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Remotely Controlled Cycling Exercise System for Home-Based Telerehabilitation

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Abstract— **Limited research has been conducted in utilizing telemedicine to promote upper and lower limb rehabilitation using remotely controlled home-based ergometers. The goal of this study was to develop and assess a telerehabilitation system supporting internet-controlled home-based cycling exercise. We designed an interface to control cycling speed of an ergometer from a remote server via Internet. The evaluation of the interface included consecutive transmission of 7 different cycling speed levels, each level of 2-minute duration. Overall, the mean difference between remotely setup and actual cycling speed was 0.002±0.03 miles/hour. Our evaluation demonstrated high fidelity of the proposed system and reliability of controlling individualized exercise prescription for home-based cycling equipment via Internet.**

I. Background

Cycling exercise equipment is frequently utilized to facilitate upper and lower extremity training and it is widely available in rehabilitation facilities where the patient exercise may be supervised [1]. The cycling exercise training has been shown to improve clinical outcomes in patients with chronic health conditions and promote rehabilitation in older adults and was shown beneficial for patients recently weaned from mechanical ventilation, patients in post-acute recovery phase after hip fracture, dialysis patients during hemodialysis sessions, and in active elderly [2]. However effective use of these simple and low cost exercise devices at patient homes is hampered by lack of remote connectivity with a team of rehabilitation professionals, inability to monitor exercise progress in real time using simple graphical and numerical representation, and absence of an alert system which would prevent exertion levels exceeding those approved by the geriatric rehabilitation team.

Telemedicine approaches can potentially facilitate safe and effective use of cycling equipment at patient homes for rehabilitation. Despite this growing need [3-4], limited research has been conducted in utilizing telemedicine to promote upper and lower limb rehabilitation using remotely controlled home-based ergometers.

In our previous study, we demonstrated feasibility of Interactive Biking Exercise (iBikE) system [3]. The previously described iBikE system was designed to address barriers for effective home-based rehabilitation by developing a system aimed at real-time monitoring of cycling exercises, evaluate its feasibility, and describe design and implementation of a geriatric telerehabilitation system facilitating safe cycling exercise at senior citizen homes [3-4].

The comprehensive telerehabilitation systems utilize specific plans of fitness-related activities that are designed for a specified purpose, which is often developed by a rehabilitation specialist for the patient. Due to the specific and unique needs and interests of the patient, the goals of exercise prescription should successfully integrate exercise principles and behavioral techniques that motivates the participant to be compliant, thus achieving their goals [1-2]. However, frail patients, or patients with multiple chronic diseases may have difficulties in following the prescribed exercise plan. Telerehabilitation system should be designed to guide patients in following their individualized rehabilitation plans.

In this article, we seek to introduce and assess a telerehabilitation system supporting internet-controlled home-based cycling exercise. The system design is discussed and results of the system fidelity assessment are presented.

II. System

Our ultimate objective is to build a distributed web-based system which would facilitate comprehensive rehabilitation by remote telemonitoring and management of patients requiring upper and lower limb rehabilitation by using cycling exercise equipment at home in an effective and safe way.

A. iBikE System Design

The iBikE system is an extension of Home Automated Telemanagement system which was previously described [3-5]. The HAT system follows Wagner's model of chronic disease care [6]. The HAT system supports the major components of this model including patient self-care, tailored education and counseling, individualized treatment plan, guideline- concordant decision support, comprehensive patient provider communication, and multidisciplinary care coordination [3-6].

The iBikE system consists of the clinician unit, the iBikE server, and the home unit as shown in Fig. 1.

The clinician unit is designed to access the patient data and history, to adjust patient-specific parameters related to the decision support, the patient exercise plan, and the patient prescription, to review alerts, and to exchange message between the clinician and the patient. The iBikE server consists of the iBikE web server, the iBikE database, and the decision support module. The iBikE server makes a secure access to all data between the clinician and the patient via internet from the iBikE database. The decision support module analyses and controls all data traffic from BikER system participants. The home unit supports real-time data transmission between the iBikE server and the patient unit.

