Proceedings of the 29th Annual International
Conference of the IEEE EMBS
Cité Internationale, Lyon, France
August 23-26, 2007.

Development of a wearable motion capture suit and virtual reality biofeedback system for the instruction and analysis of sports rehabilitation exercises

Diarmaid Fitzgerald, John Foody, Dan Kelly, Tomas Ward, Charles Markham, John McDonald, Brian Caulfield

Abstract—**This paper describes the design and development of a computer game for instructing an athlete through a series of prescribed rehabilitation exercises. In an attempt to prevent or treat musculoskeletal type injuries along with trying to improve physical performance, athletes are prescribed exercise programmes by appropriately trained specialists. Typically athletes are shown how to perform each exercise in the clinic following examination but they often have no way of knowing if their technique is correct while they are performing their home exercise programme. We describe a system that allows an automatic audit of this activity. Our system utilises ten inertial motion tracking sensors incorporated in a wearable body suit which allows a bluetooth connection from a root hub to a laptop/computer. Using our specifically designed software programme, the athlete can be instructed and analysed as he/she performs the individually tailored exercise programme and a log is recorded of the time and performance level of each exercise completed. We describe a case study that illustrates how a clinician can at a later date review the athletes progress and subsequently alter the exercise programme as they see fit.**

I. Introduction

DUE to the high rate musculoskeletal injuries in sporting participation, modern day athletes must perform individually tailored exercise programmes to help prevent injury occurrence and as part of the rehabilitation process if injuries do transpire. Typically these programmes are prescribed by sports physicians, physiotherapists or athletic trainers following detailed assessment and screening tests of the athletes' physical function. A rehabilitation plan is then put together for optimal management of any problem areas identified which usually includes prescribed exercises among other strategies (e.g. manual therapy).

The ultimate goal of rehabilitation for athletes is to regain the highest functional level in the most efficient manner. To achieve this an athlete must comply rigidly to the prescribed program and perform all exercises effectively and at the appropriate frequency as advised by the clinician.

There is therefore a need for guidance and supervision of athletes to ensure exercise programmes are completed correctly. This can be accomplished by a qualified personal trainer/instructor or a device that can monitor and instruct individuals as they perform their daily exercise programs. A technological solution must be capable of objectively monitoring subjects in a reliable and sensitive manner. Additionally it should be sensitive to changes in the athletes' performance of the exercise and highlight any areas where they deviate from the correct performance of each exercise. Such a solution is described in this paper.

II. Exercise in Virtual Reality Computer Games

Exercise programmes incorporated into Virtual reality-based games are typically employed where the player can see themselves or an animated avatar mimicking their movements on-screen in a computer-generated environment. Engaging with a game in this fashion makes the exercise experience more enjoyable therefore increasing their motivation to participate [1]. Similar systems that exist to instruct and assess exercise include the EyeToy games for the Playstation®2 console (Sony Computer Entertainment Inc., Japan), the Cybex Trazer (Cybex International, Inc., USA) and the Gestxtreme and IREX exercise system (GestureTek Inc™, Canada) [2].

The EyeToy game uses a single USB camera placed above or below a television screen to capture the players movements and places them in an on-screen mixed reality environment. Interaction with on-screen objects is facilitated through pixel collision but this can only track movements in a single plane and cannot record body movements.

The Cybex Trazer® employs a single infrared beacon mounted on a belt worn around the waist of the player. The position of this sensor is monitored by the tracker bar of the system to capture motion of the player which can move an on-screen avatar as one rigid block to play various drills and games.

GestureTek Inc™ have produced many camera-enabled computer control systems. The Gesxtreme system is a virtual reality-type game where the player can also see their virtual body on-screen and interact with objects to play the games.

Manuscript received April 16, 2007. This work was supported in part by the Higher Education Authority of Ireland.

