Mechatronics 23 (2013) 646–651

Contents lists available at SciVerse ScienceDirect

Mechatronics

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

A tele-monitoring system for gait rehabilitation with an inertial measurement unit and a shoe-type ground reaction force sensor

Joonbum Bae [a,*], Masayoshi Tomizuka [b]

[a] School of Mechanical and Advanced Materials Engineering, UNIST, Ulsan, Republic of Korea
[b] Department of Mechanical Engineering, University of California, Berkeley, CA 94720, USA

ARTICLE INFO

Article history:
Received 22 December 2012
Accepted 18 June 2013
Available online 26 July 2013

Keywords:
Tele-monitoring
Gait rehabilitation
Inertia measurement unit
Ground reaction force

ABSTRACT

In this paper, a tele-monitoring system is proposed, using an inertial measurement unit (IMU) and a shoe-type ground reaction force (GRF) sensor called a Smart Shoe to measure a patient's walking data, and transmitting the measured data via the Internet. In our previous work, a mobile gait-monitoring system was developed, which provided visual feedback based on GRFs measured by a Smart Shoe (used as a mobile platform). However, the limited information provided by the Smart Shoe alone may not be adequate for a tele-monitoring system using the Internet. In the present tele-monitoring system for gait rehabilitation, a Smart Shoe is combined with an IMU for detailed monitoring of walking motions. By analyzing the signals from the IMU and the Smart Shoe, foot trajectories, walking distance, length of stride, etc., can be estimated. A user-friendly graphic interface displays the measured or estimated data on separate computers at the patient's location and the physical therapist's office. Thus, using the proposed system, it is possible to monitor a patient's walking motion via the Internet, without restrictions on time or place.

1. Introduction

Gait rehabilitation treatment is usually administered manually by a physical therapist in a rehabilitation facility. The physical therapist diagnoses the patient's status based on walking data, and then provides an appropriate gait rehabilitation intervention. Since evaluation of the patient's status from detailed monitoring data is one of the most fundamental aspects of the rehabilitation process, numerous evaluation methods and monitoring systems have been developed. The Fugl-Meyer Assessment [9], Functional Independence Measure (FIM) [11], and Barthel Index [7] have been widely used to evaluate motor and sensory impairment. However, these questionnaire-based methods are difficult to use for observation or assessment of the dynamic motions of daily living, such as walking motions, and monitoring such dynamic motions mainly depends on the experience, knowledge, and observational skills of the physical therapist.

The sensor sets required to quantitatively measure and assess dynamic motions are usually complicated, and are applicable only in specially equipped environments, such as research laboratories or hospitals. Also, rehabilitation treatments are administered to patients only when they visit a rehabilitation facility, and thus the rehabilitation effect is experienced only during rehabilitation sessions. Camera-based methods such as VICON [20] are widely used for observing gait motions. These methods require several optical markers to be mounted on the human body, and the light reflected from the markers is detected by cameras. They produce well-quantified and accurate results regarding joint motions of the lower extremities, but are restricted to a laboratory environment, and are difficult to apply to activities of daily living. Tight clothes are also required for marker placement, which may cause patients to alter their gait.

Recent advances in mobile and wireless communication technologies have enabled the development of mobile or tele-rehabilitation systems for improved rehabilitation. Pappas et al. developed a gait-phase detection system that uses various sensors, including a force-sensitive resistor (FSR) for measuring foot pressure [18]. Bamberg et al. devised a shoe-integrated wireless sensor system, which measures foot pressure using four FSRs [6]. Morris et al. developed a shoe-integrated sensor system for wireless gait analysis that provided real-time feedback [15]. However, an FSR cannot reflect the actual foot pressure over a large area, due to its small size and low maximum range. Several commercial shoes with hundreds of embedded FSRs provide a detailed pressure distribution [19,16], but are redundant for gait monitoring and assessment of gait abnormality in terms of cost efficiency.

In our previous work, a mobile gait-monitoring system (MGMS) was developed to monitor the ground reaction forces (GRFs) and

* Corresponding author. Tel.: +82 52 217 2335.
E-mail addresses: jbbae@unist.ac.kr (J. Bae), tomizuka@me.berkeley.edu (M. Tomizuka).

