EVALUATION OF A WEARABLE SYSTEM FOR THE REAL TIME MONITORING OF REHABILITATING ATHLETES

C. Glaros *, D.I Fotiadis**, A. Stafylopatis ***

* Department of Materials Science, University of Ioannina, GR 45110, Ioannina, Greece
** Unit of Medical Technology and Intelligent Information Systems, Department of Computer Science, University of Ioannina, GR 4510, Ioannina, Greece
*** Dept. of Electrical & Computer Engineering, National Technical University of Athens, GR 15780, Athens, Greece

cglaros@cc.uoi.gr, fotiadis@cs.uoi.gr, and andreas@cs.ntua.gr

Abstract: A preliminary evaluation of a wearable system for the real-time monitoring of athletes rehabilitating from knee surgery is presented. The system aims to help optimize treatment and training procedures during rehabilitation, and assist in the prompt return to peak athletic condition. It is composed of the Athlete Subsystem, the Rehabilitation Station and the Portal. The Athlete Subsystem includes a range of non-invasive sensors, a signal collector and a processing-transceiver unit for preliminary evaluation and for exchanging information with the Rehabilitation Station. The Rehabilitation Station is the main control, access and communication part of the system carrying most of the processing, generating feedback and alerts. It features a virtual reality interface, also visible to the athlete through a wearable monitor. The Portal is a web based data storage and presentation facility, collecting long-term data for research purposes. The system is evaluated in terms of reliability, functionality, usability and user acceptability. The results indicate that the main objectives of its design have been met in a reliable manner. A more compact industrial prototype would greatly enhance the usability and user acceptability of the system.

Introduction

Most professional athletes suffer from major or minor injuries throughout their career. This is either due to cyclic stress induced injuries provoked by intensive and repetitive training, or directly through contact in sports such as rugby and football. Common sporting-related injuries associated with the lower extremities include anterior cruciate ligament (ACL) tears, meniscal injuries, patellar tendonitis, achilles tendon tendonitis, hamstring muscle strain and bone stress fractures [1]. Since injuries are an unavoidable part of an athlete's career it is important to minimize the rehabilitation period and the time required for their return to peak athletic condition. Rehabilitation from a serious injury or surgery initially involves medical treatment and physiotherapy, and then at some stage the athlete starts following a "light" training program. Jogging is the most common exercise for aerobic training and for regaining fitness, and as such, forms a major part of a rehabilitation training program in most sports.

Continuous monitoring of athletes during rehabilitation can help optimise their training program, and reduce the possibility of injury relapses through the timely detection of potentially dangerous conditions. In that sense, appropriate monitoring can help reduce the overall rehabilitation period. Monitoring of a rehabilitating athlete involves the monitoring of a range of physiological parameters related to physical condition, the type of injury, and performance. Futhermore, monitoring is often required in the athlete's natural training environment where direct medical supervision may not always be available. This can be achieved through the use of wearable medical devices.

Wearable medical devices are autonomous, non-invasive devices worn by a person and that provide a specific medical function such as monitoring or support over a prolonged period of time [2]**.** Current developments include real-time feedback, alerting mechanisms, medical decision support, and wireless access to information. A great design concern is their ergonomics and wearability, which deal with issues including their physical shape, their active relationship with the human anatomy in motion, their acceptability as a function of comfort, fashion, and purpose, the relationship between the wearable device and the work environment, the physical factors which affect their use, and the human-device interaction [3-5]. In addition, they need to address a number of reliability and technical considerations related to the monitoring, processing and overall data handling tasks of the system [6, 7].

In this work, a wearable system [8] for the real time monitoring of athletes rehabilitating from knee surgery is presented along with a preliminary evaluation in terms of functionality, usability, user acceptance, reliability and overall sensor management. The system is intended for use by patients from the early stages of rehabilitation in a non-clinical environment and features a range of wearable physiological and kinesiological sensors, multiple feedback and interaction interfaces including virtual reality and remote accessibility to information through a web-based portal.

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System Description

The system is composed of three primary subsystems: the Athlete Subsystem, the Rehabilitation Station and a Portal.

