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Low-cost implementation of a self-paced treadmill by using a commercial depth sensor

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Abstract— **A self-paced treadmill that can simulate overground walking has the potential to improve the effectiveness of treadmill training for gait rehabilitation. We have implemented a self-paced treadmill without the need for expensive equipment such as a motion capture system and an instrumented treadmill. For this, an inexpensive depth sensor, ASUS Xtion™, substitutes for the motion capture system, and a low-cost commercial treadmill is considered as the platform of the self-paced treadmill. The proposed self-paced treadmill is also convenient because the depth sensor does not require markers placed on user's body. Through pilot tests with two healthy subjects, it is quantitatively and qualitatively verified that the proposed self-paced treadmill achieves similar performance as one which utilizes a commercial motion capture system (VICON) as well as an instrumented treadmill.**

I. Introduction

A treadmill provides a safe and reliable environment for intensive gait practice with the goal of improving gait function in overground walking (OW) [1]. It was reported that treadmill walking (TW) is very similar to OW at constant speeds [2], and typical treadmill training has focused on constant speeds. TW differs from OW in the following critical aspect; the user's speed on the treadmill belt is basically determined by the treadmill. Since the user soon habituates to a fixed or pre-determined treadmill speed, the training requires little conscious engagement.

In order to make TW even more similar to OW, a novel self-paced treadmill (SPT), was proposed [3, 4]. SPT consists of a controllable treadmill, sensors for measuring the user's body position and/or force (ground reaction force [5] or force in a mechanical tether [1, 6]), and a speed control scheme that keeps the user within the length of a treadmill belt during walking that involves acceleration/deceleration. This would allow users on a SPT to naturally change walking speed while the treadmill follows his/her intention of speed change. In a gait training protocol using SPT, trainees might need to pay greater attention than during conventional treadmill training, and practice walking skills closer to OW.

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Owing to the perceived advantages of SPT, there have been several attempts to implement SPT [1, 3-5, 7-10]. These attempts, however, require expensive equipment and sophisticated setup procedures that are more appropriate for laboratory or major hospital settings and might not be practical in smaller clinical or rehabilitation settings. Commercial motion capture systems that have been widely used for continuous monitoring of user's body position/movement are expensive as well as cumbersome [7-10]. Moreover, these requires additional setup procedures for attaching passive or active markers to proper locations on the user's body and analysis procedures for determining positional changes. Ground reaction force measurement using an instrumented treadmill does not require motion capture systems [5], but is still more expensive than one without force plates. Less expensive sensors such as an ultrasonic range finder [4], potentiometer [3] or force sensor [1, 6] need a rigid harness for sensor attachment causing inconvenience and unnatural feeling to the users. Moreover, most treadmill rehabilitation studies have used custom designed [1, 3, 9] or instrumented treadmills [5, 7, 8] that may be too expensive (over 100K USD) for many clinical settings.

The aim of this paper is to propose an inexpensive implementation of SPT for expanded clinical uses. As a sensor for measuring user's position, we employed the ASUS Xtion™ sensor that is similar to the Microsoft Kinect™, a recent development in computer gaming technology. The sensor is inexpensive, portable, and has little setup time since it does not require the placement of markers on anatomical landmarks [11]. SPT requires a treadmill with high control performance; therefore, very expensive custom designed or instrumented treadmills have been used in existing SPTs. In this paper, we opt for a control scheme in [9] that is able to provide acceptable performance in simulating OW with a commercially available far less expensive treadmill. Through pilot experiments with two healthy subjects, the performance of the proposed SPT is qualitatively and quantitatively evaluated.

II. Methods

A. Proposed self-paced treadmill

1) Sensor for measuring user's body position

An inexpensive depth sensor, The ASUS Xtion™, contains infrared sensors to create 3D map of its view and uses an adaptive algorithm to automatically determine anatomical landmarks on a user's body in close to real time [11, 12]. By using the open source drivers (OpenNI and NITE [13]), it can acquire 3D positions of 15 landmarks based on the user's skeleton model, illustrated in Fig. 1, at 30 Hz sampling frequency in normal mode, and 60 Hz in fast mode. In contrast to commercial motion capture systems, it costs just less than 200 USD, and allows measurement of the user's body position without placing markers. Therefore, the depth sensor is selected for the proposed SPT for low-cost and convenience.