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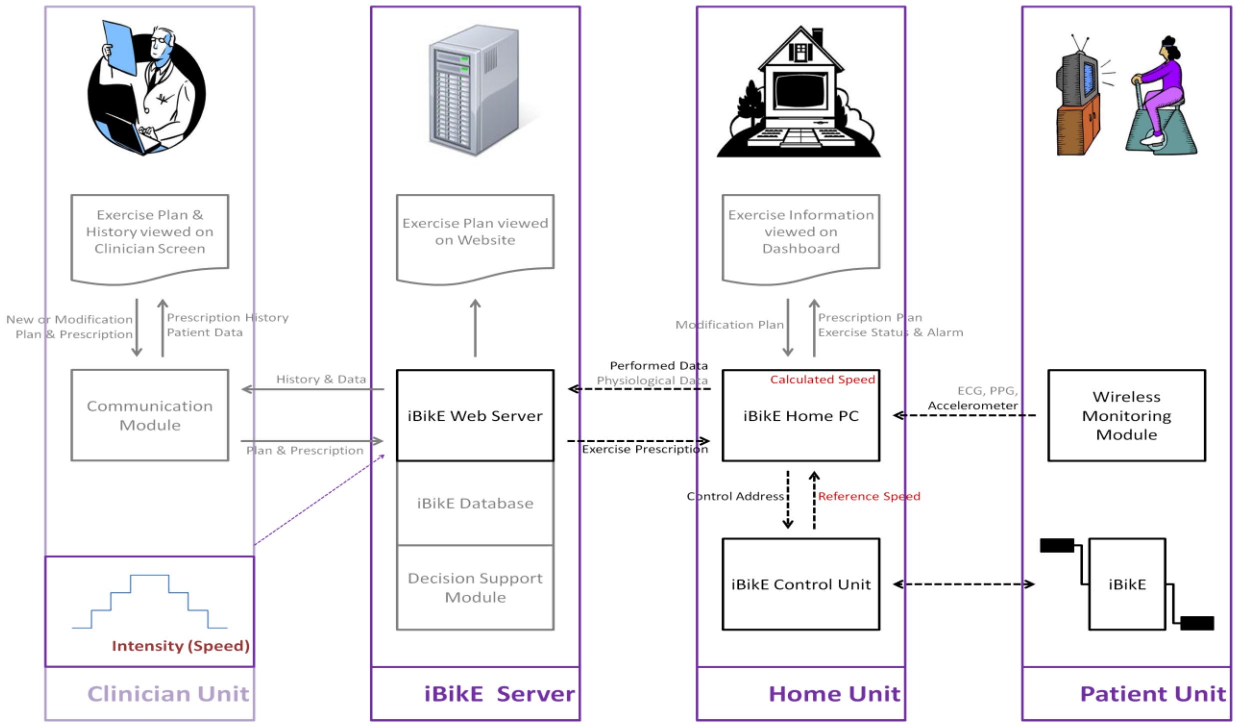

Figure 1. Design of the Internet-Controlled Interactive Exercise Biking System (iBikE)

