

An interactive 3-D application for pain management: Results from a pilot study in spinal cord injury rehabilitation

Fotios Spyridonis ^a, Jan Gawronski ^b, Gheorghita Ghinea ^a, and Andrew O. Frank ^c

^a Department of Information Systems and Computing, Brunel University, Uxbridge, UK

^b Spinal Cord Injuries Unit, Royal National Orthopaedic Hospital, London, UK

^c Centre for Research in Rehabilitation, School of Health Studies and Social Care, Brunel University, Uxbridge, UK

Corresponding author: Fotios Spyridonis, Department of Information Systems and Computing, Brunel University, Uxbridge, UB8 3PH, UK, Phone: +441895265503, Email: Fotios.Spyridonis@brunel.ac.uk

Keywords: Biomedical technology; Pain measurement; Spinal Cord Injuries; Imaging, Three-Dimensional; User-Computer Interface; User acceptance

Abstract

Research on pain following Spinal Cord Injury (SCI) has revealed that patients not only experience several types of pain that could prove to be challenging to address, but also that each individual can interpret such pain in different subjective ways. In this paper we introduce a 3-D system for facilitating the efficient management of pain, and thus, supporting clinicians in overcoming the aforementioned challenges. This system was evaluated by a cohort of 15 SCI patients in a pilot study that took place between July and October 2010. Participants reported their experiences of using the 3-D system in an adapted version of the System Usability Scale (SUS) questionnaire. Statistically significant results were obtained with regards to the usability and efficiency of the 3-D system, with the majority of the patients finding it particularly useful to report their pain. Our findings suggest that the 3-D system can be an efficient tool in the efforts to better manage the pain experience of SCI patients.

1. Introduction

Pain is one of the most common and prevalent consequences of SCI that imposes severe implications on individuals who have suffered this kind of physical trauma. Roughly one-half to two-thirds of spinal cord injured persons suffer from some form of chronic pain, and in approximately one third the pain is very severe and disabling [1]. Specifically, a summary of results from past studies [1, 2] in patients with SCI indicates that the average reported estimate of the prevalence of chronic SCI pain is approximately 65%, with roughly one-third of those affected reporting the severity as being greater than seven in a scale of ten on a Visual Analogue Scale (VAS). Although loss of function is the main consequence of SCI, the symptoms experienced from the presence of such chronic pain could be so severe that it has been reported to frequently interfere with sleep and everyday activities [3]. To this end, approximately 37% of SCI patients reported that they would like to be relieved from this burden even if they had to trade it with additional loss of bladder, bowel, or sexual function [2].

It is generally agreed that pain following SCI is complicated to assess and manage in that it may be either neuropathic or nociceptive [2, 4]. Specifically, spinal pain may arise at the level of the lesion, or above or below the lesion [2]. However, nociceptive pain may arise due to specific joint or musculoskeletal pains e.g. shoulder pain from self-propelling a wheelchair [5, 6, 7], generalized pain related to the discomfort of sitting in a wheelchair for prolonged periods of time [8], or visceral pain e.g. related to sphincter dysfunction [9]. Consequently, identifying the relative site in which pain has occurred most accurately may assist in the proper management of pain following SCI.

1.1 Current pain management practices

Many approaches to the management of pain have been evolved over the last decades as a response to its impact. Most of these approaches have been based on a questionnaire format, and have therefore relied on the ability of a patient to self-report his or her pain. Three of the most typical approaches currently in use are the ranking of the severity of pain, the assessment of quality of life [10, 11], and the recording of the spatial location or site of pain [12, 13]. The latter – also known in the literature as pain drawing - is one of the most commonly used assessment methods with applications to various medical conditions over the years. This method involves the use of a paper-based 2-D body outline (see Figure 1), where patients are asked to mark on the type and distribution of the pain being experienced.

Nonetheless, despite their widely reported usefulness [10, 11, 12, 14, 15, 16, 17], there seems to be a lack of consensus regarding the applicability of such instruments in managing pain for persons with SCI. For example, asking an individual with SCI a question about pain interference with walking, a common question in many quality of life measures, is not applicable for someone who uses a wheelchair every day [18]. Similarly, notwithstanding its reported advantages, the pain drawing has also limitations as statements of the form *“I have a pain on the inside of my thigh”* are not easily captured in a 2-D representation of the body.

