Short communication

A low cost real-time motion tracking approach using webcam technology

Chandramouli Krishnan *, Edward P. Washabaugh, Yogesh Seetharaman

Department of Physical Medicine and Rehabilitation, University of Michigan Medical School, Ann Arbor, MI, USA

ABSTRACT

Physical therapy is an important component of gait recovery for individuals with locomotor dysfunction. There is a growing body of evidence that suggests that incorporating a motor learning task through visual feedback of movement trajectory is a useful approach to facilitate therapeutic outcomes. Visual feedback is typically provided by recording the subject's limb movement patterns using a three-dimensional motion capture system and displaying it in real-time using customized software. However, this approach can seldom be used in the clinic because of the technical expertise required to operate this device and the cost involved in procuring a three-dimensional motion capture system. In this paper, we describe a low cost two-dimensional real-time motion tracking approach using a simple webcam and an image processing algorithm in LabVIEW Vision Assistant. We also evaluated the accuracy of this approach using a high precision robotic device (Lokomat) across various walking speeds. Further, the reliability and feasibility of real-time motion-tracking were evaluated in healthy human participants. The results indicated that the measurements from the webcam tracking approach were reliable and accurate. Experiments on human subjects also showed that participants could utilize the real-time kinematic feedback generated from this device to successfully perform a motor learning task while walking on a treadmill. These findings suggest that the webcam motion tracking approach is a feasible low cost solution to perform real-time movement analysis and training.

© 2014 Elsevier Ltd. All rights reserved.

1. Introduction

Gait abnormalities are common in individuals with a variety of neurological and orthopedic disorders (Beltran et al., 2014; Kao et al., 2014; Lamontagne et al., 2002; Lewek et al., 2002; Sosnoff et al., 2012). Physical therapy plays an important role in facilitating the recovery of locomotion (Hesse, 2001; Richards et al., 1999). Accordingly, therapists often spend a considerable amount of time and effort assessing and retraining locomotion with their patients. When assessing movement patterns, therapists typically rely on qualitative evaluations to quantify gait abnormalities (e.g., visual observation or videographic analysis). Qualitative gait analysis requires minimal instrumentation and is fairly simple, inexpensive, and easy to implement in routine clinical practice (Burnfield and Norkin, 2013). However, considerable training and practice are necessary to learn the observational skills necessary to perform such qualitative analysis. Further, the outcomes are very subjective and are considered to lack sufficient reliability to make any meaningful conclusions from the analysis (Burnfield and Norkin, 2013; Krebs et al., 1985).

Quantitative gait analysis addresses these limitations, and is increasingly sought by third-party payers when assessing patient function, establishing therapeutic strategies, and documenting patient progress. While there are some low cost devices for quantifying spatiotemporal parameters of gait (e.g., cadence, step length and symmetry, step and stride duration, etc.) (Bergamini et al., 2013; Salarian et al., 2010; Spain et al., 2012), there are not many low cost instrumentations for kinematic evaluation (Bonnet et al., 2012; Picerno et al., 2008). Further, these devices typically don't provide real-time data, which may be of particular interest to clinicians due to its application for gait training in virtual environment. An electro-goniometer is low cost and can provide real-time kinematic data (Peat et al., 1976); however, it can interfere with natural movement patterns due to cumbersome attachments and is less accurate when used for joints such as the hip or ankle (Manal and Buchanan, 2003). The Microsoft Kinect sensor device allows for economical and non-intrusive gait and motion analysis (Bonnechere et al., 2014; Clark et al., 2012, 2013; Galna et al., 2014; Schmitz et al., 2014). However, the software development kits are primarily designed to extract spatiotemporal parameters and typically don't work well for sagittal

* Correspondence to: Neuromuscular & Rehabilitation Robotics Laboratory (NeuRRo Lab), Department of Physical Medicine and Rehabilitation, University of Michigan, 325 E Eisenhower Parkway (Suite 3013), Ann Arbor, MI - 48108, USA. Tel.: +1 319 321 0117; fax: +1 734 615 1770.
E-mail address: mouli@umich.edu (C. Krishnan).

plane kinematics and when joints lie close to each other (Bonnechere et al., 2012, 2014; Pfister et al., 2014).