Diarmaid Fitzgerald, John Foody and Brian Caulfield are with the School of Physiotherapy and Performance Science, Health Sciences Centre, University College Dublin, Belfield, Dublin 4, Ireland (phone: 00353-1-7166500; fax: 00353-1-7166501; e-mail: diarmaid.m.fitzgerald@ucd.ie; johnfoody@gmail.com; b.caulfield@ucd.ie).

Dan Kelly, Charles Markham and John McDonald are with the Computer Science Department, National University of Ireland Maynooth, Maynooth, Co. Kildare, Ireland (e-mail: dan_kelly_ie@hotmail.com; cmarkham@cs.may.ie; johnmcd@cs.nuim.ie).

Tomas Ward is with Department of Electronic Engineering, National University of Ireland Maynooth, Maynooth, Co. Kildare, Ireland (e-mail: tomas.ward@nuim.ie).

1-4244-0788-5/07/$20.00 ©2007 IEEE

The IREX exercise system is used as a tool in physical rehabilitation and is also a camera-based system. Through interaction with on-screen objects patients can complete a clinician-controlled therapeutic exercise programme.

While these camera-based systems are very engaging from an interaction point of view the problem is that they can only track gross body movements in a single 2-dimensional plane (up-down and left-right) and do not have the capacity for discreet motion capture recordings of an athletes movements. Motion tracking sensors worn on body segments could be incorporated into such a system to provide the level of accuracy required. For this reason we chose to implement a robust 3-D motion tracking orientation sensor into a virtual reality-type system as described in the next section.

III. System Architecture

A. Motion capture suit

For the purpose of tracking the movement of body segments a motion capture suit with sensors embedded in the garment was developed (Fig 1). Ten Xsens Mtx sensors were used for the current version of the system (Xsens Technologies, The Netherlands). Each Xsens inertial-based sensor is a small lightweight sensor which detects 3D orientation using two accelerometers, a magnetometer and a gyroscope [3]. We have previously produced a low cost orientation sensor of similar design ourselves to render the system more cost effective [4].

Nine Xsens units were integrated into an extensible bodysuit, to facilitate easy donning and doffing of the entire system. Sensors were located on both left and right shank, thigh, forearm and upper arm along with one on the left side of the trunk. One sensor was also fixed to the left side of the head using an elasticated strap. The suit was constructed of 4-way stretch spandex knit, and thus was able to fit a wide variety of body sizes. Each sensor unit was affixed by velcro to the surface of the bodysuit, and secured using an adjustable elastic strap. Connecting cables were threaded through textile conduits on the surface of the suit, to prevent tangling or interference with the motions during exercise. Because differences in body size could result in inaccurate placement of the sensor units, the placement of each unit was adjustable within a velcro area, while the elastic strap minimized movement artifacts by securing the unit from the top and sides.

Each of the ten sensors are connected to a small wearable base which is attached at the waist by an adjustable belt. This hub sends data to the motion capture engine via bluetooth. If each of the sensors is placed on the appropriate body segment, the orientation of each part can be tracked dynamically during any body movements. Using this data it is then possible to animate a 3D character model mimicking the movements of the player wearing the orientation sensors as we have described previously [5].

In order for the 3D character model to accurately mimic the players' movements, the system must perform a calibration of the sensor data. The calibration consists of getting the player to stand upright with legs straight and shoulder width apart, arms parallel to the ground and looking straight. Then to calibrate, the sensors are reset having the effect of setting the current orientation to zero degrees rotation about all axes, setting the origin pose for the player. All orientation changes made to the sensors, and thus the corresponding bone on the 3D model, will be made relative to the same origin pose. Therefore the 3D model now mimics the players' movement.

B. Game design and rating of exercise performance

The game was developed using the DirectX 9 API to utilize the motion capture engine in a virtual environment while recording the whole body motion data. The aim of the game is to teach players, wearing the motion sensor suit, specific exercise routines by analyzing a player's movement and giving concurrent performance feedback.