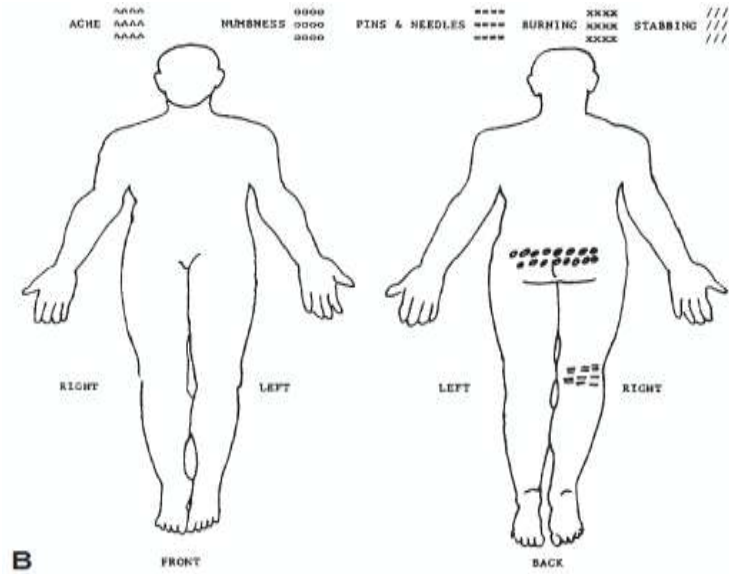


Figure 1. A Completed Pain Drawing (Adopted by [16])

In this respect, the work presented in this paper discusses the design, implementation and participant experiences of a 3-D visualization system to be used in the rehabilitation of pain by people suffering from SCI. Specifically, this work attempts to offer a computerized alternative to the pain drawing in managing pain, by offering patients an improved ability to visualize their SCI pain characteristics in 3-Dimensions – in the anticipation that it can make an important contribution to the applicability of specific instruments that could be used by clinicians in the effective management of pain for persons with SCI.

2. Computational methods and theory

The application of 3-D visualization techniques in the assessment of pain is not a recent trend. For instance, [19] and [20] explored the use of 3-D visualization methods to show whether the improved imaging quality could assist in the assessment of chest and facial pain, respectively, with the results indicating that visualization methods can be superior to traditional approaches for accurate assessment of pain.

Similar are the implications of applying 3-D visualization to the rehabilitation of SCI. In fact, considerable work has focused on the use of 3-D technology in the efforts to

reconstruct spinal cord trauma with very positive results. For instance, [21] have used 3-D computer reconstruction in order to evaluate the pathology of the spinal injury. Along the same lines, [22] employed a 3-D reconstruction technique to investigate pelvic and spinal pathologies.

On the other hand, a 3-D mechanical model of a human lumbar spine segment with the intension to be used in simulation of surgery was depicted in [23]. As a step further, [24] have introduced a 3-D biomechanical skeleton model that could be used for diagnostic and therapeutic purposes for posture and SCI. More recently, further work has focused on the employment of 3-D modeling to better understand SCI. Specifically, [25] in their work have developed a 3-D model of a human cervical spine and spinal cord segment in order to investigate different cord strain distributions after injuries. Similarly, [26] have used 3-D imaging to create a model of the adult spinal cord for diagnostic purposes.

Finally, from a different perspective, [27] in an experimental study for reconstructing SCI, they constructed 3-D virtual images from performing computerized medical scans, whereas [28] described in their work a similar 3-D reconstruction method to be used for the automatic diagnosis of spinal diseases on the basis of CT slices.

In all the above studies, the results produced were very positive and 3-D visualization was extremely beneficial because the models produced could be observed from many different viewpoints, while rotation and zooming features were combined to allow observer navigation within the tissue. The same feature benefit was anticipated from devising a 3-D application to be used in the management of SCI pain.

2.1 Evaluating patient perceptions of self-assessing pain in 3-D

As such, the research objective that has been specifically targeted in this study is to examine the usability of a 3-D system in visualizing SCI patients' pain characteristics. To address our research objective, the present study set out to examine *whether a 3-D approach to SCI pain management would be perceived better by its envisioned patient users, as compared to the traditional 2-D pain drawing*.

In so doing, our developed 3-D application will be evaluated against the well-established pain drawing of Figure 1. Specifically, this 'side-by-side' comparison and evaluation will be performed on the basis of particular content that is *common* to the two tools (see Figure 2). In this respect, only user responses about this common content will be analysed, thus reflecting user perceptions and preferences for using either the pain drawing or the 3-D visualization system to better manage their pain.