0957-4158/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.mechatronics.2013.06.007

evaluate the status of a patient [4]. The MGMS utilized a shoe-type GRF measurement system called a Smart Shoe, which measures the pressure changes in four air-bladders embedded under the insole [12,13]. Although the GRFs measured by the MGMS provide useful information for monitoring a patient's walking, the information is insufficient for detailed monitoring. Also, a physical therapist should be present to provide rehabilitative assistance.

In this paper, a tele-monitoring system that transmits gait information via the Internet to facilitate gait rehabilitation is proposed. The patient's information is measured by both an inertial measurement unit (IMU) and a Smart Shoe. Using the real-time measurements of the IMU and the Smart Shoe, it is possible to remotely monitor the patient's gait status with redundant information. The transmitted signals provide data regarding 3D foot trajectories, walking distance, length of stride, GRFs, etc., for analysis. A user-friendly graphical interface is installed on computers at the patient's location and the physical therapist's office to enable monitoring. Thus, the proposed tele-monitoring system allows gait monitoring under the natural conditions of daily life, and its use is not restricted to a rehabilitation facility.

This paper is organized as follows. Section 2 introduces the configuration of the proposed tele-monitoring system for gait rehabilitation. Detailed algorithms for monitoring walking motions using the IMU and the Smart Shoe are presented in Section 3, together with experimental results. Transmission via the Internet is discussed in Section 4. A summary and conclusions are provided in Section 5.

2. System configuration

The proposed tele-monitoring system for gait rehabilitation is illustrated in Fig. 1. The patient's walking is monitored by the IMU and the Smart Shoe, and the measured information is transmitted via the Internet to a physical therapist at a location remote from the patient.

The sensors in the proposed system consist of an inertial measurement unit (IMU) and a Smart Shoe (Fig. 2). The Smart Shoe was developed to allow detection of motion phases in the gait by measuring ground reaction forces (GRFs), which were used to evaluate the patient's status or for control of an assistive system [12,4,2,3,1]. The accuracy of the Smart Shoe was verified by comparing with a force plate and the VICON system [4]. In the present system, an inertial measurement unit (IMU) is combined with a Smart Shoe to measure the position or posture of the foot, and thus provide detailed information about the patient's walking motions.

Fig. 2. A tele-monitoring system for gait rehabilitation with Smart Shoes and an IMU.

An IMU has an accelerometer, a gyroscope and a magnetometer to measure accelerations, angular velocities and magnetic fields, respectively, in the body frame, whose coordinates are the local coordinates of the sensor. Motion in the navigation frame, whose coordinates are global, is estimated from the sensor measurements in the body frame, using the rotation matrix. The rotation matrix, which expresses the coordinate relationship between the body frame and the navigation frame, is estimated from gyroscope and magnetometer signals [8,17,10]. Position and velocity in the body frame are calculated by integrating accelerations in the navigation frame, which are converted from accelerations in the body frame via the rotation matrix. There has been considerable research on use of IMUs for indoor tracking [8,17,10]. However, IMUs have seldom been applied to gait rehabilitation systems such as that discussed in the present paper. The proposed tele-monitoring system

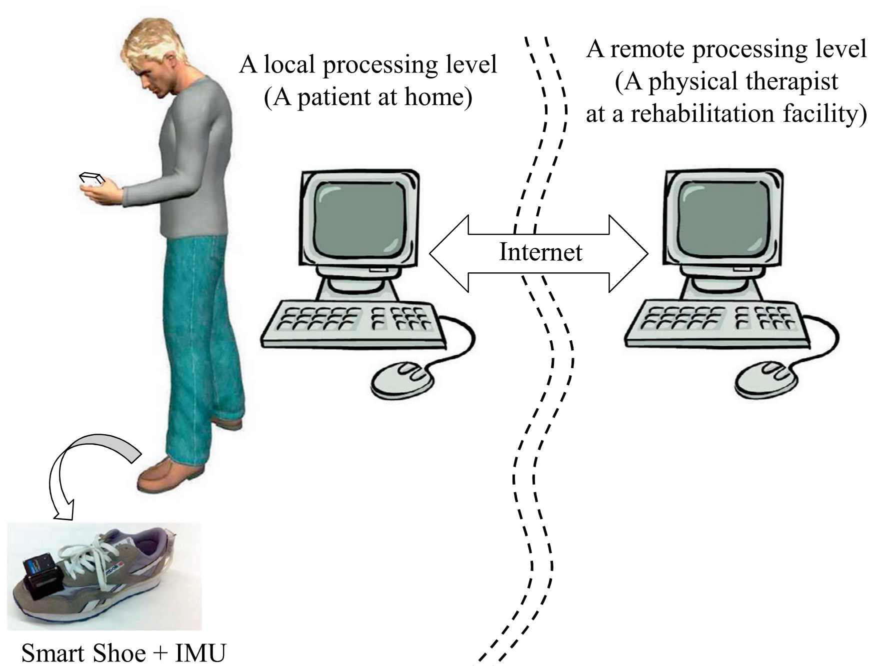


Fig. 1. Concept of a tele-gait monitoring system.

