VRACK - Virtual Reality Augmented Cycling Kit: Design and Validation

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Abstract

In this paper the virtual reality augmented cycling kit (VRACK) a mechatronic rehabilitation system with an interactive virtual environment is presented. It was designed as a modular system that can convert most bicycles in virtual reality (VR) cycles. Novel hardware components embedded with sensors were implemented on a stationary exercise bicycle to monitor physiological and biomechanical parameters of participants while immersing them in a virtual reality simulation providing the user with visual, auditory and haptic feedback. This modular and adaptable system attaches to commercially-available stationary bicycle systems and interfaces with a personal computer for simulation and data acquisition processes. The bicycle system includes novel handle bars based on hydraulic pressure sensors and innovative pedals that monitor lower extremity kinetics and kinematics. Parameters monitored by these systems are communicated to a practitioner's interface screen and can be amplified before entering its virtual environment. The first prototype of the system was successful in demonstrating that a modular mechatronic kit can monitor and record kinetic, kinematic and physiologic parameters of riders.

Keywords: Immersive Gaming, 3D Interaction for VR, Haptics, Non-Visual Interfaces, Exergaming, Rehabilitation

1 Introduction

Interest in coupling virtual environments with robotic devices and exercise equipment is high. This is in part based on findings that training on robotic devices that are augmented with virtual reality have been shown to transfer to real world function, better than training on the robotic device alone [1]. These results are explained in part by the increased training intensity that a virtual environment provides. Bicycles have been coupled with gaming applications in order to improve training intensity that promotes cardiovascular fitness [2, 3]. There are however, no modular systems that can adapt an existing bicycle into a virtual reality augmented cycle that accepts separate inputs from each component. We have created such a system using novel hydraulic force-sensing handles and smart pedal modules interfaced with a virtual environment. A modular mechatronic system as the one described in this paper would be useful for fitness training as well as rehabilitation.

Innovations in hardware have allowed a more realistic feeling with stationary bicycles by employing mechanical linkages which simulate uneven terrain by allowing the frame to lean in the coronal and transverse planes [4,5]. These have been enhanced by research with subjective feeling of presence in a virtual environment [6]. Also, the heart rate as a measure of rider's level of exertion has been suggested as a means to control the difficulty of a game interfaced with the bicycle [7, 8].

Instrumented bicycle pedals have been used in evaluating kinetic/kinematic capabilities for subjects with both healthy and plegic lower extremities [9-14]. Although there has been extensive design evolution on bike pedal instrumentation, there has been limited research on incorporating handle bar sensors alongside the pedal sensors for assessing the gripping forces. Furthermore, there are no sensorized exercise bicycle systems that are modular and have the capability of using physiological (heart rate) and biomechnical (kinetics and kinematics) inputs to drive a virtual environment while at the same time collecting performance data. Therefore, the purpose of this paper is to describe the Virtual Reality Augmented Cycling Kit (VRACK) that achieves all those goals In addition, we present preliminary findings that validate the pedal and handlebar kinetics and heart rate responses of healthy individuals as well as illustrate the modularity of the kit.

2 System Overview

The virtual reality augmented cycling kit (VRACK), shown in Figure 1, consists of novel hardware components embedded with sensors that are used to enhance the use of a typical stationary exercise bicycle. Signals are acquired from two identical handlebar systems (A), two nearly identical pedal systems (B), the heart rate monitor system (C), and sent to a practitioner interface (F). The data from the sensing systems is sorted and streamlined into a User Datagram Protocol (UDP) signal used to drive the custom developed virtual environment (G). All components are tethered and powered by the power & signal boxes (D, E) with the exception of the heart rate monitor which is wireless. Each parameter can be adjusted for sensitivity or can be turned on and off by the practitioner to further control and customize the exercise regimen.