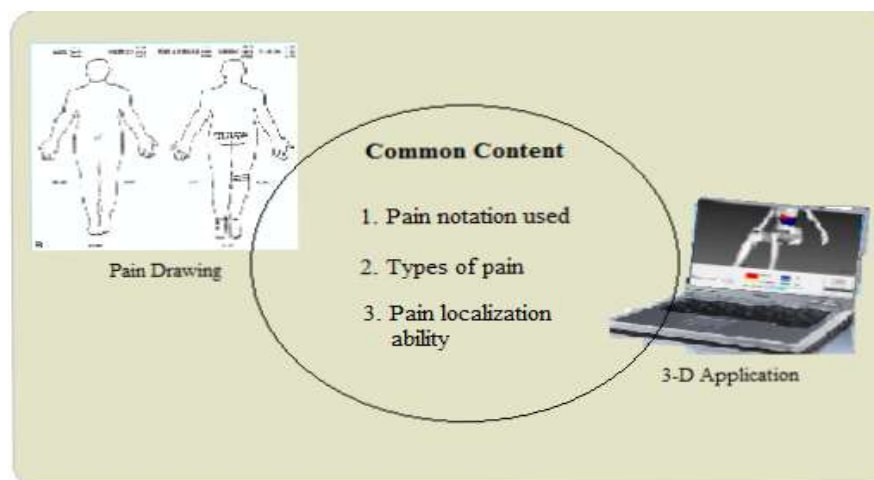


Figure 2. Common Content to Pain drawing and 3-D Application

2.2 Instrumentation

The instrumentation used for this study consists of a laptop that runs the 3-D application, and two sets of questionnaires. The first is a pain questionnaire that was formed and validated together with the clinical staff involved in the study, and which includes pain-related questions and the traditional pain drawing. Accordingly, the

second questionnaire is an adapted to our requirements version of the system usability scale [29] that was carefully designed to reflect the content that has been identified as common between the two tools, as well as to assess the usability of both. In this questionnaire, patients are asked to record their opinions about both methods on a Likert scale of 1 (Strongly Disagree) to 5 (Strongly Agree) (see Table 1). Both questionnaires had been piloted at the test site prior to their administration.

Table 1. Patients' Evaluation questionnaire

Q1. It was easy to log pain information on the pain diagram
Q2. The process was easy to learn and use
Q3. The use of the pain notations (color) was clear and helpful
Q4. Showing the type and exact location of my pain on the pain diagram was easy
Q5. I believe the pain diagram was not sufficient to express my pain
Q6. The overall layout of the interface was clear and simple

2.3 Description of participant group

The participant group consisted of 15 individuals with SCI (7 female; 8 male, mean age 52.3 years, range 28-75) who volunteered to participate in the research study between July and October 2010. This sample represented both new and consecutive admissions at the Spinal Cord Injury Unit in the Royal National Orthopaedic Hospital in London, with no previous exposure at the conventional pain drawing. Eighteen potential participants were initially asked to take part with three declining. The mean age of the eight males was 47.3 years (range 28-75), whereas 58 years (range 42-72) was the equivalent for the seven females. Details of all participants are shown in Table 2.

Table 2. Study Participant Group

Participant Number	Age	Gender	Diagnosis	Range 'Overall' VAS
1	63	F	Vascular SCI	0-7
2	70	F	Traumatic SCI	0-5
3	41	M	Traumatic SCI	0-5
4	69	M	Epidural abscess	0-2
5	28	M	Traumatic SCI	0-6
6	61	M	Traumatic SCI	0
7	42	F	Traumatic SCI	0-9
8	46	F	Disc prolapse	0-3
9	32	M	Spinal neurofibroma	0-5
10	75	M	Traumatic SCI	0-4
11	39	M	Traumatic SCI	0-4
12	66	F	Traumatic SCI	0-1
13	72	F	Epidural abscess	0-7
14	47	F	Traumatic SCI	0-9
15	34	M	Traumatic SCI	0-8

Their diagnosis varied and included ten patients with traumatic SCI, two had infective causes and one vascular, discal and tumor conditions. The criteria for selection was that the participant has spinal cord-related condition that involves pain, has an age of 18 years or more and experience some pain during the period of study. Finally, the range of pain intensity varied from 0-9, with the mean maximum pain intensity being 8.375 on a VAS, in accordance with the results cited in [1, 2].