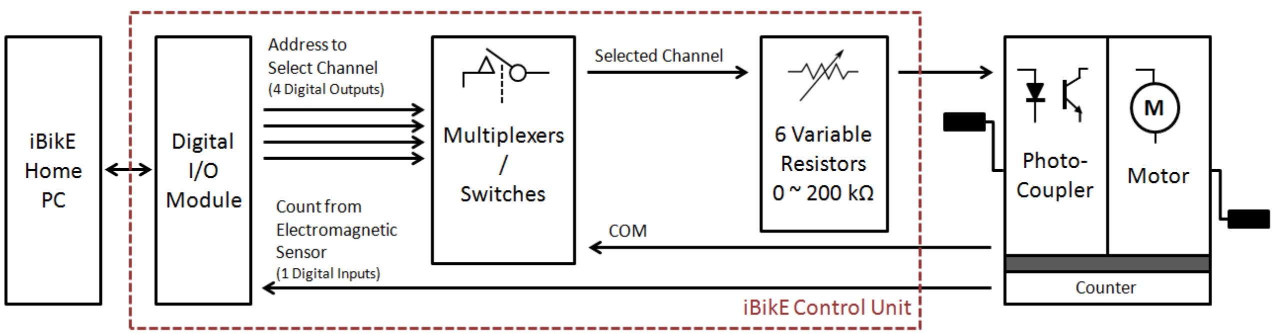

Figure 2. iBikE Exercise Control Unit

The home PC communicates with iBikE server via TCP/IP protocol, and it collects information from wireless 3-axis accelerometer (Shimmer Research, Dublin, Ireland), wireless electrocardiogram (ECG) module, and wireless photoplethysmogram (PPG) module to monitor exercise efficacy and safety. The design of the home iBikE unit supports flexible exercise prescription and remotely control of exercise settings by a comprehensive rehabilitation team, automated exercise records, real-time monitoring of patient progress towards recommended patient-specific exercise goals, and generation of exercise safety alarm when the exercise intensity or patient symptom scores are about to exceed provider recommended maximum values. The home PC generates a detailed exercise log which can be communicated to the patient rehabilitation team. This allows the patient providers determine which exercise settings are more challenging to the patient. There are also general exercise safety tips as well as specific tips for each exercise designed to minimize the risk of injury during exercise. The iBikE control unit is designed to remotely control exercise intensity of the patient exercise. A touch screen dashboard is used for the patient interface to confirm or modify the patient preferences, enter symptom information, communicate with providers or peers, to set wireless sensors, and to receive feedback on the exercise status during patient exercise. The dashboard has been optimized for individuals with possible limitations in vision, locomotion, and cognition. The patient unit includes a pedaling device (SF-B02 Motorized Mini Bike, Sunny Health Fitness, USA), a wireless 3-axis accelerometer, a wireless ECG module, and a wireless PPG module and sends physical and physiological raw data to the iBikE home PC.

B. iBikE Exercise Control Unit Design

The iBikE exercise control unit is designed to control the speed of cycling exercise by controlling resistance of a circuit which affects current supply to a mechanical motor. Higher resistance results in slower rotation of a cycling ergometer.

TABLE I. DIFFERENCE BETWEEN ACTUAL AND REMOTELY SETUP CYCLING SPEED

Step	Resistance	N	Reference Speed			Calculated Speed			Differences						
												95% CI			
			Mean	SD	SE	Mean	SD	SE	Mean	SD	SE	Lower	Upper	Min	Max
1	0.0	142	1.76	0.015	0.001	1.75	0.031	0.003	0.002	0.0334	0.0028	-0.003	0.008	-0.088	0.083
2	6.8	129	1.57	0.015	0.001	1.57	0.025	0.002	0.001	0.0286	0.0025	-0.004	0.006	-0.074	0.070
3	15.8	110	1.36	0.015	0.001	1.36	0.020	0.002	0.002	0.0233	0.0022	-0.002	0.007	-0.033	0.073
4	29.8	93	1.14	0.013	0.001	1.14	0.015	0.002	0.004	0.0190	0.0020	0.000	0.008	-0.046	0.047
5	48.9	76	0.93	0.011	0.001	0.93	0.008	0.001	0.005	0.0126	0.0014	0.002	0.008	-0.022	0.041
6	81.2	58	0.74	0.007	0.001	0.73	0.006	0.001	0.003	0.0082	0.0011	0.001	0.005	-0.018	0.021
7	189.5	43	0.55	0.003	0.000	0.54	0.004	0.001	0.003	0.0054	0.0008	0.001	0.005	-0.004	0.028
All		657	1.30	0.382	0.015	1.29	0.383	0.015	**0.002**	**0.0244**	**0.0010**	**0.000**	**0.004**	**-0.088**	**0.083**

Resistance Unit (kΩ), Reference Speed, Calculated Speed, and Defferences Unit (miles/hour), SD; Standard Deviation, SEM; Standard Error, CI; Confidence Interval, N: Number of rotations; Min: Minimum,; Max: Maximum