In this paper, we describe a novel low cost marker-based approach for real-time two-dimensional motion tracking using a webcam and an image processing algorithm in LabVIEW Vision Assistant. We also provide the results from a validation experiment performed using a high-precision lower-extremity gait robot called the Lokomat. Further, we report the feasibility of real-time motion tracking using an established target-tracking approach that has the potential to facilitate gait recovery after stroke.

2. Methods

2.1. Hardware and algorithm for real-time tracking

The hardware required for acquiring the marker data were procured from Noraxon USA, Inc. (Scottsdale, AZ). These included a Logitech HD Pro Webcam C920 (1080p, 30 FPS), a SunPAK 6600DX heavy duty tripod, a Rigid Industries floodlight, and standard 19 mm retroreflective markers. The camera was connected to a Windows computer via an USB 2.0 cable. All data were collected and processed using custom-written programs in LabVIEW and Vision Assistant, version 2011 (National Instruments Corp., Austin, TX, USA). The steps involved in processing the data are as follows:

First, the program captures a frame of the video using IMAQdx Grab VI [Video Mode=32 (800 × 600 MJPJ 30FPS), Gain=255 (maximum), Exposure=0 (minimum); Brightness=128 (medium); and Contrast=1.28 (medium)]. A region of interest is then selected using the IMAQ ConstructROI VI. The program filters the image data for the brightest (whitest) parts of the image using the IMAQ ColorThreshold VI and Binary Inverse VI. Here, pixels past a certain whiteness threshold are set to 1, the rest are set to 0. Thus, all pixels containing markers are set to 1. Next, the program discards everything outside the region of interest using the IMAQ ROIToMask 2 VI. The program looks at pixel values of 1 and selects items that are in the shape of a circle within a specified radius using IMAQ Find Circles VI. Finally, the program outputs real-time pixel coordinates of all these circles (i.e., the markers).

2.2. Real-time 2D kinematic tracking

A three-point model can be created from the hip, knee, and ankle markers to obtain two-dimensional kinematics of the hip and the knee joint during walking using the following equations.

$$Hip\ Angle = \arctan2\left([x_{knee} - x_{hip}]|[y_{hip} - y_{knee}]\right)$$

$$Knee\ Angle = (90 - Hip\ Angle) - \left(\arctan2\left([y_{ankle} - y_{knee}]|[x_{ankle} - x_{knee}]\right)\right)$$

where *Hip* (relative to the vertical trunk) and *Knee Angles* represent the anatomical joint angles, x_{hip}, x_{knee} and x_{ankle} represent the *x*-coordinates, and y_{hip}, y_{knee} and y_{ankle} represent the *y*-coordinates of the markers over the respective anatomical landmarks.

2.3. Validation experiment using the Lokomat gait robot

A validation experiment using a lower extremity driven gait orthoses called as the Lokomat was conducted to validate the kinematic data obtained using our webcam tracking methodology. The Lokomat is a robotic device commonly used for gait training in individuals with neurological disorders (Jezernik et al., 2003; Krishnan et al., 2013a; Mayr et al., 2007). The device has four linear actuators for controlling the hip and knee joint motions and four potentiometers to measure hip and knee joint angles. We used the Lokomat system as our test bed for validating the results from our tracking system for two reasons: (1) The device can be configured to a 'position control mode', where the robot's stiffness is high, which enables it to impose predefined motions with high repeatability and precision (Jezernik et al., 2003) and (2) the Lokomat provides movements only in the sagittal plane, which eliminates the possibility of errors due to off-plane motions.

