Intel Serv Robotics (2012) 5:159–167
DOI 10.1007/s11370-012-0110-6

ORIGINAL RESEARCH PAPER

An adaptive treadmill-style locomotion interface and its application in 3-D interactive virtual market system

Haiwei Dong · Zhiwei Luo · Akinori Nagano · Nikolaos Mavridis

Received: 17 February 2012 / Accepted: 20 April 2012 / Published online: 12 May 2012

Abstract The key issue in this paper is estimating speed of a human. Compared with previous researches on walking speed estimation, we predict the walking intention before gait action. Our proposed hypothesis is that a composite force index is linearly correlated with the intended walking speed. We did two experiments to test the hypothesis. One gives a regression test indicating the intended walking speed has strong linear correlation with the proposed force index; the other tests the linearity by statistical analysis, guaranteeing the tolerance of individual difference. According to the regression and statistics analyses, we built a treadmill-style locomotion interface. Compared with the normal cases of treadmill control, the tested subject does not have to follow the speed of treadmill, but can actively change the speed of treadmill by his/her feet. The designed locomotion interface is applied in a virtual market system. Here the subject walks in a virtual market street with the desired speed. The stereo display based on virtual reality and the ambient sounds of the environment make the subject to have an immersed sense. The layout of shops in the virtual market system is in Japanese style, making the subjects experience much more realistic.

Keywords 3-D interactive VR system · Human intended walking speed · Virtual market development

Electronic supplementary material The online version of this article (doi:10.1007/s11370-012-0110-6) contains supplementary material, which is available to authorized users.

H. Dong (✉) · N. Mavridis
New York University, 70 Washington Square South, New York, NY, 10012, USA
e-mail: haiwei.dong@nyu.edu

N. Mavridis
e-mail: nikolaos.mavridis@nyu.edu

Z. Luo · A. Nagano
Kobe University, 1-1 Rokkodai-cho, Nada-ku, Kobe, 6578501, Japan
e-mail: luo@gold.kobe-u.ac.jp

A. Nagano
e-mail: aknr-ngn@phoenix.kobe-u.ac.jp

1 Introduction

The treadmill-style locomotion interface is an adaptive treadmill which can automatically adjust its speed to the subject's walking speed. It has been studied for two decades. The early work was done by Noma et al. [1] who built a treadmill locomotion interface system ATLAS. Stance duration and body position are measured as walking status. Motion control is achieved by optical foot tracking, employing a video tracking system that tracks bright markers on the foot. Turning is achieved by swiveling the treadmill in the direction where the user is stepping. Darken and Carmein [2] developed the first omini-directional treadmill to facilitate turning. A two-orthogonal belt arrangement creates the 2-D surface. A top belt is composed of rollers whose axes are parallel to the direction of rotation of that belt. Iwata and Yoshida [3] built another 2-D treadmill which employs 12 small treadmills to form a large belt. Hollerbach et al. [4,5] designed two generations of treadmill-style locomotion interfaces named Sarcos Treadport I and II, which imitate slope by pushing or pulling a tether located at the back of the subject. Body pose measurements from the tether are employed to control the rate of turning.

Actually, the key issue for locomotion interface design is how to estimate human's walking speed. The estimation of walking speed is not a new topic. In the early studies of gait, researchers used high speed camera to calculate the walking speed [6]. In the last few decades, as sensors (especially accelerometer and gyroscope) became available, many researches used optimal estimation to fuse information of acceleration and orientation to calculate human's walking speed. Popular algorithms include regression method series, like Gaussian process-based regression (GPR) [7], Bayesian linear regression (BLR) [8], least squares regression (LSR) [9], support vector regression (SVR) [10], and machine learning series, e.g. neural network [11]. The basic scheme is based on the periodic pattern of gait which implies acceleration and deceleration at each step. Such pattern provides a good target for accelerometer to recognize. After classifying different phases of gait, data from typical inertial sensors containing accelerometer and gyroscopes are fused and the kinematics information is able to be obtained by the optimal estimation algorithms. Additionally, there are also other methods to obtain walking speed. For example, Alberto et al. [12] from Philips research laboratories assessed human ambulatory speed by measuring near-body air flow.

It is noted that the previous researches measure walking behavior after action. Nevertheless, it is better to estimate the walking speed before the walking behavior, which we call intended walking speed estimation [13,14]. However, the walking intention of the human is hard to estimate. Although brain computer interfacing (BCI) is a promising method [15], until now there still have been many limitations, such as the information bandwidth is narrow, the estimation accuracy is not high enough, etc. Another feasible solution is using motion capture to obtain the joint motion data. By solving inverse dynamics and kinematics, the walking speed can be predicted [16,17]. However, such a solutions can be complicated and time-consuming.

