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Towards an affordable mobile analysis platform for pathological walking assessment

V. Bonnet [a,*], C. Azevedo Coste [b,c], L. Lapierre [b], J. Cadic [b], P. Fraisse [b], R. Zapata [b], G. Venture [d], C. Geny [a,e,f]

[a] M2H/EUROMOV, University of Montpellier 1, Montpellier, France
[b] LIRMM, CNRS-University of Montpellier 2, Montpellier, France
[c] INRIA-LIRMM, DEMAR, Montpellier, France
[d] Department of Mechanical Systems Engineering, Tokyo University of Agriculture and Technology, Japan
[e] CHU Montpellier, Neurology Department, France
[f] CHU Montpellier, Internal Medicine and Gerontology Service, France

HIGHLIGHTS

- Mobile robot for clinical assessment of gait.
- Kinect sensor based gait analysis platform.
- Autonomous mobile robot for freezing of gait detection.

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ABSTRACT

This paper proposes an affordable mobile platform for pathological gait analysis. Gait spatio-temporal parameters are of great importance in clinical evaluation but often require expensive equipment and are limited to a small and controlled environment. The proposed system uses state-of-the art robotic tools, in contrast to their original use, for the development of a robust low-cost diagnostic decision-making tool. The mobile system, which is driven by a Kinect sensor, is able to (1) follow a patient at a constant distance on his own defined path, and (2) to estimate the gait spatio-temporal parameters. The Robust Tracking-Learning-Detection algorithm estimates the positions of the targets attached to the trunk and heels of the patient. Real-condition experimental validation including the corridor, occlusion cases, and illumination changes was performed. A gold standard stereophotogrammetric system was also used and showed good tracking of the patient and an accuracy in the stride length estimate of 2%. Finally, preliminary results showed an RMS error that was below 10° in the 3D lower-limb joint angle estimates during walking on a treadmill.

1. Introduction

Evaluation of gait abnormalities is important in the clinical assessment of a patient over time in a large number of medical disorders related to the central nervous system, muscular system, or orthopaedic disabilities, which often affect gait pattern [1]. This evaluation is essential for diagnosis or research purposes and can be performed via a simple visual observation during the medical consultation, i.e., a standard procedure such as the six-minute walking test [2] or a more complete quantitative evaluation in a dedicated laboratory [3]. Devising low-cost and easy-to-use tools to measure the nominal value and the variability of gait spatio-temporal parameters such as step length, gait events [4] or 3D trunk orientation [5] has been the target of extensive studies in or during the last two decades. Indeed, these parameters are representative of the compensatory mechanisms adopted in pathological walking [6]. Some studies have also focused on the detection and identification of a particular gait disorder, such as the freezing of gait [7], which is observed in the majority of people with Parkinson's disease. This freezing of gait (FOG) is the temporary, involuntary inability to move when initiating gait,

* Corresponding author.
E-mail address: bonnet.vincent@gmail.com (V. Bonnet).

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passing through a door, turning, or negotiating an obstacle. The freezing of gait is closely related to the risk of falling [8] and can occur at any time. FOG can occur for very different periods of time and is usually studied using video recordings of the patient's gait [7]. Consequently, trigging protocols of freezing in a confined environment in which video recording, using single or multiple cameras, have been developed [7,8].

Thus, measuring and visualising the patient's walking ability in the clinic but outside of a dedicated motion analysis laboratory for extended periods of time and mobilising the less possible medical staff is one of the goals of bioengineering studies. Although these studies have been performed for decades, most of the existing systems are task- and/or population-specific and/or often require a large investment.

To achieve these purposes, inertial measurement units (IMUs), embedding a 3-axes accelerometer and gyroscope, have gained in popularity due to their low cost and their ease of use [4,5]. Unfortunately, the IMU outputs are subject to a large non-linear drift over time, which jeopardises their time integration [9]. Advanced adaptive filters [5,9] have been used for orientation assessment, but they are task- and population-specific. An assessment of displacement during gait is based on the detection of the zero crossing of the trunk or shank accelerations corresponding to gait events. These events are subsequently used in combination with inverted pendulum models to estimate the step length [10] during straight walking. These biomechanical assumptions can result in very large discrepancies in the case of pathological walking or over prolonged periods of time, and IMU positioning is very sensitive [4,6]. With regard to the detection of freezing events, recent studies have used several IMUs located in the lower limbs for a maximal rate of detection of 80% of positive detection when compared to manual detection performed by clinicians on videotape [7].