The game engine manages creation of game modules, communication between game modules, input via mouse and keyboard, timing and rendering to the screen. User interface modules render user interface graphics and manage user input via buttons and text boxes.

Sensor data is processed in real-time to administer audio and visual biofeedback to the users along with recording data for post game analysis. This is based on their performance in the game (i.e. how close the player is to the correct body alignment throughout the exercise programme) against pre defined expert level of performance. Modifiable

Fig. 1. Motion tracking suit with embedded Xsens sensors.

programmes to meet the goals and capabilities of all ages can be included. Games designers can incorporate this into the games using their own creativity.

When in game mode the game can be in one of four different states at any given time. In the calibrate mode the character model is animated using live sensor data. A button is provided so users can calibrate sensors to neutral standing position. After a successful calibration the 3D character model will mimic player movement. In the expert playback mode the character model is animated using pre-recorded expert kinematic data and an audio description of each exercise milestone is played at the beginning of each exercise sequence. In the live mode the character model is again animated using pre-recorded expert kinematic data, while kinematic data for live player is being retrieved and stored in background. During this mode audio feedback is provided to the player. After completing the exercise programme offline analysis can be performed on the players' kinematic data. This is achieved by comparing data to that of the expert. Feedback on performance is then given and a detailed breakdown of the players' performance is displayed. In player playback mode the character model is animated using pre-recorded data recorded during the live state i.e. playback of users motion.

Character renderer creates a character 3D model from a specified .X file and animates the character given data from a specific instance of a motion interface module. This module provides kinematic data to the character renderer object from live Xsens sensors or pre-recorded Xsens data. A choice of 2 constructor overloads determines the source of the kinematic data. These two calls reflect the two possible modes of operation for the motion interface module. The first mode sets up the object so that data is retrieved from the set of live Xsens sensors and relative orientation calculations are performed on the data. The second mode sets up the object so that data is retrieved from a specified pre-recorded motion file. Regardless of the mode, data is retrieved by the calling object in the same manner, that is, a method is called with the input being an instance of a bone enumerator. The enumerator specifies which segments' kinematic data is to be returned. As a result, different instances of motion interface modules can be easily interchanged within the character render module, therefore changing between live animation and pre-recorded animation can be done in a transparent way.

The motion storage and control module manages the loading and saving of kinematic data to and from file. When parsing from a file, kinematic data is stored in a 2D array with each row of the array corresponding to a single frame of animation. Associated with each frame of animation is a time, indicating when that frame should be used to animate the 3D character model, and a marker. Each motion sequence contains milestone postures which players must perform before progressing. The marker is used to indicate if the corresponding frame is or is not a milestone pose.

The motion object also controls frame timing. This is achieved by monitoring the amount of time elapsed since the last frame was returned to the motion interface module. Using this value it can calculate which frame to play next using the timing data associated with each frame. When in live mode and retrieving data from an expert sequence, the *get_frame* method requires an extra Boolean parameter specifying whether or not the player is in the same pose as the expert. If the expert is currently in a milestone pose then the time will not be advanced until such time as the player performs the same pose.

Environment renderer manages loading and rendering of the 3D environment, lighting and camera position. Player info storage and control module manages storing, loading and creating player accounts. Offline feedback allows a timing rating and a smoothness score to be calculated for the sequence. The smoothness score is determined through differentiation and comparative analysis of the respective movement loci.

After completing a motion sequence, the players' motion data is saved and loaded in a motion object. The offline feedback takes as input both the players and the experts motion object and calculates performance values for each of the sequences between milestones. Currently this figure is calculated using a distance metric in Euler space. This facilitates progression mapping of the players' performance over time. The following case study demonstrates how offline analysis can be utilised by a clinician to highlight the key areas that an athlete needs to improve on.

Fig. 2. Motion tracking suit with embedded sensors during the straight line lunge exercise.