A. Athlete Subsystem

The Athlete Subsystem is composed of all the components worn by the athlete during training. It consists of a range of wearable physiological and motion sensors, a signals collector for collecting and synchronizing the received signals and a custom made wearable processor for generating alerts and assisting with the athlete's interaction with the system. The processor also operates as a transceiver between the athlete and the rehabilitation station. Feedback is provided through a wearable VGA clip-on monitor over regular glass frames (MicroOptical) through a virtual reality interface. The setup of the Athlete's subsystem can be seen in Fig. 1.

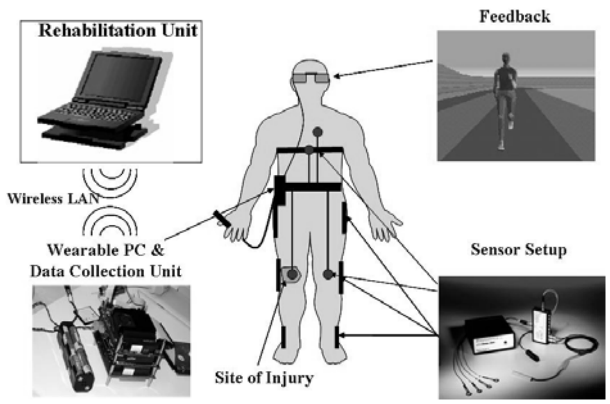

Figure 1: Athlete Subsystem

The physiological and kinesiological parameters monitored by the athlete subsystem in real time are:

1) *Electrocardiogram:* A 3-lead ECG (PASCO CI-6539A EKG Sensor) is used for monitoring heart rate (HR) and heart rate variability (HRV). The sensor uses electrode patches instantly applicable with minimal skin preparation requirements including a contact gel. Two of the electrodes (positive and negative) are placed inside the left and right elbows and the reference electrode is placed on the wrist.

2) *Respiratory effort*: It is measured with respiration transducers in the form of a belt worn on the athlete's chest (Grass-Telefactor Series 6000 Respiratory Effort Sensor), and is used for monitoring the athlete's breath rate (BR).

3) *Joint angles*: They are measured with six electrogoniometers, measuring the joint angles of both legs at the hip, knee and ankle during exercise. The goniometers are provided by Biometrics Ltd and include two SG110 goniometers for ankle measurements and four SG150 goniometers for the hip and knee measurements. They are currently used to monitor joint movement, evaluate temporal parameters of gait and running, and control the movement of the virtual athlete described in the rehabilitation station. In addition, they are intended for detecting differences in movement patterns between the injured and healthy leg and for quantifying gait adaptations and alterations in the injured leg.

4) *Temperature*: Two skin temperature thermistors (BetaTHERM Ltd. - FSR 1035102) are used, one at the site of injury and one on the contralateral site. They are used for an indirect indication of the improvement/ deterioration of the injury, which is expected to be significant in cases of severe injuries or when recovering from an operation.

5) *Pain*: A pain assessment for the injury is made by the athlete through four pain descriptions (none, occasional and slight, always present but bearable, always present and unbearable) and recorded by the system through a digital event marker button (provided by Biometrics Ltd.).

Furthermore, two other parameters can be monitored. These are:

6) *Blood pressure*: Measured by a sphygmomanometer before and after the training session to detect the young hypertensive athlete that needs special attention.

7) *Speed/Pace*: It is used to assess performance and for control the monitoring conditions. This is achieved by the use of a treadmill. For free movement conditions, the monitored parameter is the athlete's pace through the calculation of the gait or running cycle intervals.

All real-time signals are collected through a DataLink data acquisition unit (Biometrics Ltd.) and are fed to the wearable processor. The DataLink provides eight analog inputs and five digital inputs. It has a cable connection and requires a mains power supply meaning that it is not wearable.

The wearable processor is custom-made and is composed of three boards stacked above one another, and linked through a PC104 bus. The first board is a PC104 processor card, fitted with 128 MB RAM and incorporates either a 512 Mb compact flash card or a 2.5'' HDD through an IDE interface. The second board is a PCMCIA 2-slot board incorporating an IEEE 802.11b and a Bluetooth PCMCIA card. The third board is the regulated power supply board, connected to two 7.2V rechargeable batteries. The wearable processor dimensions are 90x100x90mm.