In order to measure the user's anterior/posterior position on a treadmill along walking direction, we used torso position data in the anteroposterior axis by tracking the 'torso' landmark (Fig. 2). It is because the 1) torso position does not fluctuate much during TW, and 2) 'torso' is the most accurate and reliable landmark in the depth sensing method. While the torso is the best option, it still contains greater noise than a motion capture system due to the error in detecting the 'torso' landmark. The noise was filtered by a second-order Butterworth low pass filter with 10 Hz cutoff frequency.

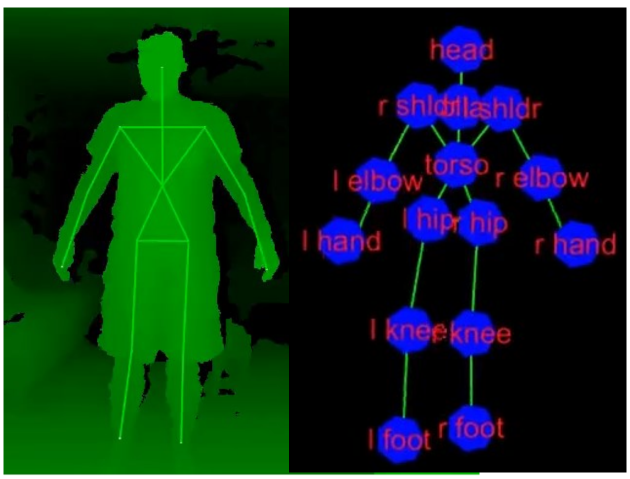

Fig. 1 Skeleton model and landmarks in the ASUS Xtion™

2) Controllable treadmill and control scheme

Along with the low-cost sensor, it is necessary to use a low-cost treadmill to reduce the cost of SPT system. In the literature, there are only few SPTs which used a low-cost treadmill [4, 10]. From these studies, the specifications of the low cost treadmill are summarized in Table I. Low-cost treadmills have a slower sampling rate and lower resolution of belt speed than more expensive instrumented treadmill systems [10].

TABLE I. SPECIFICATIONS OF LOW-COST TREADMILL [10]

Maximum sampling rate of internal belt speed controller	8 Hz
Speed resolution	0.045 m/s (0.1 mph)
Maximum belt acceleration	5 m/s

The combination of a low-cost treadmill and conventional proportional-integral-derivative (PID) control scheme would result instability of SPT [10] due to the low control sampling rate and resolution. Therefore, we searched for an appropriate control scheme that is still stable with low-cost treadmill systems. Recently a comparative study on the scheme of SPT has suggested two novel control schemes which have better performance in simulating OW than the PID scheme [8]. Of those, this paper opts for a speed control scheme that was reported in [9]. The control scheme consists of a position-feedback controller and an observer-based walking speed estimator [9]. No integral action in the scheme [9] makes it easier to guarantee stability under the slow control sampling rate and low resolution. Moreover, the scheme requires pelvic position that can be obtained by using the depth sensor. The details of the scheme and the description of control gains can be found in [9].

By combining the inexpensive depth sensor, a low-cost treadmill, and the speed control scheme, this paper proposes an less expensive and less cumbersome SPT, as shown in Fig. 2. In the proposed SPT, the ASUS Xtion™ is connected to the PC via USB, and the user's position data is acquired from OpenNI and NITE software.The belt speed command is determined from the control scheme, and sent to the treadmill via RS-232 communication.

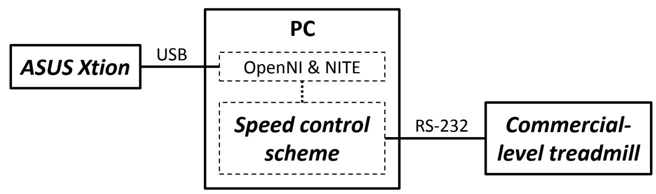

Fig. 2 The proposed self-paced treadmill system

B. Experimental setup

While the proposed SPT focuses on reducing cost, it needs to have acceptable performance in simulating OW. In order to investigate the performance degradation caused by a lower cost sensor and treadmill, we compared two SPTs: the proposed and "classic" SPTs as reported in the literature. In contrast to the proposed SPT in Fig. 2, the classic SPT, which is similar to the SPT in [9], incorporated a commercial motion capture system (VICON Inc., Denver CO, USA) and an instrumented treadmill (Bertec Co., Columbus OH, USA). Note that both SPTs used the identical speed control scheme in [9] with the same control parameters, summarized in Table II.