uses the 3DM-GX2 sensor from MicroStrain [14], which includes a three-axis accelerometer, a three-axis gyroscope and a three-axis magnetometer.

In the proposed tele-monitoring system for gait rehabilitation, the measured and estimated quantities are transmitted to a physical therapist via the Internet. Use of the Internet enables better rehabilitation services anywhere, anytime, by providing immediate guidance for rehabilitation treatment, as well as alerts for emergency situations. The network platform for the tele-monitoring system is divided into two levels: a local processing level and a remote processing level, as shown in Fig. 1. At the local processing level, raw signals from the IMU and Smart Shoe are processed to estimate foot postures or gait phases, so that the size of the data packets transmitted through the Internet is limited. A user-friendly graphic interface, which displays the foot posture in 3D space, the GRFs, etc., is installed on both the local and remote computers.

3. Monitoring gait motions

3.1. Estimation of foot position

In the navigation system, the body frame is a local frame attached to a sensor, and the navigation frame is a global frame (Fig. 3). Quantities measured in the body frame can be converted to corresponding quantities in the navigation frame using the rotation matrix, M, as follows.

$$x_n = M'x_b \tag{1}$$

where x_n and x_b represent corresponding quantities in the navigation frame and body frame, respectively.

The rotation matrix can be estimated from gyroscope and magnetometer measurements [8,17,10]. However, since the rotation matrix is directly available with a 3DM-GX2 sensor, it was not necessary to estimate it in this way. The output of the accelerometer, y_a, can be expressed as

$$y_a = a_b + \upsilon_a + M \cdot g \tag{2}$$

where a_b is the true (non-gravitational) angular acceleration in the body frame, υ_a represents noise in the output, and g is the acceleration due to gravity. The acceleration in the navigation frame can be calculated by:

$$a_n = M' \cdot y_a - g \tag{3}$$

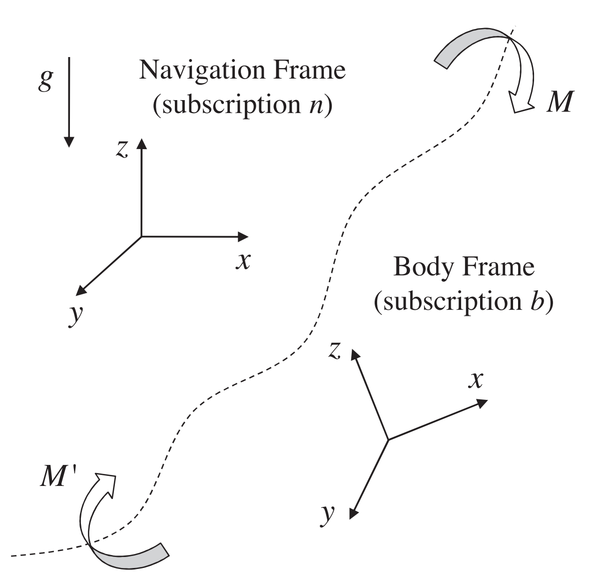


Fig. 3. A navigation frame and a body frame in the navigation system.

Velocity and position, υ_n and r_n, in the navigation frame can be estimated by integrating the acceleration formula in (3). In the discrete time domain, these are calculated as follows:

$$\upsilon_n(k) = \upsilon_n(k-1) + \frac{T}{2}(a_n(k) + a_n(k-1)) \tag{4}$$

$$r_n(k) = r_n(k-1) + \frac{T}{2}(\upsilon_n(k) + \upsilon_n(k-1)) \tag{5}$$

where k is an index and T is a sampling time.

Once the position of the foot has been estimated, supplementary information, such as length of stride and walking speed, can be calculated. Stride length is calculated from the distance between heel strikes, as detected by the Smart Shoe, and walking speed is calculated by dividing the stride length by the elapsed time per step.