IV. Demonstration Case Study

A. Introduction

In this case we based game performance on the straight line lunge exercise and we compared game performance by a healthy athlete and an athlete five weeks post knee injury. The lunge exercise is a dynamic whole body stability exercise and to perform the exercise properly requires a high level of coordination and control in the trunk and pelvis stabilizing muscles along with the hip, knee and ankle muscles to achieve good posture and body alignment throughout the exercise. Following knee injury body function and stability may be compromised and the lunge is often prescribed as a part of a typical rehabilitation programme for knee injury.

B. Methodology

1) Subjects

The injured athlete sustained a grade two strain to the medial collateral ligament of his right knee five weeks prior to testing. Following the injury he was examined by an orthopaedic surgeon and the athlete was instructed to wear a functional hinged knee brace (DeRoyal pro sport knee brace with stabilizing metal stays, DeRoyal Europe Ltd, Kells, Co Meath, Ireland) for five weeks. This brace provides support to the healing ligament but allowed the subject bend and straighten the knee as normal during walking. No running was permitted during this period. The injured athlete ceased wearing the knee brace two days before testing. The non-injured athlete, a middle distance runner, had no history of injury to the lower extremity for the past two years and was in full training.

2) The Straight Line Lunge Exercise

To perform the lunge a subject must begin by standing tall with both feet hip-width apart. Keeping the back straight and vertical, lunge/step forward with the right leg keeping the left foot in contact with the ground. The right thigh should be parallel with the ground and the right lower leg vertical (Fig 2). Finally spring back to the starting upright position again. To ensure consistency each athlete had to lunge to a target length which was calculated as 0.8 times their leg length (greater trochanter to lateral malleolus on right side of body).

3) Experimental Protocol

Both athletes were required to wear the motion capture suit and the system was calibrated. A demonstration of the lunge was performed. Subject stood behind a start line on an exercise mat and the distance the subject was required to lunge was marked (Fig 2). Testing required completion of ten lunges.

4) Data Analysis

Shank, thigh and trunk sensors were used during data analysis although full body data was collected. Shank and thigh sensors were used to derive knee flexion-extension profile. Thigh sensor roll relative to the ground was analysed to derive upper leg internal-external rotation and the trunk marker pitch relative to the ground for the movement in trunk flexion-extension.

C. Results and Discussion

A Qualitative graphical data analysis (Fig 3) of both the knee and trunk saggital plane movement and upper leg interal-external rotation angular displacement for both subjects is compiled. These three kinematic profiles were chosen for the example of offline analysis as they are the critical determinants of performance for this particular exercise.