Taking into account these considerations, an affordable mobile robot that is able to follow a patient outside the motion analysis laboratory with the purpose of measuring gait spatio-temporal parameters while providing visual video feedback recorded at a constant distance would be a great advantage to clinicians.

The person who is following the patient has two tasks, i.e., the person tracking and the robot navigation or its path generation. Person tracking can use any of the numerous sensor technologies available depending on the context. Measurements from a laser can be used to extract the subject's legs, but other persons or even tables or chair legs can make robust detection difficult [11]. To improve the tracking performance, some authors proposed to merge laser and infrared data [12] or to use an omnidirectional camera [13]. Approaches based on single or multiple cameras to follow a subject have often been proposed [14–17] and have been more recently combined with a depth map [18]. Indeed, a new type of very affordable sensor called light coding has recently become available. The Kinect sensor, which was released by Microsoft®, is a low-cost, compact and lightweight sensor that provides both colour and depth map information. It is being increasingly mainly used in mobile robotics for indoor navigation [19,20] but also for person-following [21–24]. The Kinect sensor represents a significant reduction in robot costs for the replacement of other sensors, including the expensive laser [24]. It is associated with many software that allow for various interactions with humans, but it also allows skeletal tracking or person 3D centroid detection, which is mainly based on silhouette segmentation using the depth map [24]. However, even if several groups have reported using the Kinect sensor person detection ability with mobile robots, few studies have published their results [24]. Moreover, other groups have developed their own algorithms [23,25]. In our application, algorithms such as skeletal tracking will most likely fail because one or several clinicians can be interacting with the patient or they can walk over a short period of time between the robot and the patient. Furthermore, these depth map-based algorithms were originally developed for entertainment purposes and are supposed to be used in an open environment in contrast with our application, which can occur in constrained environments such as a corridor.

To the best of our knowledge, a low-cost mobile gait analysis platform has never been developed and could become very useful for gait clinical assessment. Recently, Ojeda et al. [26] proposed a promising prototype of a mobile platform that yields high accuracy in human gait analysis and subject 3D absolute positioning. However, this approach, which embeds a high-frequency active motion capture system consisting of six cameras and a low-drift gyroscope, requires a large investment and does not provide videotaping. Importantly, no information is provided in their paper concerning the subject-following performance. Indeed, it appears that the mobile platform does not automatically follow the subject while walking and requires an external person to move. Thus, the objectives of this study were to propose a low-cost mobile platform that is able to:

– autonomously follow the patient at a constant distance outside the motion analysis laboratory but still within a clinical environment,
– provide a visual feedback for clinicians to evaluate the freezing of gait,
– accurately estimate the stride length during straight walking and validate this measurement,
– assess the future ability of the proposed system in providing amplitude and temporal information on the lower-limb joint angles.

In this study, the low-cost aspect, the ease of use and the assessment of reliability in spatio-temporal measurements are of great importance to allow such devices to be widely used among the clinician community. The novelty of the approach is the development of algorithms that allow the ability to autonomously follow a patient while accurately estimating stride length during straight walking, including a visual feedback of gait. In addition to a new, parcimonial and robust path generation method from human motion estimated from a noisy low-cost sensor, the use of state-of-the art mobile robotics path planning, path recovery and visual servoing approaches has been validated in a different context compared to previous methods. Finally, a new method to estimate human stride length from a mobile platform has been developed and has proven to be robust to noise and odometry inaccuracy.

Consequently, this paper is organised as follows: Section 2 presents a low-cost platform and its hardware components. Tracking of the person and the associated visual servoing and path construction and following are discussed in Section 3. The strategy used to estimate the stride length is detailed in Section 4. The last section discusses the experimental validation in the real-clinical assessment condition using a stereophotogrammetric system as a gold standard measurement tool.

2. Hardware

The low-cost mobile gait analysis platform was implemented on an experimental mobile robot shown in Fig. 1. The mobile robot is based on a generic differential drive mobile platform with two propulsive wheels and one castor wheel (Pioneer 3DX robotic platform). A Kinect sensor, which provides colour and depth images with 640 × 480 resolution, was mounted horizontally on a mast at a tunable height that was selected to be approximately at the subject's pelvis height. Under ideal conditions, the resolution of the depth information can be approximately 3 mm [27]. In general, the further the Kinect sensor is from the object to measure, the less accurate the depth map obtained. To measure the trunk and heel positions with the best accuracy and to account for the