3.2. Zero velocity update

Since estimates of the velocity and position are obtained by integrating the acceleration signal, they could diverge without an appropriate correction step. In order to prevent such divergence, a zero-velocity period (i.e., a period during which the velocity is guaranteed to be zero) is used. During the zero-velocity period, the velocity is assumed to be zero, and thus the value of the velocity is reset to zero.

In the proposed system, zero-velocity periods are determined from the gait phases estimated by the Smart Shoe. Previously, a hidden Markov model or fuzzy logic has been applied to estimate the gait phases with the GRFs measured by the Smart Shoe [12,1]. An example of estimated gait phases is shown in Fig. 4(a). Each gait phase value represents the probability of the corresponding gait

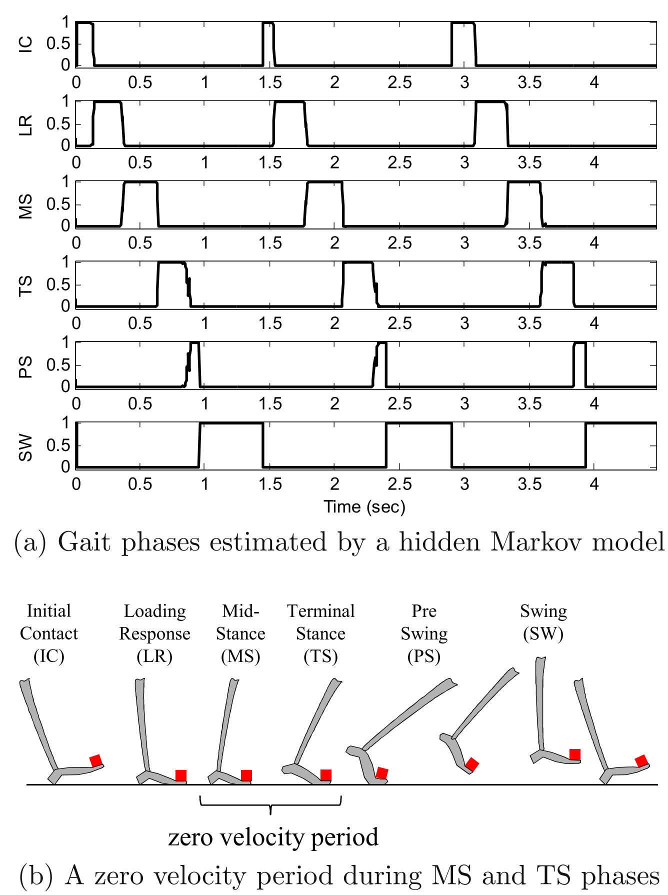


Fig. 4. A zero velocity period determined from estimated gait phases.

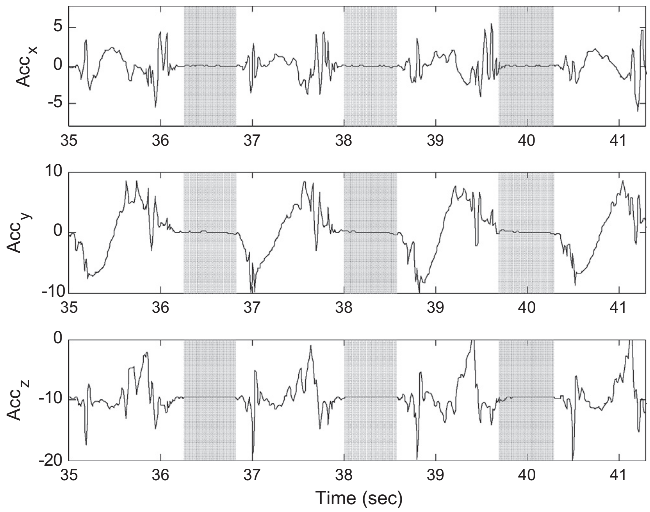


Fig. 5. Validation of the zero velocity periods with acceleration signals.

phase. Since the IMU is attached to the forefoot, the forefoot should not be moved during the zero-velocity period. Thus the mid-stance (MS) and terminal stance (TS) phases are used as the zero-velocity period, as shown in Fig. 4(b).

The zero-velocity periods were validated by accelerometer signals from the IMU, as shown in Fig. 5. The zero-velocity periods are highlighted in gray in the figure. The acceleration signals of the IMU approached zero during the specified periods, which means the forefoot did not move during this period.