In this paper, we consider the intended walking speed estimation based on the natural fact of how human's intention physically interacts with the surrounding environment. Our aim is to propose an approach that is easy to use, and which requires little processing power. The two considerations constitute our stand point. The idea of our method for intended walking speed estimation is illustrated as follows. As we all know, under the condition of low speed, macroscopic object in the world obey Newton's laws of motion, i.e., the acceleration comes from force. Taking walking as an example, there exists an interaction force between foot and ground, i.e., the ground reaction force. Notice that this interaction force is the precursor which provides the power to drive the walking motion. In the paper, we found a critical force index which is linearly correlated with the walking speed that follows after this force is applied. Two experiments verified the linearity by least-squares regression and statistical analyses.

The developed treadmill-style locomotion interface is applied in a virtual market system. The motivation came from the fact that the elderly people in Japan always choose to order goods by telephone. Such a shopping pattern causes lack of exercise leading to many problems, such as obesity, cardiovascular diseases, etc. [18,19]. To provide the elderly people with healthy living service, a virtual interactive market system is built where the elderly people can take a walk in the virtual reality (VR) environment by taking steps on a treadmill and buy goods from VR shops connected with real-world shops. Such an interactive virtual market system provides the elderly people with convenience and proper exercise. Here we developed a 3-D interactive VR system with an adaptive treadmill-style locomotion interface, which is the first step of the final aim.

In the designed virtual market system, when a subject walks on the treadmill, the force plate measures the interaction forces in x, y, z directions. Based on the force data, we estimate the subject's walking speed and adaptively adjust the velocity of the treadmill belts. Meanwhile, the 3-D projector synchronizes with the walking speed. Compared with existing treadmill-style locomotion systems, there are two novelties in the proposed system. First, we use the human's intended walking speed to drive the treadmill, i.e., the control is prior to the human walking movement. Second, the designed virtual market system not only gives a natural feeling of walking but also gives a natural sense of vision and hearing. The stereo display based on virtual reality and the ambient sounds of the environment gives the subject an immersive experience. The layout of shops in the virtual market system is in Japanese style, which makes the whole system much more realistic.

2 System overview

2.1 Apparatus and coordinate system setting

We put two separate force plates under each half of dual treadmill belt to analyze the states of human gait for both feet. Specifically, the treadmill we use is Bertec Treadmill TM07-B, including a control unit, two belts, three motors to adjust belt speed and inclination degree. Each half of treadmill incorporates an independent force measurement of six load components: three orthogonal components of the resultant force and three components of the resultant moment in the same orthogonal coordinate system. The force plates are calibrated in advance and calibration matrix is obtained from the testing. The voltage output of each channel is in a scaled form of the load with the units of N and N m for the forces and moments, respectively. The force and moment values are calculated by multiplying the signal values with corresponding scale factors.

The coordinate system is defined as follows. From the viewpoint of the walker, the positive y direction points forwards; x direction points left when looking in the y direction; z direction is defined downwards by the right-hand rule. The origin of the coordinate system is centered at the inner corner of the outer back roller support block of the corresponding (right or left) half (Fig. 1a).