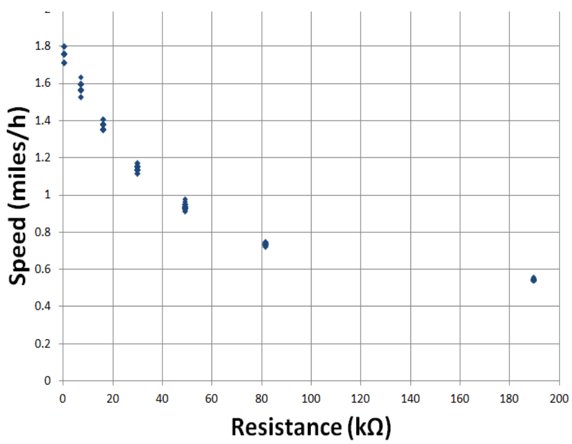

Figure 3. Resistance calibration curve for setting up cycling speed

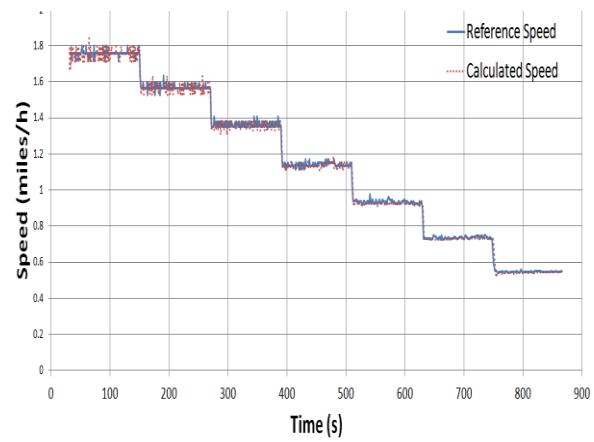

Figure 4. Correspondence between remote and actual cycling speed

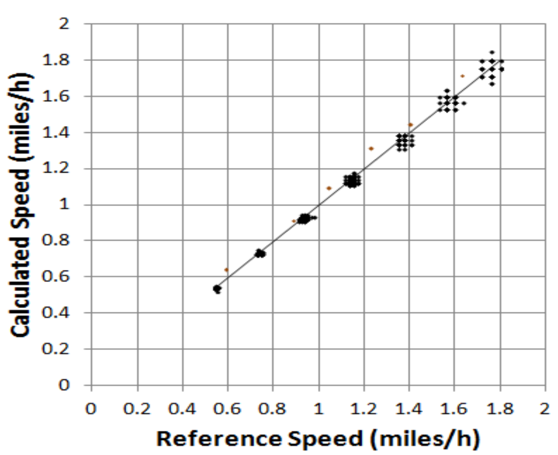

Figure 5. Correlation between reference speed and calculated speed

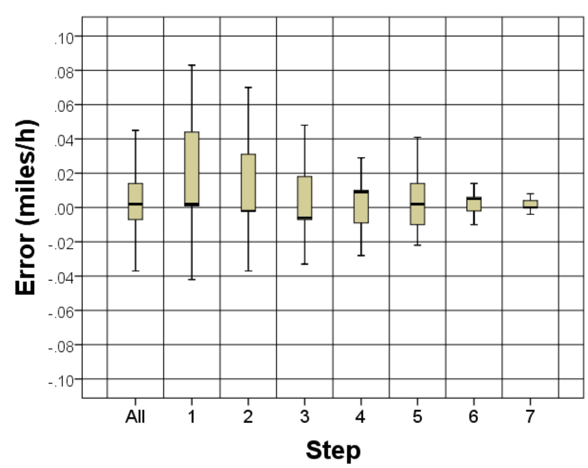

Figure 6. Calculated speed error range at each cycling speed level

The design of the iBikE exercise control unit is presented in Fig. 2.

The iBikE exercise control unit consists of an inexpensive USB digital input/output module (digital I/O module; USB-1024LS, Measurement Computing Co., USA), a low-voltage CMOS analog multiplexer (mux; MAX4051, Maxim Integrated, USA), and a set of six variable resistors that range from 0 Ω to 200 kΩ. The software for the iBikE home unit platform was designed using LabVIEW 2011and was implemented for Microsoft Windows operating system.

The iBikE home PC sends a 4-bit channel address and status information to the digital I/O module. The digital I/O module transmits this information to the mux via 4 TTL logic lines, and then the mux opens/closes the selected channel so that corresponding resistance is chosen. This information is transferred to the cycling ergometer motor by a photo-coupler thus affecting current supply to the motor and changing the cycling speed.

For precise monitoring of cycling speed, we utilized an electromagnetic sensor in the pedaling device which sent on/off information to the digital I/O module with each rotation. The digital I/O module received this information via a TTL logic line and transferred it to the iBikE home PC for analyzing the cycling speed.