3.3. Experimental results

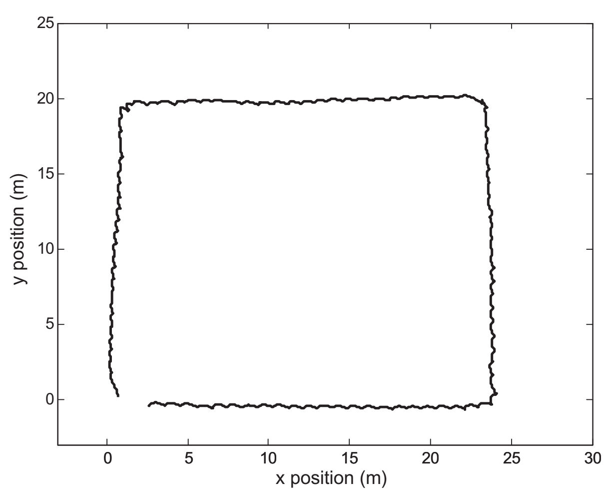
The performance of the proposed system and algorithms has been experimentally verified. A healthy male subject without known gait disorders was instructed to walk while wearing the Smart Shoe with the IMU. Raw sensor signals from the system, such as GRFs, accelerations, and angular velocities, were provided by the IMU and the Smart Shoe. Using these data, gait phases, foot positions, stride lengths, and walking speeds were estimated in real time. The data from the Smart Shoe and the IMU were transmitted to the local controller, which was a laptop in the experiments, via wires. The laptop and the sensors were connected with National Instrument (NI) USB-type Data Acquisition (DAQ) Board. The collected data were analyzed in the laptop using the NI LabVIEW program.

Fig. 6 shows results of foot position tracking. The subject was asked to walk on flat ground around a building. The walking path was 20 m $\times$ 25 m which was identified by grids on the ground. Even though fluctuations in the foot position were observed at all steps (due to the error update during zero-velocity periods), the system was able to track the rectangular position correctly. Also, foot clearance, which is critical when observing an abnormal gait, can be estimated from the *z*-coordinate. Fig. 6(d) shows the foot clearances in five steps. Fig. 7 shows the calculated stride lengths and walking speeds during the experiment. The average stride length and walking speed were 1.009 m and 0.659 m/s, respectively.

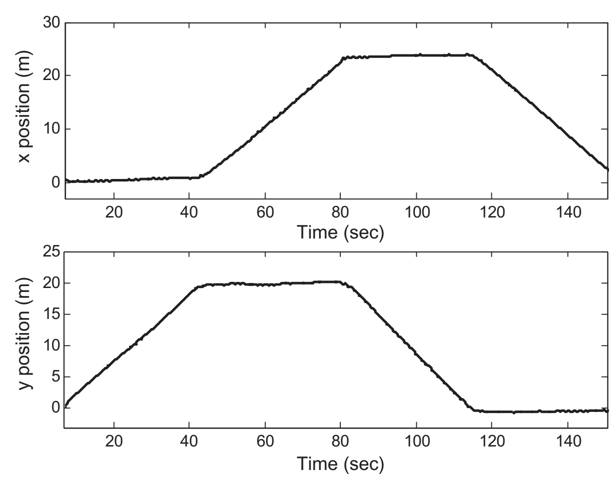
4. Internet-based tele-monitoring systems

4.1. Packet buffers for delayed packets

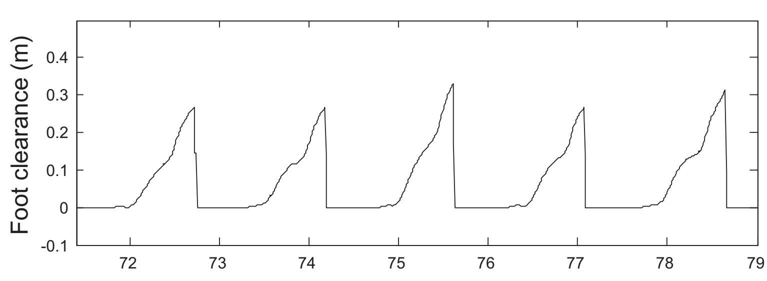
The proposed tele-monitoring system transmits the patient's information to a physical therapist via the Internet, allowing the