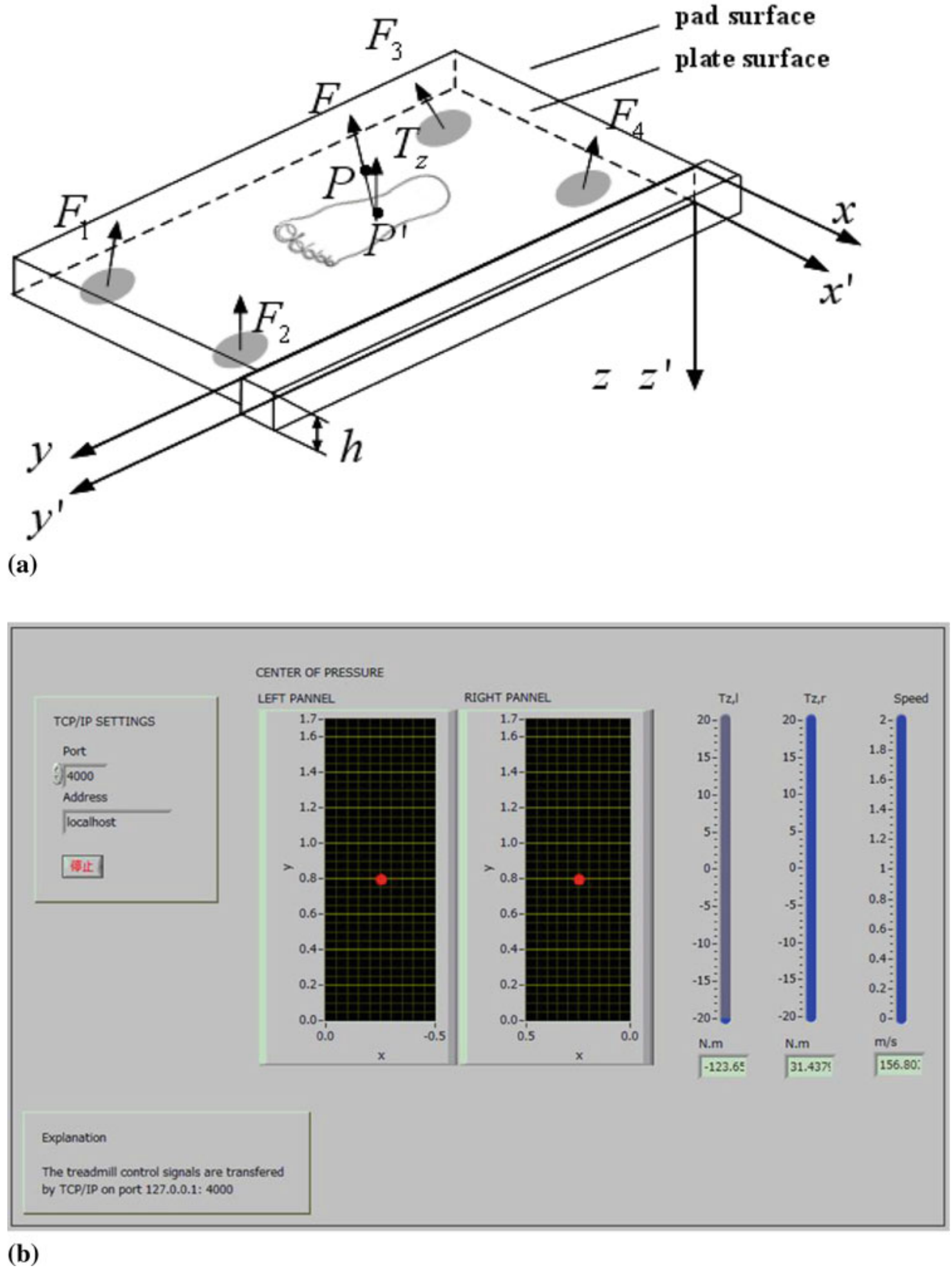

Fig. 1 Coordinate system setting and treadmill GUI development. (**a**) Four force sensors placed at the bottom of each force plate measure the interaction forces and moments in *x*, *y* and *z* directions. (**b**) A graphical user interface (GUI) is built to measure the position of center of gravity, to control treadmill, and to communicate with force plates

All the forces acting between the foot and the ground are summed to yield a single ground reaction force F and a torque vector T_z. The point of application of the ground reaction force on the plate is the center of pressure (CP). All the small reaction forces (F_1, F_2, F_3 and F_4) collectively exert on the surface of the plate at the CP. The point of force application and the couple acting can be calculated from the measured force and moment components on each half of the treadmill.

We designed a graphical user interface (GUI) by LABVIEW (a graphic programming software package) to receive measurement data from force plate sensor and send control signal to Bertec treadmill. The communication is based on TCP/IP protocol (Fig. 1b).

3 Walking intention estimation

3.1 Hypothesis on walking speed

A skeleton model simulation is done by OpenSim 2.0. The model weights 72.419 kg, which is composed of 12 parts, i.e., torso, pelvis, femur-r, tibia-r, talus-r, calcn-r, toes-r, femur-l, tibia-l, talus-l, calcn-l and toes-l (Fig. 2a). In order to sim-