In the proposed SPT, the user's position was captured by the ASUS Xtion™ at a sampling rate of 30 Hz. The depth sensor was located at 2.0 m behind of the end of treadmill and 0.8 m height from the ground (Fig. 3a). It should be noted that the characteristics of low-cost treadmill of the proposed SPT were simulated on the instrumented treadmill (Bertec Co., Columbus OH, USA). By using a custom C++ program, the belt speed command was adjusted to meet the low speed resolution in Table I, and the command was sent to the treadmill at slower sampling rate of 7.5 Hz. In the classic SPT, the motion capture system acquired the user's position at 120 Hz (four times faster than the proposed SPT), and the speed command was provided to the treadmill at 120 Hz (sixteen times faster than the proposed SPT). For the classic or standard SPT, two passive markers were placed on skin over the posterior superior iliac spines for the user's pelvis tracking (Fig. 3b) while the proposed SPT did not require any markers. Hand rails were installed on the front and two sides of the treadmill for safety (Fig. 3b).

TABLE II. CONTROL PARAMETERS OF SPEED CONTROL SCHEME

k_{pos}	k_a	k_{obv}	k_{ref}
2.0	2.0	3.0	0.4

Note that the description of parameters can be found in [9].

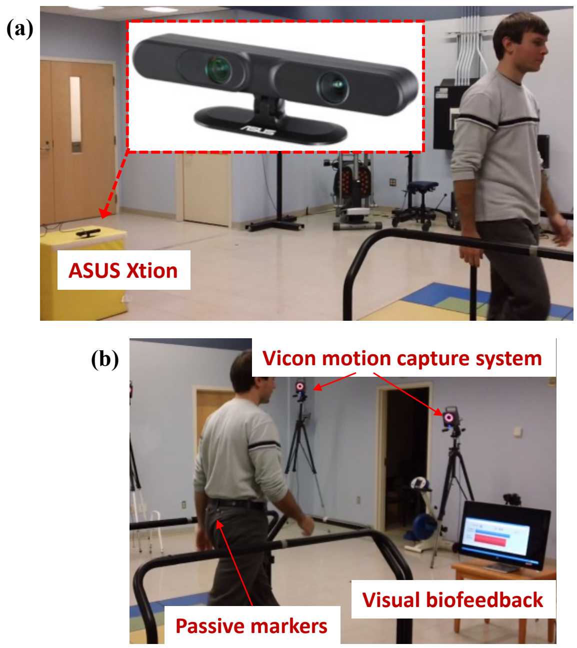

Fig. 3 Experimental setup: (a) proposed SPT, (b) classic SPT

C. Protocol

Two healthy subjects (30 year old male and 25 year old female) participated in this study. All participants signed informed consent approved by NIH IRB prior to the experiment.

Before TW, the subjects were instructed to walk freely on the ground in order to determine their preferred walking speed. Two target speeds for TW were calculated: slow (75% of preferred walking speed) and fast (125% of preferred walking speed). After that, they walked on the treadmill for 1~2 minutes with the slow/fast target speeds to get accustomed to self-paced TW. Then, the subjects walked with the two SPT schemes (the proposed and the SPTs) that were presented in random order. The subjects were blinded to the identity of the SPT schemes throughout the test. During TW, they were asked to quickly accelerate walking speed from the slow to the fast target speed, and decelerate from the fast to the slow. Visual biofeedback was provided by a custom built Labview program (National Instruments, Austin TX, USA). Since subject's walking and target speeds were displayed on a PC monitor in real time (Figs. 3b and 4), the subject could match their walking speed to the target speeds (fast or slow target speed). The subjects were asked to quickly accelerate /decelerate to maintain at the two target speeds for 10~20 seconds.. Five acceleration and deceleration trials were performed. After finishing TW with each SPT, the subjects were instructed to give a rating from 1 (least) to 10 (best) where the rating represents similarity to OW.