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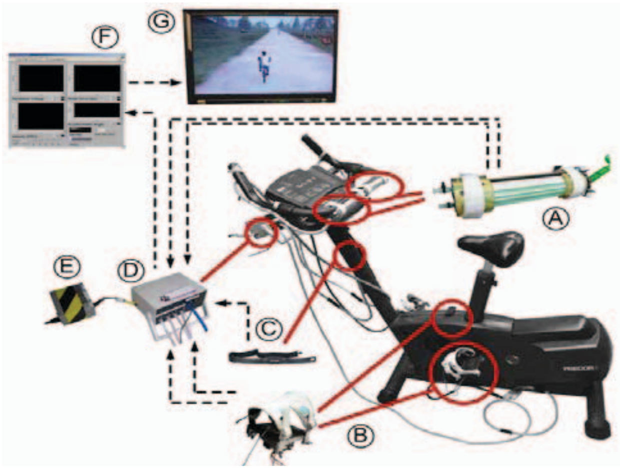

Figure 1: Bicycle system complete overview; A: handlebar module; B: pedal module; C: heart rate monitor; D: signal box; E: power box; F: practitioner interface; G: virtual environment

2.1 INSTRUMENTED HANDLEBAR MODULE

The handle system in Figure 2 is a novel type of hydraulic dynamometer, which measures applied physical force to control dynamic motion of the rider in the virtual environment. Although the handlebars themselves are static, the rider is able to apply turning forces as on a normal bicycle. It is inexpensive compared to alternatives with a compression load cell, and the built-in elasticity and spring return of the nylon hydraulic chambers provides a haptic feedback to the rider as they increase isokinetic forces to make sharper turns. The chamber arrangement measures net force from the specific side of each hand, rather than just the net torque about the front fork as with some previous work. This is advantageous because only one sensor is required per handle to measure inputs from two surfaces.

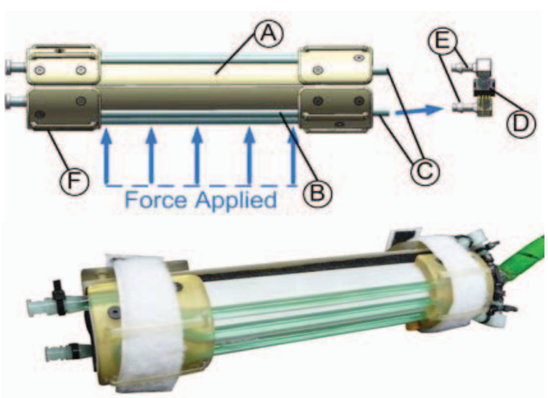

Figure 2: Instrumented handlebar model (top) and prototype (bottom). A: housing; B: sensing area; C: outlet tube sections; D: pressure sensor; E: tubing connections; F: handle caps

The sensing area of the handle is the surface area of the three exposed tube sections (B) which is contacted and compressed by the user. To alleviate pressure loss, tubing sections under the handle caps have been constrained and tubing outside of the housing has been minimized and sealed.

Each of the two hydraulic chambers is comprised of a single length of tube which is guided along channel contours embedded in the housing geometry. Fabrication of the handles using stereolithography made the contours of these channels possible.

For steering within the virtual environment it is important to mimic the reactions from a real bicycle closely to maintain the user immersion. However even straight, level pedalling regular motion causes slight oscillations in the upper trunk and handlebar trajectory. This was accounted for by a software dead zone which affects the visual feedback but not the data collection.

2.2 INSTRUMENTED PEDAL MODULE

The pedal module in Figure 3 is uniquely designed to attach to the crankshaft of a bicycle, stationary bicycle, or any other instrument with a removable pedal. This system does not require any specialized footwear from the rider, is still widely adjustable to a range of shoe sizes, and covers more surface area than conventional toe clip pedals to constrain the foot. Snowboard bindings (Flow, San Clemente, USA) attach across the dorsal side of the wearer's foot and accommodate anthropometric variability.

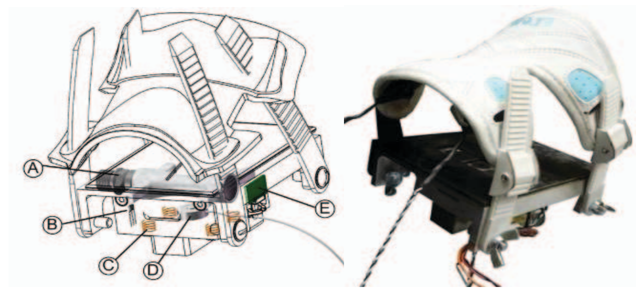

Figure 3: Instrumented pedal module schematic and instrumented pedal module prototype; A: pedal raceway; B: hall-effect sensor; C: pre-load; D: load cell; E: Accelerometer

A non-zero net force between the left and right pedals will 'lean' the virtual rider to the stronger side. The pedal forces must remain symmetric to keep the virtual rider vertical. Another novel feature of this module is sensing forces in both compression and tension, individually measureable for each foot rather than an indistinguishable average between the two by using a single-axis compression load cell with mechanical preload.

