Medical Engineering and Physics 38 (2016) 442–449

Contents lists available at ScienceDirect

Medical Engineering and Physics

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

Objectively quantifying walking ability in degenerative spinal disorder patients using sensor equipped smart shoes☆

Sunghoon Ivan Lee[a,b,c,d,*], Eunjeong Park[c,d], Alex Huang[e], Bobak Mortazavi[c,d,f], Jordan Hayward Garst[e], Nima Jahanforouz[e], Marie Espinal[e], Tiffany Siero[e], Sophie Pollack[e], Marwa Afridi[e], Meelod Daneshvar[e], Saif Ghias[e], Daniel C. Lu[e,g,h,i], Majid Sarrafzadeh[c,d]

[a] Department of Physical Medicine & Rehabilitation, Harvard Medical School, Charlestown, MA 02129, USA
[b] Spaulding Rehabilitation Hospital, Charlestown, MA 02129, USA
[c] Computer Science Department, UCLA, Los Angeles, CA 90095, USA
[d] Wireless Health Institute, UCLA, Los Angeles, CA 90095, USA
[e] Department of Neurosurgery, UCLA, Los Angeles, CA 90095, USA
[f] Center for Outcomes Research and Evaluation, Yale School of Medicine, New Haven, CT 06510, USA
[g] Neuroplasticity and Repair Laboratory, UCLA, Los Angeles, CA 90095, USA
[h] Neuromotor Recovery and Rehabilitation Center, UCLA, Los Angeles, CA 90095, USA
[i] Department of Orthopaedic Surgery, UCLA, Los Angeles, CA 90095, USA

ARTICLE INFO

Article history:
Received 31 May 2015
Revised 27 November 2015
Accepted 7 February 2016

Keywords:
Lumbar spinal stenosis
Spinal cord disorder
Self-paced walking test
Pressure mapping
Smart shoes
Functional level
Walking ability

ABSTRACT

Lumbar spinal stenosis (LSS) is a condition associated with the degeneration of spinal disks in the lower back. A significant majority of the elderly population experiences LSS, and the number is expected to grow. The primary objective of medical treatment for LSS patients has focused on improving functional outcomes (e.g., walking ability) and thus, an accurate, objective, and inexpensive method to evaluate patients' functional levels is in great need. This paper aims to quantify the functional level of LSS patients by analyzing their clinical information and their walking ability from a 10 m self-paced walking test using a pair of sensorized shoes. Machine learning algorithms were used to estimate the Oswestry Disability Index, a clinically well-established functional outcome, from a total of 29 LSS patients. The estimated ODI scores showed a significant correlation to the reported ODI scores with a Pearson correlation coefficient (r) of 0.81 and $p < 3.5 \times 10^{-11}$. It was further shown that the data extracted from the sensorized shoes contribute most to the reported estimation results, and that the contribution of the clinical information was minimal. This study enables new research and clinical opportunities for monitoring the functional level of LSS patients in hospital and ambulatory settings.

1. Introduction

Lumbar spinal stenosis (LSS) is a condition closely related with age-associated degeneration of the lumbar (i.e., lower back) spinal disks [1]. It is known as the most common diagnosis leading to spinal surgery in elderly patients of age greater than 65 years [2], and approximately 40% of general adult populations are known to carry moderate conditions of LSS [3]. As a consequence of the worldwide trend of aging societies in developed and developing countries, a significant majority of the elderly population is expected to experience LSS [4].

LSS is characterized by a narrowing of the spinal canal and compression of nerve roots in the lower back [1], which lead to various clinical symptoms including leg pain, numbness, and weakness [5]. Thus, patients with LSS have considerable walking limitation [1,3,6,7], which is the leading cause of spinal surgery in Medicare recipients [3,8]. The primary objective of medical treatment has been focused on improving functional outcomes, e.g., the walking ability [3]. Consequently, researchers and clinicians have focused their attention on the development of objective, inexpensive, and accurate assessment tools to quantify the level of functional capacity, which can be used to track the longitudinal progress of patient conditions.

☆ The word count of this document is 4735 (words), which does not include the title, author list, abstract, and references.

* Corresponding author at: Department of Physical Medicine & Rehabilitation, Harvard Medical School, Charlestown, MA 02129, USA. Tel.: +1 617 952 6332.

E-mail addresses: slee117@partners.org (S.I. Lee), ejpark@cs.ucla.edu (E. Park), ahuang@mednet.ucla.edu (A. Huang), bobak.mortazavi@yale.edu (B. Mortazavi), jgarst@mednet.ucla.edu (J. Hayward Garst), dclu@mednet.ucla.edu (D. C. Lu), majid@cs.ucla.edu (M. Sarrafzadeh).

http://dx.doi.org/10.1016/j.medengphy.2016.02.004
1350-4533/

Instrumented examination of walking ability has the potential to support such a need compared to traditional clinical tools such as radiographic testing (e.g., X-ray, Magnetic Resonance Imaging (MRI), and Computed Tomography (CT) images [1]) and self-reported functional outcomes (e.g., Oswestry Disability Index (ODI) [9], Swiss Spinal Stenosis Questionnaire, and Oxford Claudication Score [10]). Several observational studies recently validated the clinical efficacy of gait parameters recorded from self-paced walking tests (SPWT) or motorized treadmill tests (MTT) [3,6,7,11]. In these works, patients were asked to walk on a flat surface (SPWT) and/or a treadmill (MTT) at preferred speeds until they voluntarily stopped due to symptoms of LSS or until they reached the predefined maximum time duration (e.g., 30 min). Two parameters related to walking capacity (i.e. time and distance traveled) were tested for their correlations to the perceived functional level obtained by using patient-reported outcomes. The work by Conway et al. [6] concluded that the traveled distance of SPWT had a statistically significant correlation with ODI scores. The work by Rainville et al. [3] performed both SPWT and MTT, and concluded that gait parameters extracted from MTT has better correlation to the functional outcomes than SPWT. The work by Tomkins-Lane et al. [11] examined the changes in the value of ODI and the changes in the traveled distance of SPWT, and found a significant correlation between the two. The work by Conway et al. [6] also monitored levels of physical activity (i.e. activity count and maximum time of continuous activity) of LSS patients using a waist-worn accelerometer over several days, but their correlations to the patient-reported outcomes were not as significant as the gait parameters from walking tests.