(a) Foot tracking

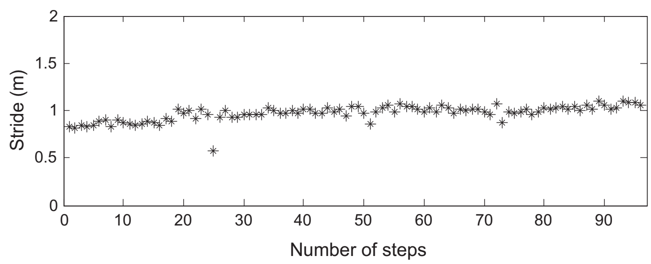


(b) x, y coordinates

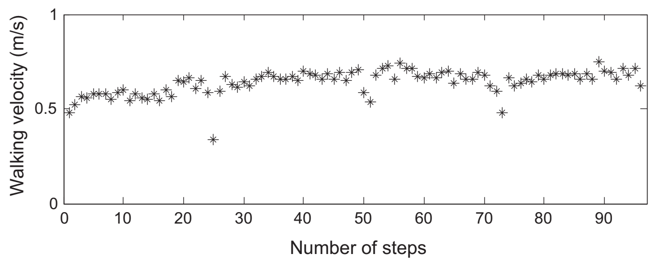


(c) Foot clearance (five steps)

Fig. 6. Experimental results: foot tracking.



(a) Stride length



(b) Walking speed

Fig. 7. Experimental results: stride length and walking speed.

therapist to monitor the patient's status anywhere, anytime, and administer customized rehabilitation services. Using the tele-monitoring system, it is possible to provide immediate guidance for online rehabilitation, and also to alert specialists to emergency situations. Therefore, the proposed system could be utilized as a health-monitoring network to benefit the individual patient and improve the management strategy of the provider.

The network platform for the tele-monitoring system is divided into two levels: a local processing level and a remote processing level. Estimation algorithms for gait phase and foot posture are implemented at the local processing level to reduce the size of the data packets transmitted through the Internet. The user-friendly graphical interface is installed on the local and remote computers. The patient's status is monitored by a physical therapist, using the information on the computer screen, and interactive guidance is provided to the patient in real time. The extensive infrastructure of the Internet (including the wireless Internet facilities available in many public areas) makes it possible for a physical therapist to access the patient-carried monitoring system anywhere, anytime.

For tele-monitoring via the Internet, TCP (transmission control protocol) is used, as in ordinary Internet communication. TCP is a reliable data transmission protocol, since it uses an acknowledgment scheme to verify that a signal has been delivered correctly. In TCP, if the sender does not receive an acknowledgment before a specified time has elapsed, the packet is re-sent [21]. In the proposed system, a packet buffer, which is responsible for maintaining a queue of previous values, is utilized in both the local host controller and the host controller, so that delayed packets can be transmitted. When a packet buffer is used, a time delay corresponding to the packet buffer size is permitted, as a slight time delay may not cause a serious problem for a monitoring system [5]. The size of the packet buffer is determined by the network conditions: a longer packet delay requires a larger packet buffer.

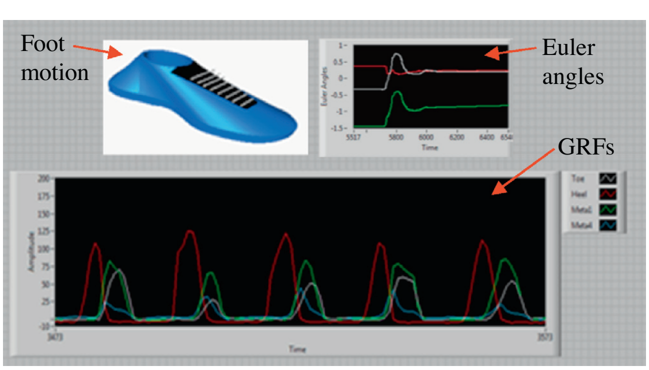


Fig. 8. The user interface of the monitoring software.

4.2. Monitoring software user interface

To monitor the patient's walking remotely, adequate information must be delivered and displayed to a physical therapist. In the proposed system, the transmitted information is displayed as shown in Fig. 8. The foot model (created by SolidWorks) moves according to the transmitted position data, and the Euler angles are displayed. Also, the GRFs are shown in the graph at the bottom. Additional information, such as stride length, and walking velocity, can be added to the software interface.