Range of motion of the ankle is monitored by an accelerometer to detect tilt in dorsi and plantarflexion. Velocity of the crank arm is measured by a latching Hall Effect sensor embedded in the pedal which passes four magnet posts on the frame of the bicycle, which drive the speed of the virtual rider.

Vibration elements provide haptic feedback, triggered by events within the virtual environment to alert the rider such as riding off the path. The combination of haptic and visual feedback has been studied for ankle movements with patients post-stroke to improve selected physical parameters [15], but there is currently no commercial system which enhances the virtual experience using haptic feedback this way. If the rider had loss of sensitivity to the dorsal side of their foot the vibrators could be re-located, or remain in place to direct the rider's attention to their affected foot.

2.3 ADDITIONAL ELECTRONICS

A wireless heart rate receiver (RE07L, Polar Electro Inc., Lake Success, NY, USA) drives a pace rider in the virtual environment. The heart rate of the rider directly controls the pacer's relative location as a motivational tool to speed up or slow down. If the rider deviates too far from the practitioner-set heart rate then the pace rider will overtake or slow down to encourage the rider to increase or decrease their exertion.

3 Data Acquisition Software & Interface

LabVIEW Signal Interface and Main Interface Virtual Instruments (VIs) were created for this system, which utilize User Datagram Protocol (UDP) to send information from the VI to the Virtual Reality Software. The flow of information throughout the system is outlined in **Error! Reference source not found.**

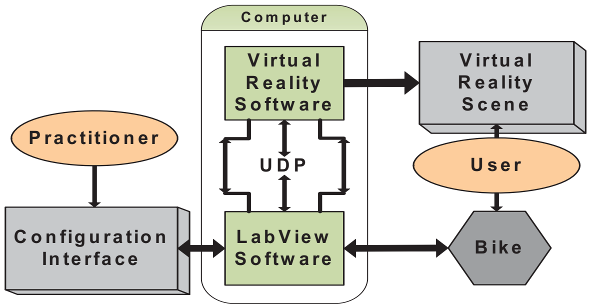

Figure 4: Information communication diagram

3.1 Signal Interface

The VRehab Signal Interface was used to prototype the third party virtual reality simulation. The bike system includes eight sensors and all of these sensors are emulated using the signal interface. The signal interface is programmed to send signals using UDP that are identical to the signals that the actual sensors will send on the device.

3.2 Practitioner Interface

The Practitioner Interface has several components and objectives. The interface is used to acquire all the sensor data from the DAQ card at 100Hz, as well as do any signal processing necessary to the data. It is also used to display that data in real-time and log that data into two different files for later evaluation. The last objective of the interface is to send modified data to the VR simulation so that is can provide accurate and updated visual feedback to the user. Figure 5 shows a screen capture of the interface's front panel.

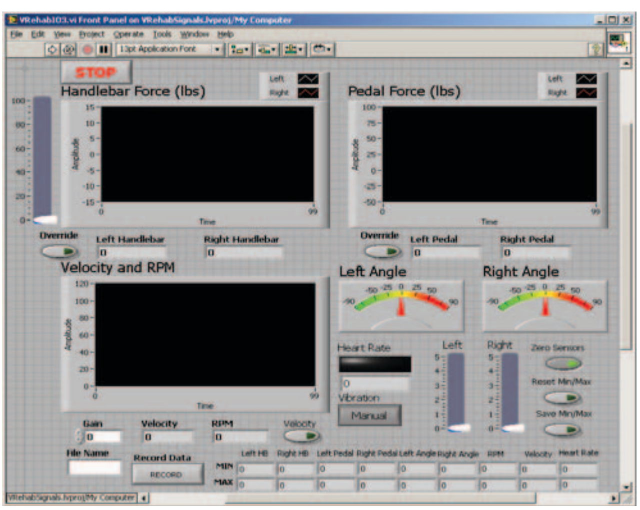

Figure 5: VRehab main interface front panel

The zero sensors button is used to normalize all the sensor readings to prevent drift as well as display comparison data. The file name and record button are used for naming and recording the data files. Data are sent from the interface to the VR simulation by using UDP communication.