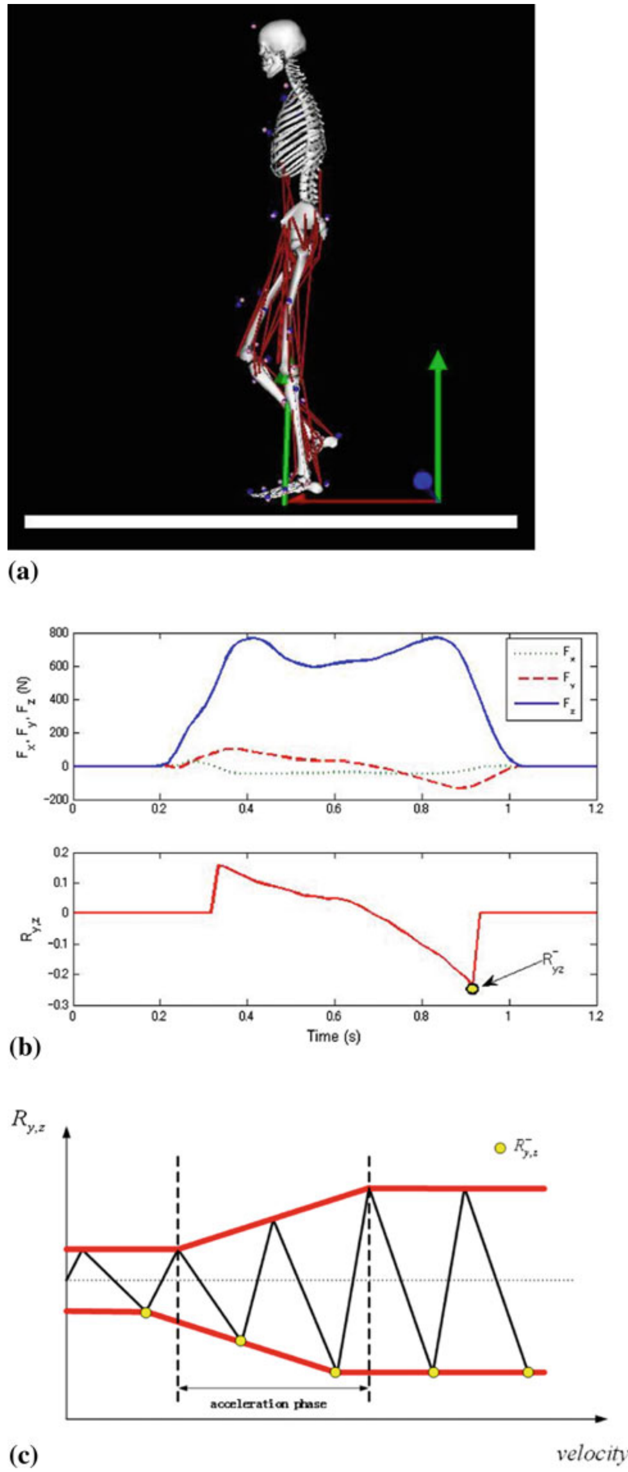

Fig. 2 Walking behavior analysis. (**a**) A human skeleton model is simulated for analyzing interaction force between foot and ground surface. (**b**) A critical force ratio $R^{-}_{y,z}$ is created based on the interaction forces computed in simulation. (**c**) In walking acceleration phase, the envelope of $R_{y,z}$ is linearly correlated with walking speed

ulate the walking behavior better, 28 muscles are included in the model. Additionally, contact force is also considered. The coordinate system is set as that red arrow, green arrow and blue arrow denoting y, z and x directions, respectively. Because the upper limbs are not of crucial importance, the model is built without upper limbs for simplicity.

The simulation results show that in one dynamic circle, the force F_z is a bell-shaped signal, and F_y is a sine-shaped signal (Fig. 2b). The signal shapes are explained as follows. When the foot gets in touch with the treadmill surface, F_z increases very rapidly. At the same time, the foot breaks to adjust its speed to the belt speed by friction. After the breaking process, the foot applies a force with inverse direction to drive the leg for taking a step, which indicates making a preparation for higher speed of leg in the next moment. Compared with the breaking process, F_y changes its direction. Until now, the foot has been firmly placed on the treadmill. Hence, F_z maintains a large value (for the skeleton model with 70-kg weight, F_z is about 700 N). Finally, the body alternates the other foot to support body and F_z decreases rapidly.

Considering the duration when foot is firmly on the ground (i.e., F_z maintains large), we define a force ratio $R^{-}_{y,z}$ as

$$R^{-}_{y,z} = \begin{cases} \min\limits_{0 \le t \le T} \left\{ \frac{F_y}{F_z} \right\} & F_z \ge \xi \\ 0 & \text{others} \end{cases} \quad (1)$$

where ξ is a threshold normally chosen as $\xi = \max\{F_z\} \times 80\,\%$. T is the circle period for making a step. $R^{-}_{y,z}$ is directly proportional to the force driving the body forward F_y and inversely proportional to the supporting force F_z. Considering the relation between $R^{-}_{y,z}$ and interaction force, we give a reasonable hypothesis, i.e., $R^{-}_{y,z}$ is a critical index for estimating human's walking speed. Below, we give two experiments to prove this hypothesis.

3.2 Experiment 1: least-squares regression studies

We measure the interaction force when a subject walks on the treadmill with a specific speed. After simple computation (Eq.(1)), we get a discrete sequence of treadmill speed V_i and corresponding force ratio $R^{-}_{y,z,i}$ where $1 \le i \le n$.

$$(V_1, R^{-}_{y,z,1}), (V_2, R^{-}_{y,z,2}), \ldots, (V_n, R^{-}_{y,z,n}) \quad (2)$$

Assuming $R^{-}_{y,z}$ can be described as a function of treadmill speed V, we can model this situation by

$$R^{-}_{y,z} = f(V, \lambda) + \varepsilon \quad (3)$$

where λ is parameter vector. The random variable ε is independent of V and statistically on average it is equal to zero, i.e., $E(\varepsilon) = 0$. To find f which fits the measurement data best and we define the loss function to measure the quality of the fit as

$$L(\lambda, \varepsilon) = \|R^{-}_{y,z} - f(V, \lambda) - \varepsilon\|_2 \quad (4)$$

By minimizing L over all choices of parameter vector λ, the solution of the above optimization problem is

