Gait & Posture 51 (2017) 77–83

Contents lists available at ScienceDirect

Gait & Posture

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

Full length article

Improved kinect-based spatiotemporal and kinematic treadmill gait assessment

Moataz Eltoukhy[a], Jeonghoon Oh[a], Christopher Kuenze[b], Joseph Signorile[a,c,*]

[a] Department of Kinesiology and Sport Sciences, School of Education & Human Development, University of Miami, Coral Gables, FL 33143, USA
[b] Department of Kinesiology, School of Education, Michigan State University, East Lansing, MI 48824, USA
[c] Center on Aging, Miller School of Medicine, 1695 N.W. 9th Avenue, Suite 3204, Miami, FL 33136, USA

ARTICLE INFO

Article history:
Received 23 June 2016
Received in revised form 27 September 2016
Accepted 2 October 2016

Keywords:
Gait analysis
Optoelectronic motion capture
Biomechanics

1. Introduction

Gait analysis is an effective clinical tool used for a wide range of applications including evaluating neurological diseases [1,2], fall risk [3], orthopedic disability [4], and progress during rehabilitation [5]. While optoelectronic motion capture systems are the gold standard for dynamic movement assessment, the high financial cost and technical expertise required to operate these systems and analyze the data, make them an unrealistic option for clinical use. Although movement patterns are commonly used to assess injury risk, progress during rehabilitation, and functional performance, these assessments are often subjective limiting their effectiveness, reliability and sensitivity to change [6,7]. The objective, quantitative nature of motion analysis could provide a clear improvement over these techniques and be of significant value within the clinical environment. Therefore, a publically available, cost-effective and clinician-friendly motion capture solution, allowing valid and reliable assessments of kinematic and spatiotemporal variables during functional movements, represents a logical step toward improved patient care.

Newly developed motion analysis technologies afford researchers and clinicians multiple options for assessing functional movement characteristics; however, many of these solutions have significant limitations. For example, wearable electromagnetic sensors are readily available [8,9]; but data are affected by gravity noise and signal drift [10]. Additionally, this technology is costly and requires technical expertise for data analysis. Alternatively, the Kinect sensor is a commercially-available, cost-effective video game accessory [11,12] capable of extracting data from 3D skeletal modeling [13]. The Kinect's validity, and its use with various biomechanical applications, has been examined previously [14–17]. While the first version of the Kinect (v1) had poor accuracy and tracking capacity [18], the new version (Kinect v2) may provide improved skeletal tracking with its higher camera and depth resolutions. The color (1920 × 1080 pixels) and depth (512 × 424 pixels) resolution of the Kinect v2 was significantly higher than the v1, allowing more precise joint trajectory tracking [2–5]. The Kinect's technological advancement, ease of data acquisition and processing software, increase its potential for accurately analyzing gait.

Poor agreement between Kinect v1 and optoelectronic motion capture systems for sagittal plane kinematic variables has been reported during treadmill lower extremity gait [19] and other functional movements [20]. These differences are not unexpected given the technological limitations of the Kinect v1. Studies have also demonstrated that the Kinect v1 and v2 are significantly better at assessing spatiotemporal parameters compared to lower extremity kinematic variables [21]. With the technological advancement of the v2 over the v1 camera, it is logical that tracking of sagittal plane joint range of motion during functional movement would significantly improve. But before the Kinect v2 can be utilized clinically for applications like gait analysis, its validity when assessing lower extremity kinematics must be established and compared to previous findings. To our knowledge,

---

* Corresponding author at: Department of Kinesiology and Sport Sciences, University of Miami, 1507 Levante Ave. Max Orovitz Building 114, Coral Gables, FL 33146, USA.
E-mail address: jsignorile@miami.edu (J. Signorile).

http://dx.doi.org/10.1016/j.gaitpost.2016.10.001

no studies have done this; therefore this study seeks to establish the validity of the Kinect v2 in assessing lower extremity sagittal plane kinematic and spatiotemporal parameters during treadmill gait analysis.

2. Methods

2.1. Subjects

Ten healthy subjects (5 males, 5 females, age: 26.7 ± 5.4 years, height: 174.4 ± 7.9 cm, mass: 71.8 ± 11.4 kg) participated in this study. All subjects were free of previous lower extremity surgery and were free of current injury that resulted in limitation of physical activity level. The study was approved by the University's Human Subjects Review Board, and all participants provided written consent.