2.4 Protocol and algorithm

The study protocol was approved by North London 1 Research Ethics committee. As such, prior to initiation of pain measurements, informed consent was obtained by each participant. A within-subjects design was employed for data collection in this study, where the patients used (in a randomized order to avoid presentation bias) both the 2-D pain drawing and the 3-D system to assess their pain. After consultations with the clinicians, it was decided that the measurements would take place in four points in time

over a period of one day for each participant, with an approximately 2-3 hour time difference between them (between 8.30am and 5pm), based on the patients' daily schedule of activities.

Accordingly, the first measurement of the day started between 8.30-9.00am in the SCI unit of the above hospital, with the participant randomly given either the questionnaire with the 2-D pain drawing or the 3-D application to record details about his/her medical background, as well as information regarding pain relieving/worsening factors and treatment received. The next step was to score the current, at the time of measurement, level of his/her pain intensity, and the data collection finished by reporting in the assigned tool the type and location of his/her current pain. To satisfy the requirement for evaluation of only the common content to both approaches, patients were presented only with functionality that matched the conventional pain drawing's, making other aspects of the 3-D application (see section 4.1) intentionally unavailable.

The protocol continued for three more measurements in 2-3 hour intervals, and at the end the evaluation questionnaire would be handed to the patient. Each measurement had duration of approximately 25 minutes and, at the end of the day the patient would have used both tools twice (the order of use was randomized to prevent order effects).

2.5 Data Analysis

The data generated at the end of the measurements consisted of a. information about each patient's pain characteristics and b. the results of the evaluation questionnaires. For the former, a medical interpretation would be performed by the clinicians involved in this study, in order to examine the practicality of the 3-D approach in the management of pain in everyday medical practice. The results of this interpretation are not presented in this paper, as they are outside the purpose of the present study.

For the latter, a statistical analysis was sought by using specialized software such as Predictive Analytics Software (PASW) v18.0, in order to identify whether statistical evidence occurs in support of our research objective. Specifically, each question of the questionnaire shown in Table 1 was assigned with a corresponding dimension that was used to measure *user perception* with respect to the *type of tool* (2-D pain drawing or 3-D system) being evaluated (see Table 3). Accordingly, paired samples t-tests were performed for each of these questions to find out whether there were statistically significant differences in the aforementioned dimensions when using the two tools. If the t-tests were found to be statistically significant, follow-up graphical analysis was performed to visually represent the results.

Table 3. Description of Measured Variables and Results

		Independent Variable				
Dependent Variable	Type of tool Dimensions of User Perception	2-D Pain Drawing		3-D approach		p-value
		Mean Response	St. Deviation	Mean Response	St. Deviation	
	1. Ease of pain logging	3.1	1.6	4.6	0.5	0.02
	2. Ease of learning and use	4.7	0.4	4.4	0.9	0.3
	3. Clarity and helpfulness of pain notation	3.6	0.6	3.6	1.6	1
	4. Clarity of the pain diagram	2.3	1.2	4.4	0.6	0.003
	5. Sufficiency of pain diagram to express pain	3.5	0.8	1.09	0.3	<<0.05
	6. Simplicity and clarity of the User Interface	3.1	0.8	3.9	0.7	0.02

3. System description

3.1 Defining the system's potential users

The developed system was envisioned to support two main groups of users, namely both *primary* and *secondary* users. For the purpose of this study, the **primary** users are identified as being the SCI patients who would *directly* interact with the application by

using it in order to record pain that they experience.

Accordingly, the system's **secondary** users will consist of clinicians and other clinical staff who would either *directly* interact with the system by using it to record SCI patients' pain perception, therefore acting as an intermediary to the patient, or who would *indirectly* interact with the system by using its stored pain information for pain assessment and management purposes.

To put the discussion into the context of the study's aim, it was envisioned that secondary users would potentially integrate the system in their daily medical practice, in order to allow primary users to directly record their pain experience using the 3-D application. The recorded information would be then indirectly used by secondary users involved in their healthcare provision.

3.2 Identifying the system's user requirements

In retrospect, the design and implementation of the system was conducted in collaboration with a team of five members of clinical staff, and three of this study's participants from the Spinal Cord Injury Unit of the Royal National Orthopaedic Hospital in London, who would potentially interact with the system. In order to participate in this activity, the former group had to have experience with using the conventional pain drawing, whereas the latter had to experience SCI pain and be computer literate. Interviews with these stakeholders were held in order to define the desired requirements of the system. In brief, the identified requirements were to:

1. *Be user friendly.* It should be extremely friendly and very easy to use and understand as the clinical staff and patients alike might not be computer-oriented. On the basis of this, the system should be able to match the real world by having a User Interface (UI) layout that provides clear, familiar and relative information to the potential user, instead of computer-oriented terms.