Table 1 Least-squares regression result

Model type	Regression result	Norm of residuals
Linear	$R^-_{y,z} = -0.13V - 0.011$	0.039887
Quadratic	$R^-_{y,z} = 0.067V^2 - 0.2V - 0.00072$	0.034701
Cubic	$R^-_{y,z} = -0.08V^3 + 0.19V^2 - 0.25V + 0.0022$	0.034094
4th degree polynomial	$R^-_{y,z} = -0.6V^4 + 1.1V^3 - 0.56V^2 - 0.097V - 0.0021$	0.031844

Linear, quadratic, cubic and 4th-degree polynomial models are used in regression analysis. The residual result shows that the four models do not have much difference in model description

Table 2 Analysis of variance (ANOVA)

Subject no.	Coefficients		Relevance (R^2)	Sum of squares		*F* test		*t* test	
	λ_1	λ_0		Regression	Residual	*F*	Sig.	*t*	Sig.
1	0.198	0.023	0.951	0.071	0.004	215.416	0.000	−14.677	0.000
2	0.189	0.006	0.933	0.065	0.005	152.858	0.000	−12.364	0.000
3	0.183	0.014	0.944	0.061	0.004	187.050	0.000	−13.677	0.000
4	0.165	0.035	0.905	0.050	0.005	104.727	0.000	−10.234	0.000
5	0.198	0.000	0.967	0.071	0.002	323.460	0.000	−17.985	0.000
6	0.148	0.015	0.946	0.040	0.002	193.564	0.000	−13.913	0.000

Three tests (including relevance test, *F* test and *t* Test) are executed to statistically prove the linear hypothesis. *Sig* significance value)

$$\frac{\partial L(R^-_{y,z}, f(V,\lambda), \varepsilon)}{\partial \lambda} = 0 \tag{5}$$

In the experiment, for one-specific subject, we set the treadmill speed from 0 to 1.3 m/s with increment of 0.1 m/s and search for proper model in Eq.(3). Using Eq.(5), we obtained four types of regression models including linear, quadratic, cubic and 4th degree polynomial. The regression result is shown in Table 1. We found that the residual errors of the four models do not have big difference. Hence, we choose the linear model. For this subject, the walking speed linearly correlates with $R^-_{y,z}$

$$R^-_{y,z} = \hat{\lambda}_0 + \hat{\lambda}_1 V + \varepsilon \tag{6}$$

where ε is independent variables (white noise). To conclude, the linear model parameters which change from subject to subject can be calculated as follows. We will use this parameter calculation in Experiment 2.

$$\begin{cases} \hat{\lambda}_0 = \bar{R}^-_{y,z} - \bar{V}\hat{\lambda}_1 \\ \hat{\lambda}_1 = L_{xy}/L_{xx} \end{cases} \tag{7}$$

where

$$\bar{V} = \frac{1}{n}\sum_{i=1}^{n} V_{\mathrm{i}}, \quad \bar{R}^-_{y,z} = \frac{1}{n}\sum_{i=1}^{n} R^-_{y,z,i}$$

$$L_{xy} = \sum_{i=1}^{n} (V_{\mathrm{i}} - \bar{V})(R^-_{y,z,i} - \bar{R}^-_{y,z}), \quad L_{xx} = \sum_{i=1}^{n} (V_{\mathrm{i}} - \bar{V})^2$$

where n is the number of observation sample pairs.

3.3 Experiment 2: statistical analysis

In this experiment, we prove the linear relation Eq. (6) is suitable across different subjects. Six subjects, including three males and three females, were studied (mean ± SD): age 24.17 ± 0.75 years; body mass 58.50 ± 17.85 kg; body height 168.67 ± 11.71 cm; and body mass index (BMI) 20.22 ± 3.41 kg/m^2. All the subjects gave written informed consents.

We used analysis of variance methods to test the model's linearity for all the subjects (Table 2). The coefficient of determination R^2 is the squared value of the correlation coefficient. It shows that more than 90 % of the variation is explained by the linear model. The regression displays information about the variation accounted for by the linear model. The residual denotes the difference between the observed and model-predicted values of the dependent variable. The regression is more than ten times larger than the residuals, which also implies the validity of model. The significance value of the F statistic is $<$0.05, which means that the variation explained by the linear model is not due to chance. All the significance values of the t statistic are $<$0.05. Thus, the remaining predictors are adequate in the model. Hence, considering the individual differences and by the above verification, the linear model (Eq. (6)) is suitable for all individuals.

3.4 Physical meaning of linearity

According to the curve shapes of F_y and F_z, the curve shape of F_y/F_z is a composite signal of sine-shaped signals and zero signals (Fig. 2b). Without loss of generality, the zero signals are ignored in analysis. As $R^{-}_{y,z}$ is actually the extreme value of F_y/F_z, the extreme value of F_y/F_z in every walking cycle has a statistically linear relation with the walking speed. Joining all the extreme points with a line shapes an envelope of F_y/F_z. Thus, the physical meaning of linearity is that the envelope curve has a linear relation with the walking speed (an acceleration example is explained in Fig. 2c where the yellow points denote $R^{-}_{y,z}$ under different walking speeds).