2.2. Subject preparation

Upon arrival at the laboratory, subjects were familiarized with the experimental setup and outfitted with spandex attire to ensure optimal skeletal mapping during gait trials. Subjects were permitted to wear self-selected running or walking shoes. Subjects' heights, weights, and anthropometric measurements (leg length, knee width, and ankle width) were then recorded. Leg length (mm) was assessed by measuring the linear distance between the anterior superior iliac spine (ASIS) and the medial malleolus. Knee (medial epicondyle to lateral condyle) and ankle (medial malleolus to lateral malleolus) width (mm) were assessed using a spring caliper. Sixteen reflective markers were placed on anatomical landmarks according to the Vicon Plug-in-Gait lower extremity model [22]. Although significant limitations are associated with this marker set and gait model, it was selected due to its frequent use in clinical and research environments. Subjects were then asked to practice walking on the treadmill (LifeSpan TR1200, Human Solutions, Texas, USA) until they became comfortable during both testing speeds (1.3 and 1.6 m s^{-1}).

2.3. Experimental setup

Kinematic data were collected concurrently using an eight infrared camera motion analysis system (SMART-DX 7000, BTS Bioengineering, Milano, Italy) and a single Kinect v2 sensor (Microsoft Corp. Redmond, WA), positioned directly in front of the data collection area to optimize data collection within the treadmill's operational area. The Kinect sensor was placed 2.5 m from the subject, at a height of 0.75 m (Fig. 1).

2.4. Experimental procedures

Subjects began by holding a T-pose for 3 s to allow calibration of the systems prior to testing. To evaluate the Kinect at consistent normal and fast walking speeds, treadmill walking was performed at predetermined speeds, rather than self-selected, of 1.3 and 1.6 m s^{-1} respectively. To ensure gait pattern consistency and allow collection of a full gait cycle which not negatively influenced by trial initiation or termination, each trial lasted 15 s following the subject walking at least 30 s. Two trials were collected at each gait speed for each subject and the data collected in each trial at a given gait speed were averaged prior to analysis.

BTS data were sampled at 100 Hz and processed using Vicon Nexus software (VICON Motion Systems, Inc., Oxford, UK). Kinect data were sampled at 30 Hz using custom-built software. The Kinect's depth data stream was analyzed by isolating background depth information and tracking subjects' movements using anthropometric models to extract 26 joint trajectories utilizing the dynamic link library (DLL), .NET framework, and a customized MATLAB code (MathWorks, Massachusetts, USA) [23]. Joint angles were calculated as the angle between two vectors using the global coordinate system [24].

Heel strike (HS) was used to synchronize data streams between the systems. During the walking gait cycle, HS and toe off (TO) were defined using the method of Zeni et al. [25]. HS was defined as the point at which maximum anteroposterior distance between the ankle and mid-posterior superior iliac spine (PSIS) occurred; while TO was the point at which the minimum distance occurred.

2.5. Data analysis

The joints' coordinate system for both motion capture systems was consistent with International Society of Biomechanics recommendations (X-axis = mediolateral, Y-axis = vertical, Z-axis = anteroposterior) [26].

2.5.1. Kinematic analysis

Hip, knee, and ankle kinematic variables were calculated for each trial at each gait speed. Sagittal plane variables included total hip, knee, and ankle ranges of motion (ROM). Event-based

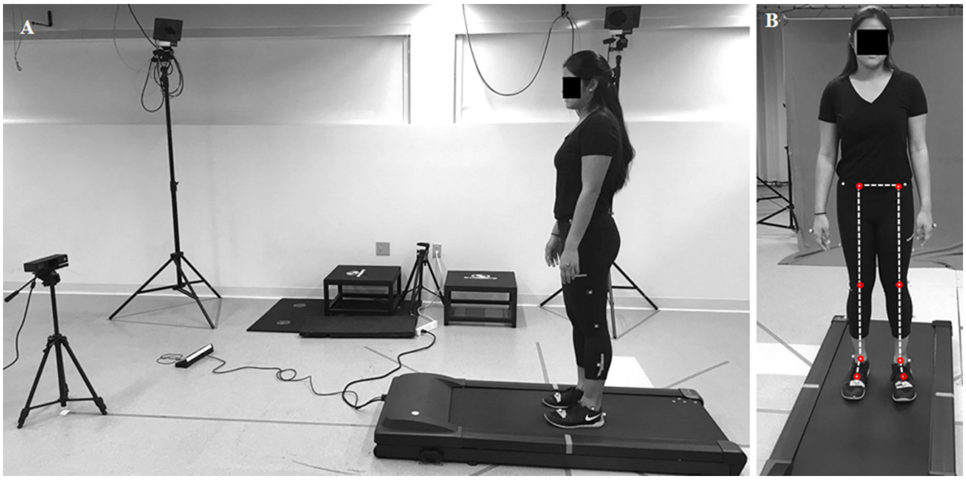

Fig. 1. (A) The experimental setup including eight BTS infrared cameras, one Kinect v2, and the LifeSpan treadmill. (B) Reflective markers attached to the subject's lower extremity and the Kinect skeleton (hip, knee, and ankle joints).