III. Evaluation

To evaluate the functionality of our remotely controlled cycling exercise system we investigated correspondence between the intensity of exercise prescription setup as 7 different levels of cycling speed at the iBikE web server and actual cycling speed of a remote arm ergometer to be used at patient homes. The iBikE home PC controlled the iBikE arm ergometer via iBikE exercise control unit according to the cycling speed levels transmitted to the iBikE home PC from the iBikE web server via internet in real time.

A. Methods

The evaluation included consecutive transmission of 7 different cycling speed levels, each level of 2-minute duration. The actual cycling speed on the home arm ergometer was obtained using two approaches. One approach utilized a TTL signal generated by an electromagnetic sensor in the pedaling device with each rotation. This signal was sampled at 50Hz by the digital I/O module connected with pc via a USB. Because of high precision, the cycling speed defined by this approach was called "reference speed." Not each ergometer may be equipped by an electromagnetic sensor. To address this limitation, we employed another approach for measuring cycling speed which utilized a 1-axis 12-bit accelerometer with 1.5g range and the 0.024g sensitivity. The accelerometer was mounted on one of the two rotating handles of the arm ergometer. The signal from accelerometer was sampled at 51.2 Hz and transferred via class 2 Bluetooth radio communication to PC to calculate cycling speed. This approach was called "calculated speed."

B. Analyses

The reference speed was calculated by finding the rising edge of the digital signal generated by the electromagnetic sensor. The calculated speed was obtained by applying previously described and evaluated iBikE Parameters Detection Algorithm (iBikE PDA) to the 1-axis accelerometer signal [3].

To estimate the fidelity of the proposed system, we compared correspondence between each prescribed cycling speed level and actual cycling speed of the home arm ergometer obtained using two approaches described above. For the future practical application of the iBikE system, the correlation between the reference speed from the pedaling device and the calculated speed from the accelerometer sensor was analyzed. This was done to assess accelerometer potential for wider applications that could measure additional exercise parameters from other axis, as well as signal vector magnitude, cycling pattern, and movement smoothness.

C. Results

The cycling speed increments in the experiment were set at about 0.2 miles/hour ranging from 1.76 miles/hour to 0.55 miles/hour. For the pedaling device that we used, the maximum speed was about 1.8 miles/hour (mean; 1.76, standard deviation (SD); 0.015) and the minimum allowable speed setting was near 0.6 miles/h (mean; 0.55, SD; 0.003). To control the cycling speed by changing resistance, we built a calibration curve based on experimental identification of association between actual resistance and cycling speed. The resulting estimation equation based on the experimental speed data ($y = 8.492x^{-0.518}$, $R^2 = 0.9938$) is depicted in Fig 3. It is clear from the calibration curve, that using different resistance values continuous change in cycling speed may be achieved. The correspondence between remotely prescribed cycling speed, reference speed, and calculated speed is demonstrated in Fig. 4. The correlation between the reference speed and the calculated speed ($R^2 = 0.9959$) is shown in Fig. 5. Table I shows differences between the reference speed and the calculated speed for each remotely prescribed cycling speed level. Mean difference varied from 0.002 to 0.005 miles/hour (SD ranging from 0.0054 to 0.0190 miles/hour), and the maximum difference in the cycling speed was -0.088 miles/hour. Overall, the mean difference in cycling speed was 0.002 miles/hour (SD = 0.0244 miles/hour), and difference ranges were from -0.088 to 0.083 miles/hour. The speed differences are presented by an error bar chart with 95% confidence interval for mean errors in Fig. 6.

IV. Discussion

The iBikE system takes advantage of the current technology to provide patients with an individualized treatment plan and exercise regimen as well as enforcing adherence to rehabilitation through more comprehensive monitoring and feedback. Our evaluation demonstrated high fidelity of the proposed system and reliability of controlling individualized exercise prescription for a home-based cycling equipment via internet.

V. Conclusion

The proposed approach has significant potential in enhancing patient recovery and facilitating home-based telerehabiliation. Clinical evaluation of the proposed system in patients requiring upper and lower limb rehabilitation is warranted.

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