3.5 Control performance

We used the linear relation Eq.(6) to control the treadmill. Here, the estimated walking speed is computed by real-time $R^{-}_{y,z}$ data. We asked subjects to test the adaptive treadmill-style locomotion system. The subjects walk on the treadmill and control the speed of treadmill by foot. Each subject is asked to test the locomotion system for about 2 min. The test includes three kinds of walking behaviors, including acceleration, deceleration, and constant speed. For example, Fig. 3 shows experiment environment and the three walking

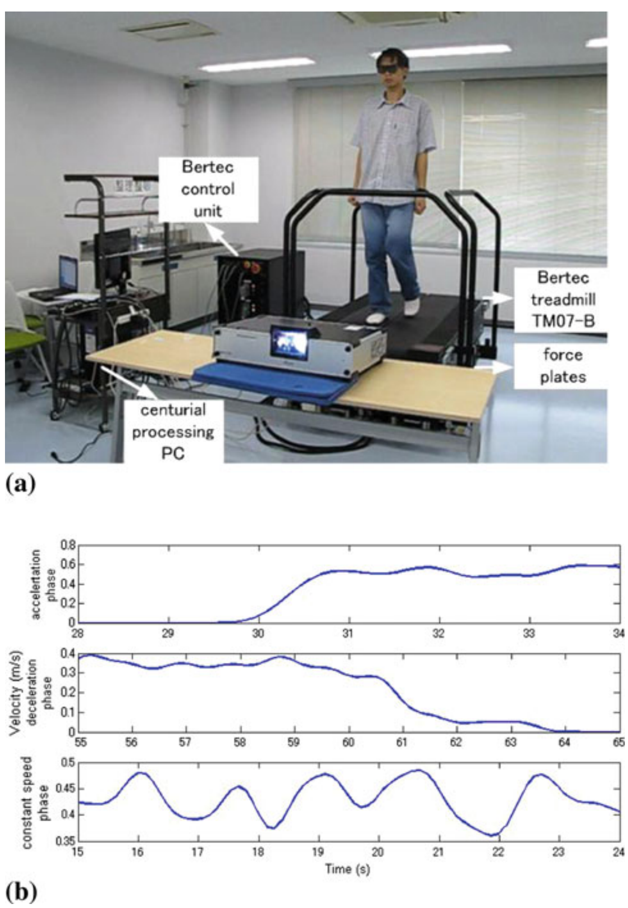

Fig. 3 Treadmill-style locomotion interface control. (**a**) One subject walks on the locomotion interface and watches the 3-D virtual street at the same time. (**b**) The control performance is verified in three walking behaviors, i.e., acceleration, deceleration and constant speed

states for the test of one of the subjects. The subject controls the treadmill to accelerate from stop position to 0.5 m/s in the time interval [28, 34] s; decelerate from 0.4 m/s to stop position in the time interval [55, 65] s; and maintain the speed of 0.43 m/s in the time interval [15, 24] s.

4 Virtual market application

4.1 System architecture

The virtual market system consists of three modules as central processing PC, Bertec treadmill and 3-D stereoscopic display (Fig. 4a). When the subject walks on the treadmill, the dual force plates (placed under the treadmill) measure the force and moment signals in x, y, z directions as F_x, F_y, F_z, M_x, M_y, M_z and output them as analog signals. After amplifying them and processing analog-to-digital (A/D) conversion by LABVIEW, the digital signals are transferred to central processing PC. Based on the force signals, intended walking speed of the user is estimated. The estimated speed is used in two ways: one is to drive the two motors corresponding to left and right belts speed control; the other is to drive the 3-D virtual reality scene to move on.

From the viewpoint of control theory, the control plant is Bertec treadmill which is controlled by treadmill inner controller in the inner feedback loop (Fig. 4b). When the user walks on the treadmill, there is also sensor noise added to the control signal. The control objective is to control the treadmill by the subject's will. Hence, we establish an outer loop feedback between the subject's intended walking speed V_{intend} and the treadmill inner controller. In this case, the force plate is chosen as an observer measuring the interaction forces between foot and treadmill surface.

4.2 Stereo display

The virtual market display module is connected with central processing PC module by TCP/IP protocol. At each moment, the 3-D display adjusts according to the estimated walking speed.

The virtual market is Japanese style and thus, the environment has culturally appropriate features. Right now, the market is designed as a north-south street with a length of 80 m, including one traffic corner and numerous cross roads. There are 20 shops in all with 10 shops distributed on each side of the road. At the end of the road, there is a train station by entering which the program terminates (Fig. 5).