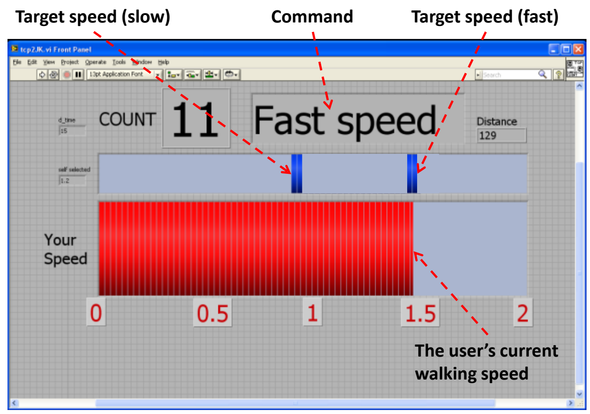

Fig. 4 Visual biofeedback

The proposed SPT was quantitatively compared with the SPT by using the following outcome measures: 1) e_{speed}: the root mean square error (RMSE) of walking speed and constant target speed while user attempted to maintain the target speed (steady-state phase), and 2) a_{mean} : the user's mean acceleration while the user changed walking speed (transient phase). The outcome measures represent the similarity between the two SPTs in steady-state and acceleration phases, respectively. In addition, the qualitative comparison was also conducted by using a questionnaire.

III. RESULTS

Subjects could easily control their walking speed on the proposed SPT as well as the SPT. Both subjects' preferred walking speeds were 1.2 m/s.

The steady-state phase of TW was classified into two zones determined by target walking speed: slow zone with the slow target speed and fast zone with the fast target speed. The average e_{speed} with the two SPTs are summarized in Table III. The results show that e_{speed} with the proposed SPT were not significantly different from the classic SPT. The only exception appeared in the female subject's slow zone. Even in this zone, she was remarkably more accurate and consistent at maintaining her walking speed with the proposed SPT.

The average a_{mean} in the transient phase, which consists of the user's acceleration and deceleration, is also summarized in Table III. In both acceleration and deceleration, a_{mean} with the proposed SPT were lower but not significantly different than the classic SPT, except for the male subject's deceleration. With the proposed SPT, the male subject decelerated at more than twice quicker with the classic SPT.

TABLE III. COMPARISON OF PROPOSED AND PROPESSIONAL SPTS

			Proposed SPT (mean±SD)	Classic SPT (mean±SD)
e_{speed} (m/s)	Subject #1 (female)	slow	0.092±0.012	0.139±0.046
		fast	0.084±0.006	0.081±0.012
	#2 (male)	slow	0.129±0.016	0.136±0.022
		fast	0.086±0.012	0.096±0.009
a_{mean} (m/s^2)	#1	acc	0.964±0.292	1.013±0.251
		dec	0.730±0.179	0.860±0.253
	#2	acc	0.741±0.168	0.883±0.190
		dec	0.314±0.104	0.754±0.234

Note that 'acc' and 'dec' denote acceleration and deceleration, respectively.

From the questionnaire about the level of similarity to OW, the mean score of the proposed SPT was 8, which is same as the score with the classic SPT. Of the two subjects, one gave a higher score to the proposed SPT (10 for the proposed and 8 for the classic), but the other gave opposite feedback (6 for the proposed and 8 for the classic).

IV. DISCUSSION

The experimental results show that the proposed SPT achieves an acceptable performance, which is similar to the classic SPT. The only drawback of the proposed SPT noted appeared in the transient phase: slower acceleration (a_{mean} in Table III). This resulted from the relatively large latency of the proposed SPT. The proposed SPT has a larger latency because of the slow sampling rate of the inexpensive depth sensor and low-cost treadmill as well as the low-pass filtering. The users' reaction to the latency was to reduce their acceleration/deceleration for safety. While the drawback was significant in the male subject's decelerations, the other subject's decelerations were quite similar across the two SPTs, as shown in Table III. We will test more subjects for more definitive results, but regardless of the amount of acceleration, both subjects could change walking speed in a similar way to OW.

The feedback from the questionnaire was consistent with the result of quantitative comparison. The subject #1 (female) who gave a higher score to the proposed SPT maintained her walking speed remarkably better with the proposed SPT in slow zone (Table III). The subject #2 (male) rated a lower score to the proposed SPT than the classic SPT because he experienced reduced deceleration with the proposed SPT during the transient phase (Table III).