B. Rehabilitation Station

The Rehabilitation Station is the main control and processing component of the system, which receives and processes the received signals from the athlete subsystem. It transmits the required feedback to the users, including the raw signals, the detected features and the derived assessments, which are graphically visualized through a synchronized virtual reality display of a running athlete. Furthermore, it updates the content of the portal through a regular update service.

Its current real time functions include the recording and presentation of joint motion (joint angles), the

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electrocardiogram and respiratory effort curves used for the biomechanics assessment of running and cardiopulmonary monitoring [9,10], the temperature measurements and the pain level as recorded by the athlete. Furthermore, it includes the evaluation of the gait/running cycles, the heart and breath rates, and the temperature difference. This process involves the extraction of the features from each received signal and a classifier (where necessary). In particular, motion cycle times (gait / running cycles) are calculated using the joint space distance criterion [11], an approach that increases the robustness of the system by using redundant sensor information to calculate the pace, and can be achieved with at least one or up to six electrogoniometers. Thereafter, these features are further processed to provide alerts and decision support assessments. This involves the use of a rule-based mechanism provided by medical experts, for providing local decisions (alerts), with respect to the patient-specific medical and anthropometric profiles. The system includes a few basic rules implemented for demonstration purposes on the heart rate intensity level, joint angle differences between legs, and temperature difference.

The Rehab Station interface (Fig. 2) displays the recorded signals, features and alerts, and includes a parametric virtual reality model of a running athlete. The VR interface (designed with 3D Webmaster – Superscape Inc.) is visualized on a laptop by doctors and trainers, and through the clip-on monitor by the athlete. The leg movement is controlled by the measurements made by the goniometers whereas the upper body movements are simulated [12].

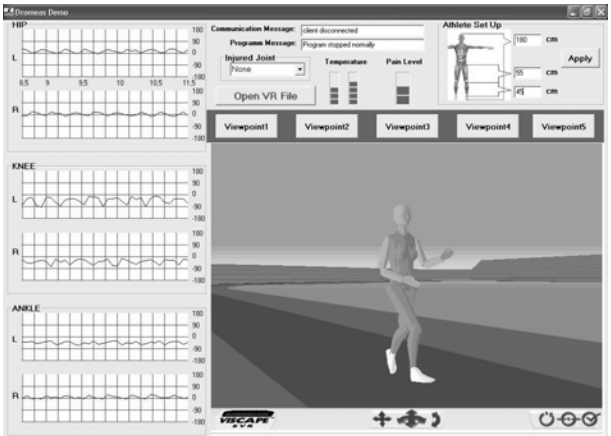

Figure 2: The Rehab Station Interface

C. Portal

The portal is a web-based long-term data storage facility that collects selected information from multiple rehabilitation stations over long time periods in a repository for statistical analysis and research purposes. It includes an update service, which is a twofold service updating the repository of the portal with data from various rehab stations and updates rehab stations with data from the portal. The portal incorporates all the necessary accessibility and information security mechanisms and provides statistical, demographic and plotting functions.

Materials and Methods

Sensor measurements and algorithm detection efficiency were evaluated for their clinical usefulness, reliability and repeatability. All measurements were based on healthy volunteers, and each set of sensors was tested individually. The measurements were taken in controlled speed conditions on treadmill tests that involved walking, fast walking, jogging and running. Where necessary, the algorithm sensitivity (sens) and positive prediction accuracy (PPA) were calculated as:

$$\text{sens} = \frac{\text{Total No. of peaks detected by the classifier}}{\text{Total No. of peaks (independent expert)}} \times 100\%$$

$$\text{PPA} = \frac{\text{No. of peaks correctly classified by the classifier}}{\text{Total No. of peaks detected by the classifier}} \times 100\%$$

Motion analysis evaluation involved the assessment of the motion cycle detection algorithm and the repeatability assessment of measurements between three different treadmill testing sessions with controlled speeds on healthy volunteers. Each time the sensors were removed and repositioned by independent test supervisors using the manufacturer's protocols. The goniometers sampling rate was 100Hz and the monitored parameters were the angle span over one gait or running cycle and the cycle time. The heart and breath rate detection algorithms were also assessed for various testing conditions (resting, walking, jogging, and running), again on treadmill tests. The ECG sampling rate was 500Hz, and the respiratory effort 50Hz. The system outputs were compared with experts' observations produced by visual inspection of the signals. A preliminary study on ten post surgery patients was performed to assess the usefulness of skin surface temperature measurements for patients recovering from knee surgery. The temperature thermistor measurements were recorded at a rate of 10Hz and were also compared with conventional thermometers.