The aforementioned works demonstrated the clinical effectiveness of gait parameters for their use as objective measures. However, SPWT and MTT are not fully automated and require presence of a clinical professional who needs to manually record the gait parameters. Moreover, these tests may require patients to walk for up to 30 min. These may serve as barriers to use the SPWT and MTT in clinical and ambulatory settings, considering the patients' adherence (or preference) to the testings for frequent and longitudinal tracking of functional level. Furthermore, all the aforementioned analyses investigate correlation between a single-dimensional gait parameter and the clinical score, rather than incorporating multi-dimensional gait parameters. This may restrict the quantification of motor function to be relatively simple and prohibit integrating multiple walking characteristics in the measure.

This paper introduces a fully automated system and its method that quantify the functional level of LSS patients by analyzing their walking ability using a pair of sensorized shoes equipped with pressure sensors. The method employed a self-paced walking test on a 10 m flat trail, which took approximately 6 min to complete. A total of 76 spatio-temporal features that were extracted from the smart shoes and 12 clinical variables that were previously found to be relevant to the functional level were used to estimate the clinical scores obtained by using the ODI [12], a clinically well-established outcome measure in lower back pain patients [13]. This paper discusses two machine learning algorithms designed to estimate clinical scores collected during the preoperative and postoperative visits, respectively. The clinical efficacy of the system was investigated through a pilot cohort involving 29 LSS patients.

2. Materials

2.1. Participants

A total of 29 patients (11 males and 18 female) with LSS were recruited from the UCLA Spine Center. The ages of the participants ranged from 28 to 78, with an average and standard deviation of 57.4 ± 15.9 at the time of surgery. All patients were diagnosed with LSS as a result of lumbar disk herniation, lumbar spondylolisthesis, or adjacent segment disease. All patients had radiculopathy or axial pain in the lower limbs, which affected their walking ability. Patients who had comorbidities that may affect their lower motor function and gait performance were excluded from the study. All patients received lumbar decompression and/or lumbar fusion surgery performed by a single neurosurgeon (DCL). The experimental procedure was approved by the UCLA institutional review board, and all patients provided consent to participate in the study.

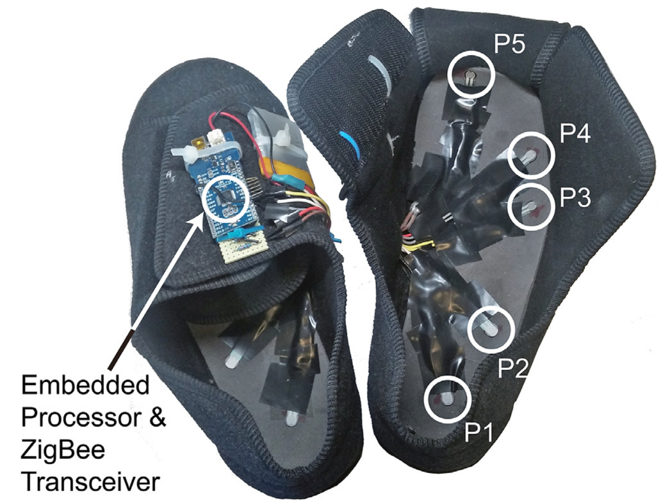

Fig. 1. A picture of the sensorized shoes containing an array of five pressure sensors and a wireless data transceiver. Pressure sensors on the insole were positioned to detect heel-strike (P1), mid-lateral plantar pressure (P3), toe pressure (P5) and other spatio-temporal information (P2 and P4).

2.2. Sensory platform

A pair of shoes equipped with an array of five pressure sensors was developed as shown in Fig. 1. The pressure sensors on the insole were positioned to detect heel-strike (P1), mid-lateral plantar pressure (P3), toe pressure (P5) and other spatio-temporal information (P2 and P4). An embedded system on each shoe collects sensory data at a sampling rate of 80 Hz and transmits the data in real-time to the base station (i.e. a laptop) via the IEEE 802.15.4 standard (i.e. ZigBee protocol) [14]. Each shoe establishes a wireless connection to the base station independently. A total of five shoes with different sizes were made for both males and females. The pressure sensors on the insole were positioned linearly proportional to the size of the shoe.

2.3. Experimental protocol

Fig. 2 illustrates the experimental protocol. A straight 10 m long trail was marked on a level floor as was suggested by Perry [15] for a stride analysis. Patients were asked to wear the sensorized shoes and walk on the trail at a self-paced speed, turn around, and walk back to the original position. Patients were asked to pause for five seconds before walking, before the turn, before walking back, and after reaching the final destination (Fig. 2); these five second defaults were used as annotations to segment the collected data. No further instruction was given to the patients regarding their gait performance and behavior. Patients repeated this procedure twice, which resulted in a maximum of four 10 m walks per clinical visit (or per test).

All 29 patients performed the walking test approximately one hour before their surgical operation. In this work, the sensor and