3.3 Virtual Environment

The purpose of the virtual environment is to engage the user by providing multi-sensory and performance feedback. Initial parameters are set on the VR Simulation Menu before a session begins.

The upper right corner of the simulation displays a map of the virtual environment, and below it the instantaneous heart rate of the rider is displayed (Figure 6). The virtual environment is divided into two regions: the sandy tan path that the user traverses and the green rough that surrounds it. Data are sent from the UDP Sub VI of the interface to the VR Simulation to control the virtual rider. The rpm data control the speed, the handlebar force data control the heading, and the pedal kinetics control the tilt of the rider. The dark muddy patches on the trail slow down the rider and are intended to be avoided, whilst driving onto the green is a trigger for the vibrating elements.

Figure 6: The virtual rider must stay with the pace rider whilst include turning and leaning and avoiding mud puddles

4 Preliminary Testing

A healthy rider and two individuals post-stroke participated in an 8 week training program to determine if cardiovascular and motor control improvements could be measured after training. The data reported here are for a healthy subject as preliminary validation of the system's measurement capabilities.

***Heart Rate*:** Representative heart rate data collected from the system (blue) for a training trial is shown in Figure 7. The noise in the heart rate data were eliminated using a linear spline interpolation (red) followed by a 4^{th} order low pass Butterworth filter with a cutoff frequency of 0.5 Hz (green). These data demonstrate an appropriate response to exercise and corresponded to concurrent measurements taken manually by an experienced clinician.

Figure 7: Heart rate data for the first 5 min of the training trial.

***Pedal Forces*:** Figure 8 shows the pedal force characteristics for approximately 40 consecutive cycles for a healthy participant.

The pedal data represented in the figure are the data filtered post collection using a 4^{th} order low pass Butterworth filter with a cutoff frequency of 5 Hz. The peaks indicating the maximum compressive force on the pedal occur during the down-stroke around 30-40 percent of the pedalling cycle for the healthy individual consistent with the literature [16].

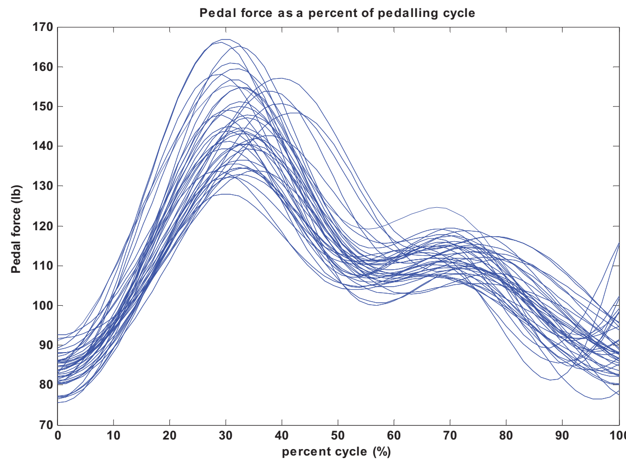

Figure 8: Typical pedal force for one complete pedalling cycle.

Hande Bar Forces**:** Figure 9 presents the handlebar forces applied on the left and right handle bar modules during a trial by a healthy participant. As depicted in the figure the handlebar modules recorded nearly zero forces when hands were off the handlebars and recorded positive grasping forces when used the handlebars to manoeuvre in Virtual Environment.

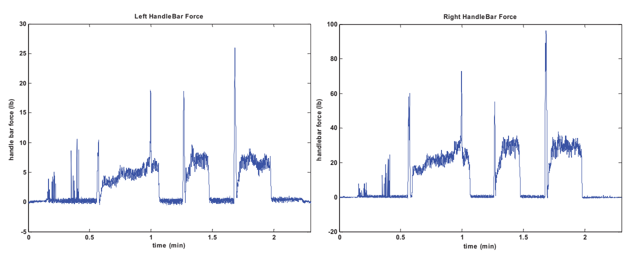

Figure 9: The handlebar forces for the left and right sides while pedalling.

System Integration: The modularity of the system is one of its greatest strengths. The handles have adjustable Velcro fasteners to mount to the current range of stationary bicycle handlebar diameters. The pedals are fitted with 9/16" threads standard for most stationary exercise bicycle pedals, and readily replaced them via insertion to the crank arm. The prototype was evaluated on both a recumbent (Biodex, Shirley, NY, USA) and upright stationary bicycle (Precor, Woodinville, WA, USA) with transfer between them completed without special training in less than 5 minutes.