Miniature battery operated LED markers were placed over the hip joint, knee joint, and the distal end of the Lokomat's leg for tracking robotic gait movements. We used miniature LED markers for motion tracking as passive reflective markers cannot be tracked well over reflective surfaces. The pelvis of the Lokomat was secured to the rails of the Lokomat treadmill system to minimize unwanted vertical oscillatory movements. The robotic legs of the Lokomat were then set to move on a predefined gait trajectory at several walking speeds (1.0, 1.2, 1.5, 1.7, 2.0, 2.2, 2.5, 2.7, and 3.0 km/h randomly ordered). Kinematic data were recorded simultaneously from the potentiometers of the Lokomat and from the Webcam system for 2 min at each testing speed.

2.4. Human subjects experiment for assessing reliability and feasibility of real-time tracking

Experimental data were collected from four young healthy adults on two consecutive days to test reliability and feasibility of real-time target tracking. Prior to participation, subjects signed an informed consent document approved by the University of Michigan Human Subjects Institutional Review Board. Three 19 mm retroreflective markers were placed over the subject's greater trochanter, lateral femoral epicondyle, and lateral malleolus. The subject then walked over a motorized treadmill (Woodway USA) with their hands placed on a custom built treadmill rail system (Fig. 1A). The kinematic data during treadmill walking were captured using the real-time marker tracking algorithm described above. The baseline kinematic data collected for 1 min during normal walking were then ensemble averaged across gait cycles and scaled to generate a target-template trajectory. The target-template trajectory corresponded to a gait pattern that required increasing the hip and knee joint angle by a scale of 30% during the swing phase of the gait and was projected in the end-point space (i.e., spatial path of subject's lateral malleolus on the sagittal plane) (Fig. 1B) (Krishnan et al., 2012, 2013b). A forward kinematic analysis on the hip and knee joint angles was used to obtain the position of the subject's ankle
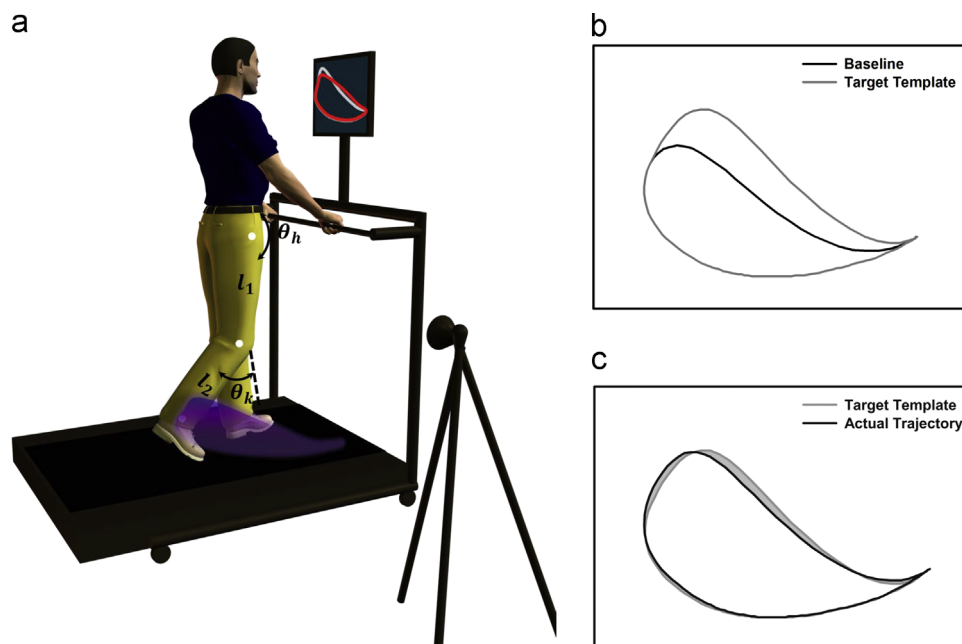

Fig. 1. (A) Schematic representation of real-time tracking set-up. (B) Schematics of target-template and (C) tracking error computation.