The functionality, usability and user acceptability of the system were evaluated with questionnaires on twenty potential users based on the Goal/Question/Metric (GQM) approach [13]. The users included orthopaedic surgeons, patients, technical personnel and healthy volunteers. The interviews included a brief system presentation and demonstration followed by a physical test before the questionnaires were answered. The questionnaires dealt with the technical, functional and usability aspects of the system and intended to assess the degree of achievement of the pre-set goals. Further comments were invited in a discussion session. The athletes/patients answered questions on the athlete subsystem, while the technical and medical professionals dealt with all the subsystems of the platform.

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Results

We present here preliminary results only.

Motion Analysis

Fig. 3 shows the joint space distance evaluated for all six goniometers with respect to the sampling interval (10 sec) for walking and sprinting conditions. A motion cycle is determined where the joint space distance is minimised. The detected motion cycles are denoted with perpendicular lines on the figure.

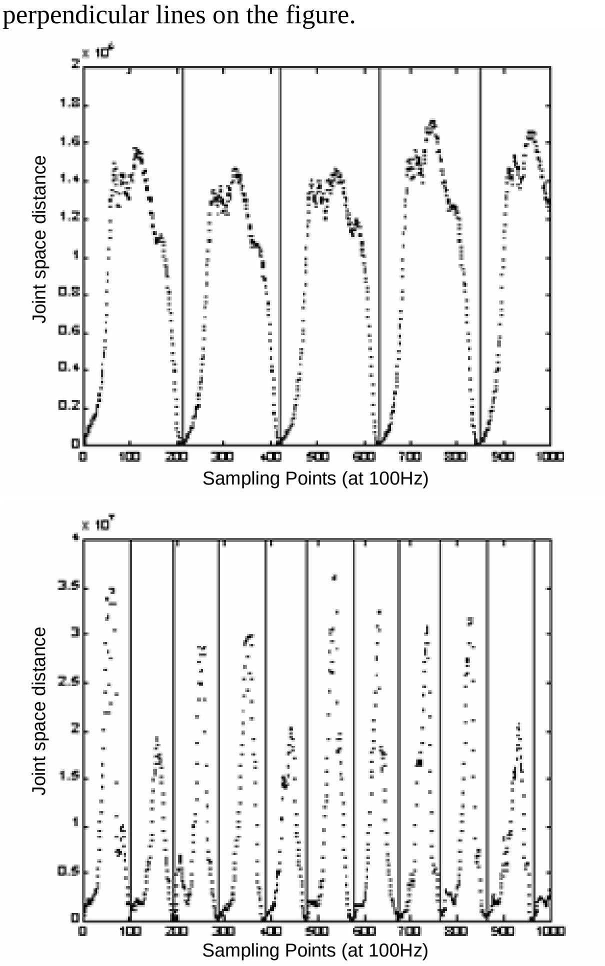

Figure 3: Joint space distance with respect to sampling interval during walking and sprinting

The cycle detection performance of the algorithm is shown in Table 1.

Table 1: Algorithm performance under different tests

Test Type	Sensitivity	PPA
Walking 2km/h	100%	100%
Walking 4km/h	100%	100%
Jogging 4km/h	100%	100%
Jogging 6km/h	100%	100%
Sprinting	100%	100%

Repeatability tests performed on all goniometers indicate that the measurements are consistent between tests. Table 2 displays the results of the measurements taken from the right knee electrogoniometer. The variability between the measurements can be attributed to the repositioning of the sensors as well as the natural variability in stride patterns during a single test or between tests. The latter is evident from the standard deviation values from each individual test.