In retrospect, the interaction process between that UI and the user should be extremely easy to learn and the system should be very easy to use by both experienced and inexperienced users, as well as by people with some form of impairment. This necessitates that the navigation capabilities that it should provide (e.g. buttons, input/output devices, selection lists, etc.) be as much simplistic and efficient as possible.

2. *Record pain information.* It should be extremely *practical* in recording SCI pain characteristics and information that map to patients' realistic daycare. As such, it should provide the functionality to also record pain information for various aspects of the daily patient's life (e.g. personal care, physical activities, treatment) and allow the details (pain location, type, intensity, time of input) to be recorded over time, and saved for later analysis and for record keeping on a patient's file, all in the form of a questionnaire.

Although measuring the aforementioned pain information is not something new in the pain literature, studying the change of these pain characteristics over time and/or in relation to physical (or other) activities has never been performed on patients with SCI to the best of the authors' knowledge. In anticipation, the system would represent an improvement over conventional scalar methods, as it would provide the user with an increased dimensionality to measuring SCI pain. This multidimensional nature of the system is represented by the capability that it should offer to collectively measure SCI pain characteristics, their changes over time, and their relation to physical or other activities. The end result of this improved functionality should be an increased sensitivity in detecting any changes of pain and how/what affects them.

3. *Provide improved visualization.* The visual quality of the conventional pain drawing should be significantly increased. As such, the system should encompass a 3-D representation of the human body, as an improved version of the 2-D format of the pain drawing, and it should provide fully navigational controls (zoom and rotate) that would allow for achieving an optimal visual quality through direct interaction with the system.

In doing the above, the system should be also able to accurately represent different body postures, which typically reflect a patient's everyday life, and should enable selection of body regions that most closely and precisely reflect a patient's topology of pain. The conventional pain drawing does not currently provide any similar functionality.

In retrospect, the 3-D system would represent a significant improvement to visualization over the conventional method, as not only it would provide the user with increased visual quality, but it would also enhance the accuracy of SCI pain assessment through the capability to further select a body posture that best reflects the user's seating behaviour at the time of measurement. As such, a better differentiation between types/causes of pain could be achieved that would eventually lead to a more accurate diagnosis and/or management of SCI pain.

4. *Be implemented on a laptop.* It has to be noted at this point that no specific requirements were sought during the design and implementation stage from patient users who may have specific physical or sensor constraints. Due to the pilot nature of this study, this was not taken into consideration and it could constitute an avenue for future work. Nevertheless, the patients involved in the requirements definition did highlight the fact that SCI patients suffering from

mobility or visual impairments are more likely to need a system that is developed on a PC or laptop, and be presented on a large screen. As such, a special requirement derived was that the system be developed on a laptop computer, instead of e.g. a Personal Digital Assistant (PDA) that was used in previous work by [30].

3.3 System Architecture

The developed system was designed and implemented by extending previous work by [17, 30] and according to the user requirements identified. It consists of the underlying system architecture shown in Figure 3, with the three main components being the developed application with the Virtual Reality Modelling Language (VRML) Engine for 3-D support, the web/database server, and the backend databases.

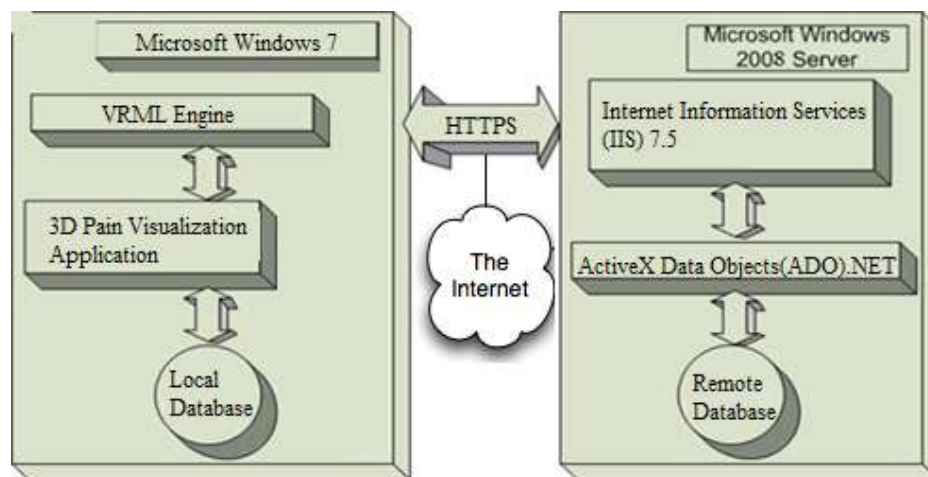


Figure 3. System Architecture

Accordingly, the application consists of a pain questionnaire that is used to collect information regarding a patient's personal data for demographic purposes, as well as information concerning factors that worsen and relieve pain in relation to physical activities and personal care, the kind of treatment received, and the current intensity of their pain at the time of measurement in several predefined body parts (back, neck,