The use of a depth sensor could add simplicityto the proposed SPT. In contrast to the other SPTs, the proposed SPT does not require subjects to have markers attached or to put on a harness for applying a force sensor, potentiometer or ultrasonic range finder. By using the 'torso' landmark, the depth sensor provided the user's accurate position, which was comparable to the motion capture system. We found that the other landmarks, especially on the feet and hands, are not appropriate because those are often determined inaccurately due to the limitation of the adaptive algorithm of the sensor performance [14]. The added convenience of using the depth sensor will practically simplify the clinical testing protocols and it will become easier and faster for clinicians to work with patients.

Since this paper is limited in that it used a small sample, more participants will need to be studied. In practice, the proposed SPT will require an emergency stop function for safety, which can potentially be implemented by a button controlled by the user or recognizing a user's specific gesture.

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REFERENCES

[1] J. von Zitzewitz, M. Bernhardt, and R. Riener, "A novel method for automatic treadmill speed adaptation," *IEEE Trans Neural Syst Rehabil Eng,* vol. 15, pp. 401-9, Sep 2007.

[2] P. O. Riley, G. Paolini, U. Della Croce, K. W. Paylo, and D. C. Kerrigan, "A kinematic and kinetic comparison of overground and treadmill walking in healthy subjects," *Gait Posture,* vol. 26, pp. 17-24, Jun 2007.

[3] J. Fung, C. L. Richards, F. Malouin, B. J. McFadyen, and A. Lamontagne, "A treadmill and motion coupled virtual reality system for gait training post-stroke," *Cyberpsychol Behav,* vol. 9, pp. 157-62, Apr 2006.

[4] A. E. Minetti, L. Boldrini, L. Brusamolin, P. Zamparo, and T. McKee, "A feedback-controlled treadmill (treadmill-on-demand) and the spontaneous speed of walking and running in humans," *J Appl Physiol,* vol. 95, pp. 838-43, Aug 2003.

[5] J. Feasel, M. C. Whitton, L. Kassler, F. P. Brooks, and M. D. Lewek, "The integrated virtual environment rehabilitation treadmill system," *IEEE Trans Neural Syst Rehabil Eng,* vol. 19, pp. 290-7, Jun 2011.

[6] R. R. Christensen, J. M. Hollerbach, Y. M. Xu, and S. G. Meek, "Inertial-force feedback for the treadport locomotion interface," *Presence-Teleoperators and Virtual Environments,* vol. 9, pp. 1-14, Feb 2000.

[7] J. Yoon, H. S. Park, and D. L. Damiano, "A novel walking speed estimation scheme and its application to treadmill control for gait rehabilitation," *J Neuroeng Rehabil,* vol. 9, p. 62, Aug 28 2012.

[8] J. Kim, C. J. Stanley, L. A. Curatalo, and H. S. Park, "A User-driven treadmill control scheme for simulating overground locomotion," in *Conf Proc IEEE Eng Med Biol Soc*, 2012, pp. 3061-3064.

[9] J. L. Souman, P. R. Giordano, I. Frissen, A. De Luca, and M. O. Ernst, "Making Virtual Walking Real: Perceptual Evaluation of a New Treadmill Control Algorithm," *Acm Transactions on Applied Perception,* vol. 7, Feb 2010.

[10] L. Lichtenstein, J. Barabas, R. L. Woods, and E. Peli, "A Feedback-Controlled Interface for Treadmill Locomotion in Virtual Environments," *ACM Trans Appl Percept,* vol. 4, p. 7, Jan 2007.

[11] http://www.asus.com/Multimedia/Motion_Sensor/Xtion/#overview.

[12] R. A. Clark, Y. H. Pua, K. Fortin, C. Ritchie, K. E. Webster, L. Denehy, and A. L. Bryant, "Validity of the Microsoft Kinect for assessment of postural control," *Gait Posture,* vol. 36, pp. 372-7, Jul 2012.

[13] http://www.primesense.com/solutions/nite-middleware/.

[14] S. Obdrzalek, G. Kurillo, F. Ofli, R. Bajcsy, E. Seto, H. Jimison, and M. Pavel, "Accuracy and robustness of Kinect pose estimation in the context of coaching of elderly population," in *Conf Proc IEEE Eng Med Biol Soc*, 2012, pp. 1188-1193.