In knee flexion-extension graph the non injured athlete is

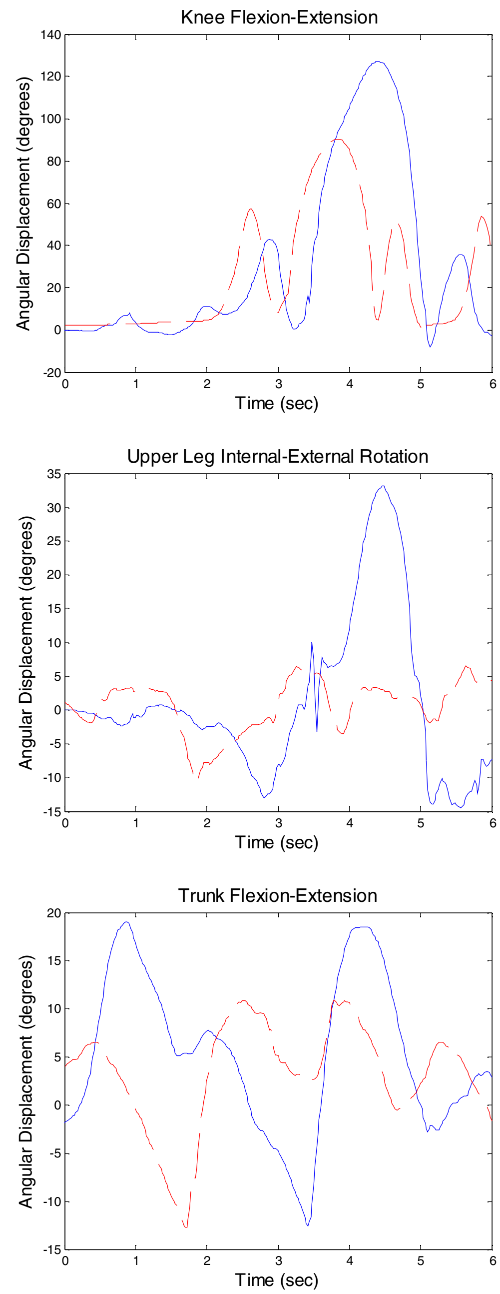

Fig. 3. Angular displacement profile for the knee flexion-extension, upper leg internal-external rotation, trunk flexion-extension. Continuous line indicates injured athlete and dashed line indicates non-injured athlete. Knee flexion, thigh internal rotation and trunk flexion are positive in all the above graphs.

notably quicker at performing the lunge compared to the injured subject while the injured athlete achieves a larger angular excursion which may be due poor eccentric muscular control when slowing down into the lunge position as in Fig 2. The thigh rotation profile indicates that the injured athlete internally rotated greater than 30° during the foot planted phase of the lunge compared to about 5° for the healthy athlete. The healthy athlete shows a higher level of neuromuscular control during the movement by always keeping the leg within about 10° of rotation either way.

On examining the trunk saggital plane movement the injured athlete shows increased extension prior to foot contact and increased flexion during the foot contact phase of the lunge. This suggests poorer control of the trunk muscles who must extend to keep the centre of gravity closer to the base of support prior to impact and flexes forward with the momentum of the lunge following impact.

These kinematic patterns outline how deficits in neuromuscular control during dynamic exercises result in altered body posture and alignment and this can be highlited through offline analysis with our virtual rehabilitation system.

V. Conclusion and Future Work

This paper has outlined the theory and current work performed in developing a rehabilitation tool for exercise therapy. The case study demonstrates how offline analysis of the data stored during exercise can be viewed at a later date to assess the athletes' performance and prioritise areas needing retraining.

Further work will involve developing a suite of similar rehabilitation exercises in the system each with a separate performance rating system and strategy for progression of difficulty levels as a athlete improves. Further to this we plan on undertaking a training affects study by comparing a group of subjects training with the system compared to a group practicing the same exercises as a home exercise programme.

VI. Acknowledgements

The authors would like to thank the Higher Education Authority of Ireland for their support in funding this project.

References

[1] T.J. O'Connor, S.G. Fitzgerald, R.A. Cooper, T.A. Thornman, M.L. Boninger. "Does computer game play aid in motivation of exercise and increase metabolic activity during wheelchair ergometry?" *Medical Engineering & Physics, 2001Vol. 23 pp. 267-273.*

[2] D Fitzgerald, J Foody, D Kumar, D Kelly, T Ward, C Markham, B Caulfield. "Integration of Kinemtic Analysis into computer games for Exercise" in *Proc. 9th International Conference on computer Games, Dublin, 2006, pp. 24-28*

[3] MT Software Development Kit Documentation, Document MT0200P. Available:http://www.xsens.com/index.php?mainmenu=support&submenu=downloads

[4] J Foody, D Kelly, D Kumar, D Fitzgerald, B Caulfield, T Ward, C Markham. "A Prototype Sourceless Kinematic-Feedback Based Video Game for Movement Based Exercise" in *Proc. 28th Annual International Coference of the IEEE Engineering In Medicine and Biology Society*, New York, 2006, pp. 348

[5] D Kelly, D Fitzgerald, J Foody, D Kumar, T Ward, B Caulfield, C Markham. "The E-Motion System: Motion Capture and Movememt-based Biofeedback Game" in *Proc. 9th International Conference on computer Games, Dublin, 2006, pp. 19-23*