buttocks, legs, arms/shoulders, hands, feet, and an overall).

The user has the ability to input all of the above information through a variation of ways, while pain intensity is inputted for a particular region of the body via a VAS (implemented in our system via a horizontal scroll bar) ranging from 0-9 (0-no pain; 9-worst pain you can imagine).

The most important part of the application is the visualization ability of SCI pain. Our application displays a 3-D human mannequin whose surface was segmented into clinically appropriate regions after consultations with the clinical staff involved in our study. Specifically, the division of the body surface was performed in three levels: level 1- least detailed division of the body in regions; level 2- moderate division; level 3- most detailed division.

Moreover, based on earlier work [30, 31] and on consultations with the clinical staff involved, we color-coded four basic different types of pain (numbness, pain, pins and needles, and ache) that the SCI patients could select from, with an enhanced functionality to further choose a combination of these pain types to more accurately highlight their pain.

In addition, according to the need to reflect a patient's everyday life, clinicians further suggested that the application provides the capability to also select between three different body postures (standing, sitting or lying). In so doing, this feature would present the clinical staff with additional and more accurate information with regards to:

1. how different body postures might affect (whether increase or decrease) their SCI pain levels;
2. whether various daily functional activities, while being in a certain posture, have any implications to their SCI pain levels;

3. lastly, it would provide a more realistic environment to the patient that helps to best reflect his/her posture and more accurately indicate SCI pain on it at the time of measurement

Finally, the user has zoom-in and zoom-out buttons for manipulating the mannequin for depth-perception, whereas rotations are implemented through mouse input. If a mistaken pain indication was given, the user can delete it by clicking again on the selected pain type and then on the 3-D body. The obtained information is then stored in a local database.

4. Samples of typical system runs

4.1 Application walkthrough

The developed system is made up of two main users, namely the clinician and the patient, as well as a control device - the laptop - that runs the 3-D application, and the web/database server with the backend database. The interaction between the system components starts with the clinician initially creating a patient profile by registering the patient user, prior any pain characteristics data collection. This entails the clinician supplying patient background information such as personal details, symptoms, type of injury, as well as any significant medical or impairment conditions. Subsequently, the system prompts the user to specify factors that worsen the pain in relation to physical activities (e.g. prolonged sitting and/or lying) and personal care (e.g. dressing, bowel care), as well as the factors that may usually offer relief from pain (e.g. rest, change of position). In addition, the treatment received (e.g. painkillers, physiotherapy) is also recorded.

Upon authentication, the patient user can then score the pain intensity for the seven predefined by the clinicians body parts. In addition, the patient can also provide

information regarding any treatment received over the last two hours, as well as specify any other painful body areas with the corresponding intensity level.

The patient user then proceeds to the 3-D diagram screen (see Figures 4 and 5). Here, the ability to choose between the three defined postures and select a better region division of the human body is provided. In order to visualize the pain, the patient user can select from the four basic pain types, or a combination of them. Each pain is represented by a different color. Following the selection of the pain type by clicking on the corresponding color, the patient user can manipulate the 3-D model through the mouse and the *zoom in/out* buttons to the required body part, and indicate the type of pain by simply clicking on it.