Table 2: Repeatability of measurements for right knee

Test Type	Measurement	Test1	Test2	Test3	Mean
Walk 2km/h	Angle Span (°)	53.58	50.22	51.72	51.84
	SD	(2.22)	(2.17)	(1.10)	(1.68)
	Cycle Time (s)	1.262	1.414	1.416	1.364
	SD	(0.053)	(0.047)	(0.035)	(0.088)
Walk 4km/h	Angle Span (°)	62.46	59.36	55.9	59.24
	SD	(1.51)	(1.08)	(1.42)	(3.28)
	Cycle Time (s)	1.020	1.033	1.041	1.032
	SD	(0.157)	(0.036)	(0.025)	(0.011)
Jog 4km/h	Angle Span (°)	60.06	55.10	54.42	56.53
	SD	(2.21)	(0.96)	(2.04)	(3.08)
	Cycle Time (s)	0.755	0.758	0.744	0.752
	SD	(0.021)	(0.018)	(0.022)	(0.007)
Jog 6km/h	Angle Span (°)	64.16	61.56	61.30	62.34
	SD	(1.30)	(1.85)	(2.43)	(1.58)
	Cycle Time (s)	0.709	0.726	0.717	0.717
	SD	(0.006)	(0.010)	(0.013)	(0.009)

Electrocardiography

Fig. 4 shows the recorded electrocardiograms for various testing conditions, in which the R peaks detected by the algorithm are denoted by a circle. The algorithm performance is summarised in Table 3.

Table 3: Algorithm performance under different tests

Test Type	Sensitivity	PPA
Resting	100%	100%
Walking 2km/h	100%	100%
Walking 4km/h	100%	100%
Jogging 4km/h	100%	100%
Jogging 6km/h	100%	100%
Sprinting	104%	92%

Respiratory Effort

Table 4 summarises the algorithm performance in the detection of the peaks in the respiratory effort curves. Reliable measurements in sprinting conditions were not achieved due to noise and sensor dislocation.

Table 4: Algorithm performance under different tests

Test Type	Sensitivity	PPA
Resting	100%	100%
Walking 2km/h	100%	100%
Walking 4km/h	100%	100%
Jogging 4km/h	100%	100%
Jogging 6km/h	100%	100%
Sprinting	-	-

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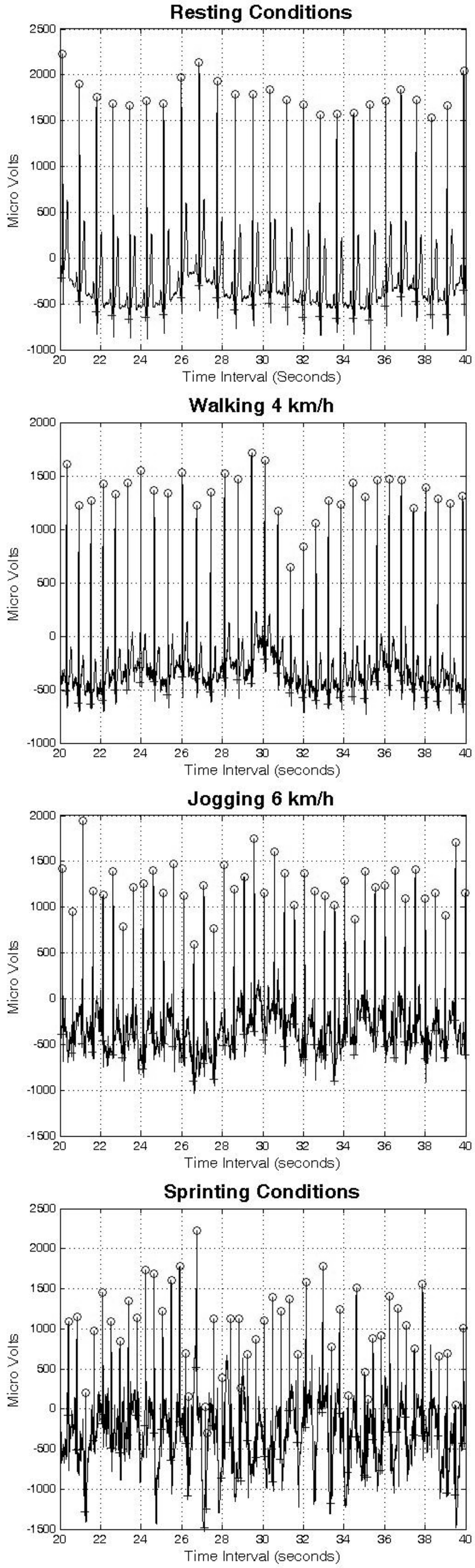

