rehabilitation for patients with knee related

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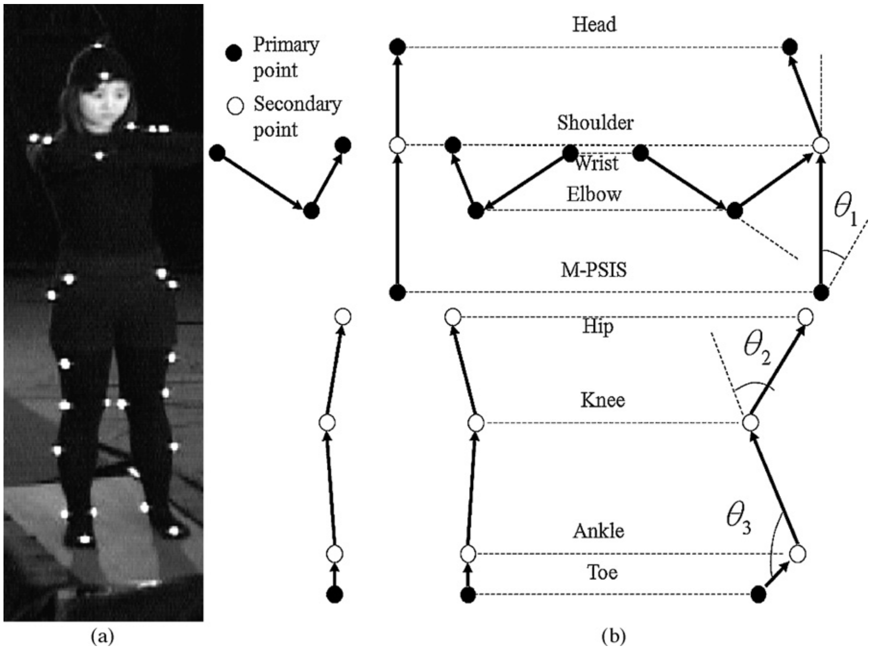

Fig. 1. (a) Positions of twenty-four reflective markers attached on selected bony landmarks of the subjects and (b) human link model constructed with the primary and secondary markers; the flexion–extension angles of the hip (θ_1), knee (θ_2), and ankle (θ_3) joints are defined from these markers in three-dimensional coordinates.

injuries can be evaluated more accurately by LE estimates than via conventional examinations with linear parameters. As reported by Stergiou et al. who compared linear parameters (range and area of circle) and nonlinear parameters (LE and approximate entropy) from Center-Of-Pressure in sitting from an infant patient with cerebral palsy, nonlinear parameters such as the LE can better detect changes concurrent with modifications of functional skills [28].

In the literature, the majority of studies reporting joint motions have focused on knee joints without investigation of differences between joints. Therefore, the first objective of this study was to determine the kinematic variability of the lower extremity joints using methods from the mathematical chaos theory in a normal walking environment in conjunction with a large population of healthy young adults. In order to accomplish this objective, LEs were estimated from a large population with both males and females and from both the right and left sides. Although it is generally known that joint movements can differ due to the different involvements of musculoskeletal and nervous systems of the joints resulting from the different roles of the joints in establishing walking stability, differences in their nonlinear dynamics have not been well characterized. Therefore, the second objective was to test the hypothesis that variability characteristics vary between joints and to further investigate differences between male and female and right and left subgroups.

2. Materials and methods

2.1. Joint motion capture system

A total of forty young healthy subjects (20 male subjects: 24.1 ± 3.1 years, 176.2 ± 5.3 cm, 73.2 ± 9.0 kg; 20 female subjects: 22.5 ± 3.2 years, 160.6 ± 5.1 cm, 52.7 ± 4.7 kg) with no history of joint diseases volunteered. The study was approved by the Institutional Review Board and all subjects provided informed consent prior to participation in the study. After enough time was given to all subjects to practice treadmill (KEYTEC® AC9, Taiwan) walking at self-selected walking speeds until they felt comfortable, their joint motions were recorded for 90 s using a three-dimensional motion capture system consisting of eight video cameras (DCR-VX2100, Sony, Japan), a custom three-dimensional calibration frame (width: 1 m, height: 2 m), and synchronization LEDs to synchronize recorded images. Twenty-four custom reflective markers (10 mm diameter hemisphere) were made with their surface covered by reflective film (Scotchlite TM 8700 series, 3 M, USA) to maximize the reflection of light. These reflective markers were carefully attached on the selected bony landmarks of subjects (Fig. 1a) in order to calculate the flexion–extension angles of the upper and lower extremities. This task was performed by one examiner to minimize positioning errors. However, this report is limited to the analysis of the lower extremity due to large information acquired. The results of joint motions in the upper extremity are still under analysis.

2.2. Flexion–extension angles

The images of joint motions were recorded for 90 s at a 60 frames/s rate while all subjects were walking normally on a treadmill. The three-dimensional coordinates of the markers attached on the subjects (primary marker coordinates) were obtained from the reference markers attached on the calibration frame using a direct linear transformation method of a KWON3D software (Visol Corp., Korea). The three-dimensional coordinates of virtual markers (secondary marker coordinates) are the temporary centers of joint motions, and should be provided to calculate the flexion–extension angles of joint motions. These secondary marker coordinates were computed from primary marker coordinates (Fig. 1b). For the ankle, the secondary marker coordinate (virtual marker coordinate) was the middle point between lateral and medial malleolus primary markers. Similarly, for the knee the secondary marker coordinate was the middle point between lateral and medial epicondyle primary markers. However, the center of the hip was calculated by adopting the methodology of Tylkowski et al. and Andriacchi et al. [34,35] from the left, right, and middle ASIS (Anterior Superior Iliac Spine) and extra greater trochanter markers. The flexion–extension angles of the hip (θ_1), the knee (θ_2), and the ankle (θ_3) were measured as a function