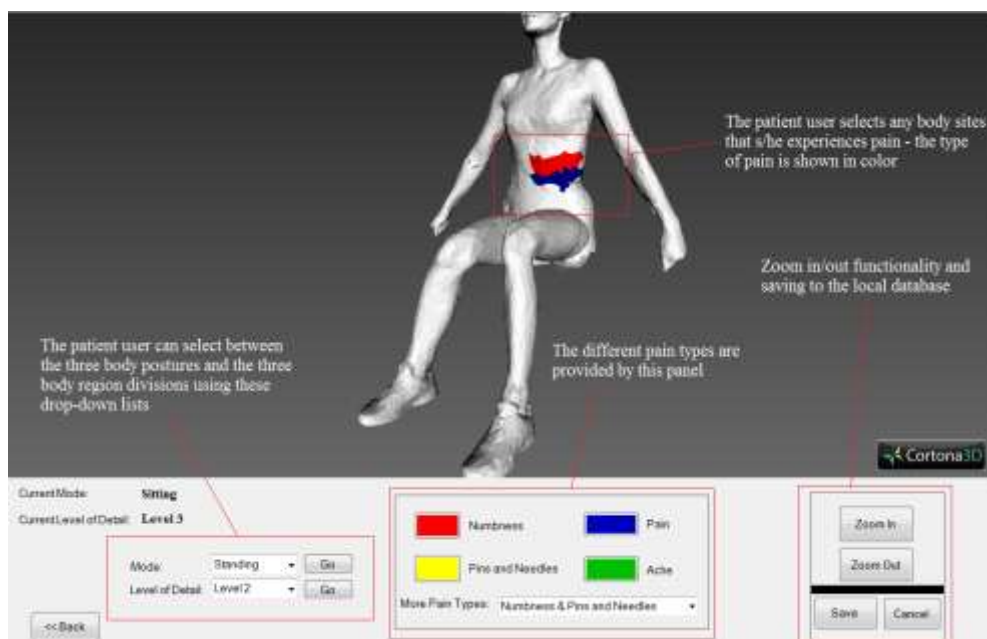


Figure 4. The 3-D Application (1) – Sitting Posture

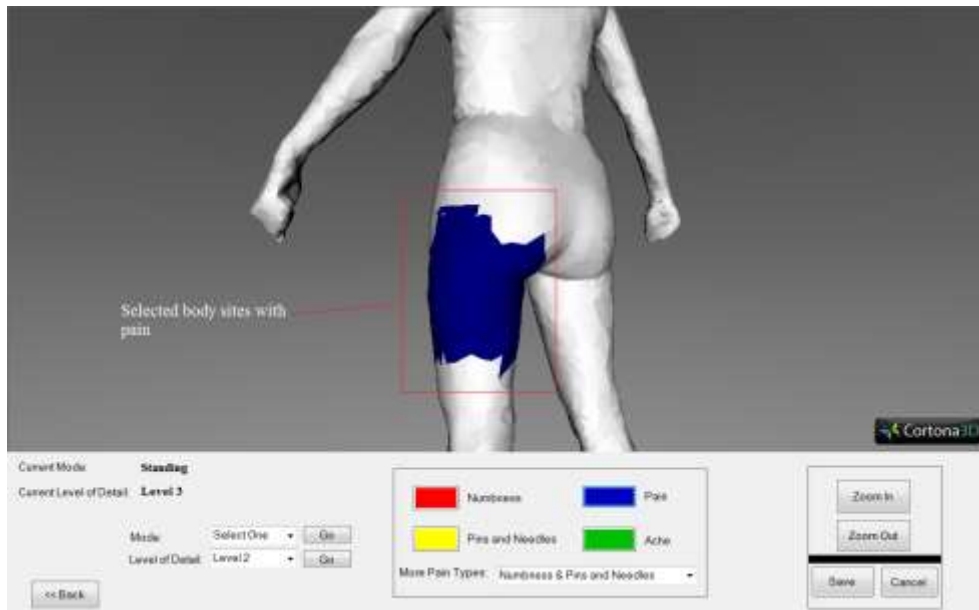


Figure 5. The 3-D Application (2) – Standing Posture

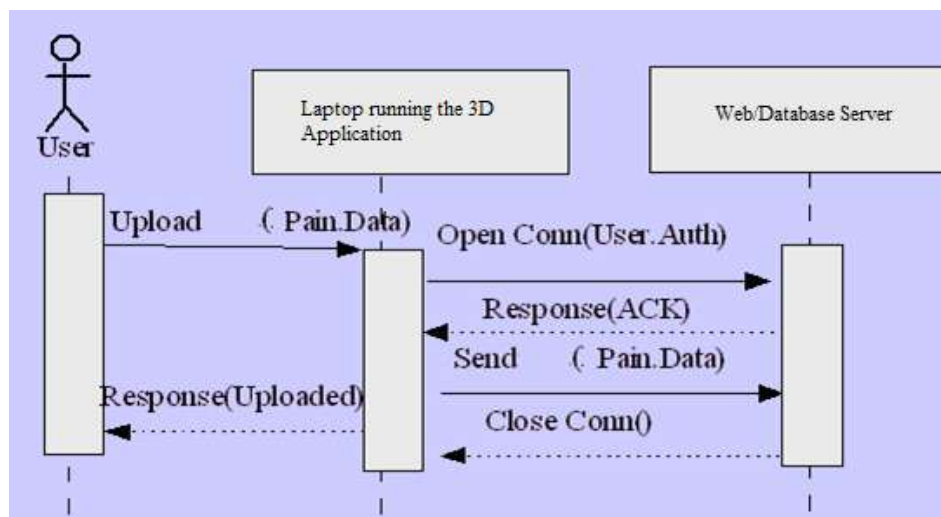


Figure 6. Sequence Diagram of the Upload Process

When the pain information collection has finished, the data can be stored to the local database, and can be then uploaded to the remote server's database using the Internet. The process of uploading (see Figure 6) is based on a user authentication technique with a username/password tuple, which, if passed, the server receives the data and saves it to the remote database, where it will remain until a clinician requests them for assessment.

At this point, it is important to clarify that from the above functionalities only the 3-D visualization of pain characteristics is of interest to the nature of this study. To this end,

aspects such as uploading and recording pain-related information have not been taken into consideration as mandatory when evaluated the system. As such, the section that follows only deals with the evaluation of the 3-D visualization aspect of the system.

5. Evaluation results

The results obtained from this study are generally in line with our expectations that SCI patients would accept the potential of the 3-D system to more accurately manage their pain experience.

5.1 Usability of user interface and navigation