Figure 4: Detected R peaks for different test conditions

Temperature

A preliminary study on post-surgical patients indicated that temperature differences between the healthy and operated legs were acute immediately after surgery and became insignificant one or two weeks later, well before the athlete could actually use the system. This indicates that the use of the temperature thermistors would be of limited clinical value for the proposed application. Furthermore, a deterioration of the patient's condition would be evident through other means before using the wearable monitoring system. Nevertheless, temperature readings with the thermistors were consistent with measurements taken by alternative thermometers.

System Functionality

All the main goals set for the system were adequately demonstrated (multi-signal monitoring, alerting, VR feedback, wireless communications, remote accessibility to information, wearability). However, adjustments and alterations will be necessary in the alerting / decision support mechanisms as well as the interfaces of the rehab station and the portal according to the clinical applications. This will require clinical trial feedback, which will also determine the clinical value of the system for specific medical conditions.

Usability

The system is straight forward and easy to use with minimal training. However, the setup period was found to be excessive for inexperienced users. It takes approximately 15 minutes to setup the hardware components of the system and 15 minutes to setup the athlete. Furthermore the excessive use of cables and the size and weight of some of the wearable components of the prototype were found to be obtrusive. In addition, some of the sensors were dislocated or failed to produce reliable measurements after extensive use or in extreme testing conditions due to vibration and sweating.

User Acceptability

All users found the system acceptable and intriguing to use, but this was easier for those more familiar with the involved technologies. The use of virtual reality as a means for feedback provided the highest incentive for use.

Discussion

The results indicate that the system is reliable in the intended exercise conditions such as walking and jogging, whereas it is less reliable in more extreme conditions such as sprinting, due to noise, sensor dislocation and cable restrictions. Overall, the system has achieved its main goals in functionality, user acceptability and usability. Considering that this is a first prototype, many of the concerns and comments raised by the users could be alleviated in a potential industrial version.

The removal of redundant sensors could simplify the setup, operation and usability of the system, depending on the clinical problem under discussion. As already mentioned in the results, in the case of ACL reconstruction patients the indications are that the system could do without the two temperature thermistors. The two ankle goniometers could also be removed as they provide less significant information (compared to the knee and hip goniomrters) in such patients, are not necessary for the motion cycle time evaluations, and can be effectively simulated in the virtual reality interface.

Additional tests under way regarding the system evaluation include goniometer measurements in conjunction with the PEAK motion analysis system (using PEAK Motus 4.3.1) using a half body spatial model in free movement conditions simulating the intended conditions of use of the system for walking, jogging, running, and jumping. Furthermore, the breath and heart rate detection algorithms need to be evaluated for a larger number of cases.

The presented system currently performs prodominantly monitoring tasks, except for a few medical rules generating alerts, incorporated mainly for demonstration purposes. Its functionality would be greatly enhanced with the addition of medical decision support with the use of more complex statistical, machine learning and sensor fusion techniques for the assessment of specific medical conditions. This approach requires clinical data for each examined condition based on the available sensors. For this purpose, the current effort is focusing on collecting data for athletes recovering from ACL reconstructions and to assess the progress of rehabilitation according to motion and pain levels with respect to the clinical evaluation of the patients.

Conclusions

The described system addresses the needs of rehabilitating athletes, medical personnel and researchers. The system has achieved its main goals in reliability, functionality and user acceptability, for the intended use conditions but adjustments may still be required in terms of functionality, along with several concerns on usability, particularly for the wearable components of the system. In addition, the system will benefit when a decision support module is added. For this purpose, a clinical study is currently under way to assess the leg joint motion patterns of athletes recovering from ACL reconstruction surgery based on goniometer readings.

Acknowledgements

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