The program was developed by Visual C++. In general, the utility toolkit GLUT was used for vision design and SDL library was used for sound design. For the vision design, 3-D models of shops, post office, etc. were constructed by Metasequoia which is a polygon modeler for 3DCG and game development. Specifically, everything is created as an assembly of

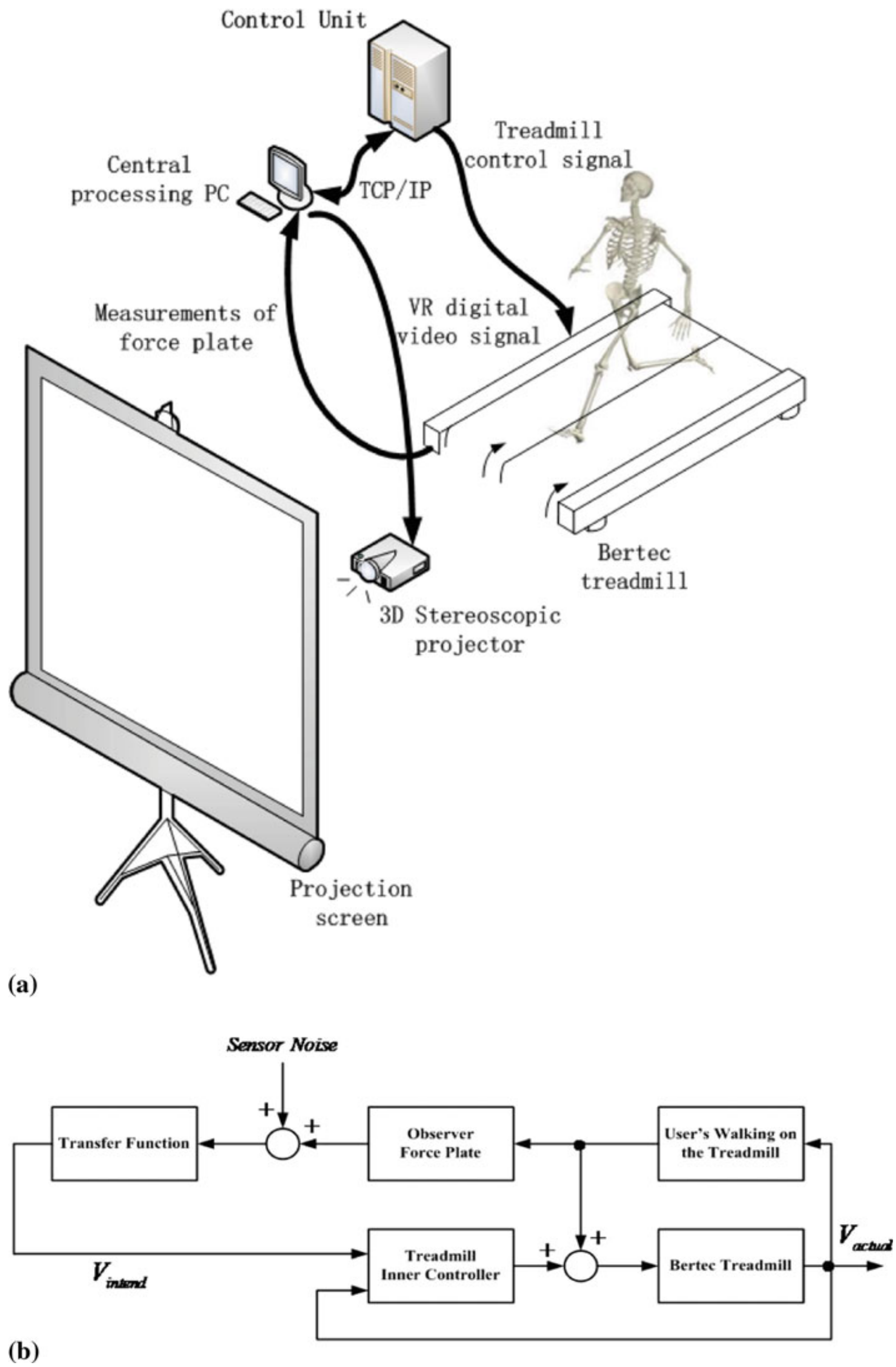

Fig. 4 Virtual interactive market system. (**a**) Subject walks in the virtual market street where the walking speed is controlled by foot. Meanwhile, the 3-D projector synchronizes with the walking speed. (**b**) Inner control loop makes the treadmill to track the desired speed. Outer control loop estimates the subject's walking speed and send it to the treadmill inner controller

several basic geometrical bodies. Each face of the composite unit is assigned with a special texture. For example, the surface of ground is mapped with asphalt material; the surface of sky is mapped with cloud. Finally, the above-generated 3-D model data were used by the utility toolkit GLUT OpenGL directly. For the sound design, we used SDL-mixer library to create various sounds, like the footstep sound, the market sell voice, etc. Even for the place near the train station, the subject can hear the jingle of the train from the distance to the close.