CONCLUSIONS

In this paper the virtual reality augmented cycling kit (VRACK), a mechatronic rehabilitation system with an interactive virtual environment, was presented. VRACK consists of sensorized pedals, handlebars and a heart rate monitor interfaced with a virtual biking environment. The VRACK system and modular design has been tested with healthy individuals and individuals post-stroke with both upright and recumbent-mode stationary exercise bicycles. Heart rate data as well as pedalling and handle bar kinetics were successfully measured and integrated with the virtual environment. VRACK was designed to benefit users with riding asymmetry by using quantitative measures to dynamically direct their attention. Work with individuals post-stroke who are present with riding asymmetry is underway and the preliminary findings are encouraging and will be reported elsewhere.

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REFRENCES

[1] A. Mirelman, P. Bonato, JE Deutsch. Effects of training with a robot-virtual reality system compared with a robot alone on the gait of individuals post stroke. *Stroke*. 40:169-174, 2009.

[2] Interactive Fitness Holdings LLC. The Expresso family of interactive bikes. www.expressofitness.com, accessed 1/8/10.

[3] Electronic Sports. Dogfight. http://electronicsports.com, accessed 1/8/10.

[4] P. Schenk, Clem, W. E., Williamson, C., Albini, M., Eghbal, D., Green, E.G., Stationary exercise bicycle with shock absorption system. United States Patent 6,508,745, January 21, 2003.

[5] N. H. Nusbaum. Exercise bicycle virtual reality steering apparatus. United States Patent 6,918,860, July 19, 2005.

[6] J. Freeman, S. E. Avons, D. E. Pearson, and W. A. Ijsselsteijn. Effects of sensory information and prior experience on direct subjective ratings of presence. *Presence,* 8(1):1-13, 1999.

[7] H. Hall-Tipping. Video game difficulty level adjuster dependent upon player's aerobic activity level during exercise. United States Patent 5,001,632, March 19, 1991.

[8] T. Stach, T. C. Graham, J. Yim, and R. E. Rhodes. Heart rate control of exercise video games. In *ACM International Conference Proceeding Series; Proceedings of Graphics Interface 2009,* Kelowna, British Columbia, Canada, pp. 125-132, 2009.

[9] D. A. Brown, S. A. Kautz. Increased workload enhances force output during pedaling exercise in persons with poststroke hemiplegia. *Stroke,* 29:598-606,1998.

[10] D. A. Brown, S. A. Kautz, C. A. Dairaghi. Muscle activity adapts to anti-gravity posture during pedaling in persons with post-stroke hemiplegia. *Brain,* 120:825-837, 1997.

[11] L. M. Rogers, D.A. Brown, K.G. Gruben. Foot force direction control during leg pushes against fixed and moving pedals in persons post-stroke. *Gait Posture,* 19(1):58-68, 2004.

[12] M. J. A. J. M. Hoes, R. A. Binkhorst, Smeekes-Kuyl, A.E.M.C., and A. C. A. Vissers, Measurement of forces exerted on pedal and crank during work on a bicycle ergometer at different loads. *Eurpean Journal of Applied Physiology,* 26(1):33-42, 1968.

[13] A. J. Sargeant, E. Hoinville, A. Young. Maximum leg force and power output during short-term dynamic exercise. *American Physiological Society,* 51(5):1175-1182,1981.

[14] D. J. Sanderson, E. M. Hennig, A. H. Black. The influence of cadence and power output on force application and in-shoe pressure distribution during cycling by competitive and recreational cyclists. *Journal of Sports Sciences,* 18(3):173-181, 2000.

[15] J. E. Deutsch, A. Merians, S. Adamovich, H. Poizner, and G. Burdea. Development and application of virtual reality technology to improve hand use and gait of individuals post-stroke. *Restorative Neurology and Neuroscience, Special issue on motor system plasticity, recovery and rehabilitation*, 22(3-5):341-386, 2004.

[16] D A Brown , SA Kautz. Speed-dependent reductions of force output in people with poststroke hemiparesis. *Physical Therapy*. 79(10):919-30, 1999.