5. Conclusion

In this paper, a tele-monitoring system for gait rehabilitation was proposed, which incorporates an inertial measurement unit (IMU) and a ground reaction force (GRF) measurement sensor called a Smart Shoe. Measured or estimated patient information is transmitted via the Internet. GRFs measured by the Smart Shoe are used to estimate the gait phases, which, in turn, are utilized as zero-velocity periods for estimating foot position. Stride length and walking velocity are also calculated from the patient information. The patient's walking information is displayed via a graphical interface installed on computers at the patient's location and the physical therapist's office. By using a packet buffer for both computers, delayed packets can be transmitted without loss. Thus the Internet-based network is able to provide immediate, personalized physical therapy in real time.

Acknowledgments

This work was supported by National Science Foundation (NSF) Grant CMMI-1013657, the Global Frontier R&D Program on <Human-centered Interaction for Coexistence> funded by the National Research Foundation of Korea grant funded by the Korean Government(MSIP) (NRF-2012M3A6A3056354), and the 2012 Creativity & Innovation Research Fund (Project No. 1.120047.01) of UNIST(Ulsan National Institute of Science and Technology).

References

[1] Bae J, Tomizuka M. Gait phase analysis based on a hidden markov model. Mechatronics 2011;21:961–70.
[2] Bae J, Tomizuka M. A gait rehabilitation strategy inspired by an iterative learning algorithm. Mechatronics 2012;22:213–21.
[3] Bae J, Kong K, Tomizuka M. Gait phase-based control for a rotary series elastic actuator assisting the knee joint. ASME J Med Dev 2011;5:031010.
[4] Bae J, Kong K, Byl N, Tomizuka M. A mobile gait monitoring system for abnormal gait diagnosis and rehabilitation: a pilot study for parkinsons disease patients. ASME J Biomech Eng 2011;133:041005.
[5] Bae J, Zhang W, Tomizuka M. Network-based rehabilitation system for improved mobility and tele-rehabilitation. IEEE Trans on Control Systems Technol 2013.
[6] Bamberg SJM, Benbasat AY, Scarborough DM, Krebs DE, Paradiso JA. Gait analysis using a shoe-integrated wireless sensor system. IEEE Trans Inf Technol Biomed 2008;12:413–23.
[7] Collin C, Wade D, Davies S, Horne V. The barthel adl index: a reliability study. Disability Rehabilitation 1988;10:61–3.
[8] Foxlin E. Pedestrian tracking with shoe-mounted inertial sensors. IEEE Comput Graphics Appl 2005;25:38–46.

[9] Gladstone D, Danells C, Black S. The fugl-meyer assessment of motor recovery after stroke: a critical review of its measurement properties. Neurorehabilitation Neural Repair 2002;16:232–40.
[10] Jimenez A, Seco F, Prieto C, Guevar J. A comparison of pedestrian dead-reckoning algorithms using a low-cost mems IMU. In: IEEE international symposium on intelligent signal processing; 2009. p. 37–42.
[11] Keith R, Granger C, Hamilton B, Sherwin F. The functional independence measure: a new tool for rehabilitation. Adv Clin Rehabil 1987;1:6–18.
[12] Kong K, Tomizuka M. A gait monitoring system based on air pressure sensors embedded in a shoe. IEEE/ASME Trans Mech 2009.
[13] Kong K, Bae J, Tomizuka M. Detection of abnormalities in a human gait >using smart shoes. In: Proc. of SPIE on sensors and smart structures technologies for civil, mechanical, and aerospace system; 2007. p. 69322G.
[14] MicroStrain. 3DM-GX2; 2011. <http://microstrain.com/>.
[15] Morris SJ, Paradiso JA. Shoe-integrated sensor system for wireless gait analysis and real-time feedback. In: Proceeding of the second joint EMBS/BMES conference; 2002. p. 2468–69.
[16] Novel (2013), http://www.novelusa.com/, Pedar/Pedoport.
[17] Ojeda L, Borenstein J. Personal dead-reckoning system for gps-denied environments. In: IEEE international workshop on Safety, Security, and Rescue Robotics (SSRR); 2007. p. 1–6.
[18] Pappas IPI, Popovic MR, Keller T, Diets V, Morari M. A reliable gait phase detection system. IEEE Trans Neural Syst Rehabilitation Eng 2001;9:113–25.
[19] Tekscan. F-Scan VersaTek System; 2013. <http://www.tekscan.com/medical/>.
[20] VICON; 2013. <http://www.vicon.com/>.
[21] Walrand J, Parekh S. Communication networks: a concise introduction. Morgan and Claypool Publishers; 2010.