In order to realize stereoscopic display, the subject wears a 3-D eyewear. The 3-D eyewear has two different eyeglasses which allow different polarized light pass separately. In such a way, the left and right eyes of the user see different images from its own viewpoint. In the system, papillary distance is set as 7 cm. Thus, the left and right optical lines of sight

Fig. 5 Binocular vision of 3-D virtual shopping street. The market is designed in Japanese style. The virtual market is a north-south street with a length of 80 m including one traffic corner and numerous cross roads. (**a**) One scene. (**b**) Another scene

cross at 1 m before the user. The configuration of the viewpoint height is as follows. Assuming that the average height of man is about 170 cm and of woman is about 160 cm, respectively, and the height of viewpoint is compromised to be 165 cm.

In addition, the system has many options. For example, the subject can choose whether there is background music or choose different streets to walk in.

5 Conclusion

This paper solves the walking speed estimation problem by foot-ground interaction force. The proposed method is simple but effective, based on which, a treadmill-style locomotion interface was developed. This locomotion interface not only shows the validity of the proposed solution but also provides a promising human machine interface (HMI) for entertainment, healthcare and rehabilitation. As an application, we applied the developed locomotion interface into a 3-D interactive virtual market system. The subject walks on the treadmill at his/her desired speed. The treadmill and stereo display automatically adjust to the subject's walking speed, correspondingly.

Acknowledgments This work is partly supported by Japan Society for the Promotion of Science (JSPS) under the grant of Research Fellowship. The authors would like to thank Tatuo Oshiumi, Hisahito Noritake, Yusuke Taki and Shouichi Katou for their assistance in experiment.

References

1. Noma H, Miyasato T (1998) Design for locomotion interface in a large scale virtual environment ATLAS: ATR locomotion interface for active self motion. In: 7th annual symposium on haptic interface for virtual environments and teleoperated systems
2. Darken RP, Cockayne WR (1997) The omni-directional treadmill: a locomotion device for virtual worlds. In: 10th annual ACM symposium on user interface software and technology
3. Iwata H, Yoshida Y (1999) Path reproduction tests using a Torus treadmill. Teleoper Virtual Environ 8:587–597
4. Hollerbach JM, Christensen R (2000) Design specifications for the second generation Sarcos Treadport locomotion interface. In: Haptics symposium of ASME dynamic systems and control division
5. Christensen R et al (2000) Inertial force feedback for the Treadport locomotion interface. Teleoper Virtual Environ 9:1–14
6. Muybridge E (1955) The human figure in motion. Dover Publications, USA
7. Herren R et al (1999) The prediction of speed and incline in outdoor running in humans using accelerometry. Med Sci Sports Exerc 31:1053–1059
8. Vathsangam H et al (2010) Toward free-living walking speed estimation using Gaussian process-based regression with on-body accelerometers and gyroscopes. In: 4th international conference on pervasive computing technologies for healthcare
9. Bendall MJ, Bassey EJ, Pearson MB (1989) Factors affecting walking speed of eldly people. Age Ageing 18:327–332
10. Su S et al (2005) Estimation of walking energy expenditure by using support vector regression. In: 27th annual international conference of the engineering in medicine and biology society
11. Rothney M et al (2007) An artificial neural network model of energy expenditure using nonintegrated acceleration signals. J Appl Physiol 103:1419–1427
12. Bonomi AG, Salati S (2010) Assessment of human ambulatory speed by measuring near-body air flow. Sensors 10:8705–8718

13. Dong H, Luo Z, Nagano A (2010) Adaptive treadmill control by human will, in emerging trends in mobile robotics. World Scientific, New Jersey 1185–1194
14. Dong H, Meng J, Luo Z (2011) Real-time estimation of human's intended walking speed for treadmill-style locomotion interfaces. In: 8th international conference on ubiquitous robots and ambient intelligence
15. Rebsamen B, et al (2006) A brain-controlled wheelchair based on P300 and path guidance. In: IEEE international conference on biomedical robotics and biomechatronics
16. Ivancevic VG, Ivancevic TT (2005) Natural biodynamics. World Scientific Publishing Co. Pte. Ltd., New Jersey
17. Winter DA (1990) Biomechanics and motor control of human movement, second edn. Wiley, London
18. Jamieson LP, Hunt KJ, Allan DB (2008) A treadmill control protocol combining nonlinear, equally smooth increases in speed and gradient: Exercise testing for subjects with gait and exercise limitations. Med Eng Phys 30:747–754
19. Schutz Y et al (2002) A new accelerometric method to assess the daily walking practice. Int J Obes 26:111–118
20. Hollerbach JM (2002) Locomotion interfaces, in Handbook of virtual environments: design, implementation, and application. Lawrence Erlbaum Associates, NJ 239–254