To this end, with respect to our research objective, while opinions about the ease of learning and use remained roughly the same for both the 2-D pain drawing and the 3-D application, the general consensus demonstrated that the process of logging pain information on the 3-D system was relatively more easy as compared to its 2-D equivalent (see Figure 7).

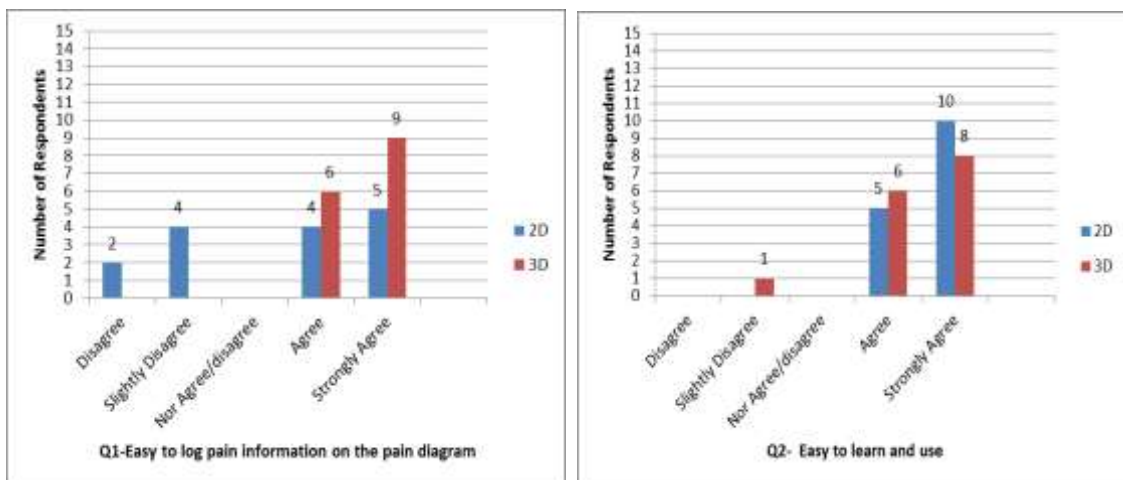


Figure 7. Histograms of Responses to Evaluation Questions 1 - 2

Moreover, performing a paired samples t-test on our results revealed that while the mean opinion score regarding the ease of learning and use was higher in the case of the 2-D pain drawing, the difference was not statistically significant (see Table 3). In fact, we expected patients to have more problems learning and using the laptop application

than the paper-based method, considering the age variation and some mobility impairments that were present in this patient group. However, our results suggest that patients' perceptions were considerably different than our expectations, as the fact that they found logging pain information on the 3-D system easier ($p<0.05$), demonstrates.

Since the 3-D system was devised to enhance the limited abilities that the 2-D pain drawing was offering, it comes as no surprise that patients further found that showing the type and *exact* location of their pain on the 3-D model (Figure 8) was also significantly easier than when using the 2-D drawing ($p<0.05$) (see Table 3).

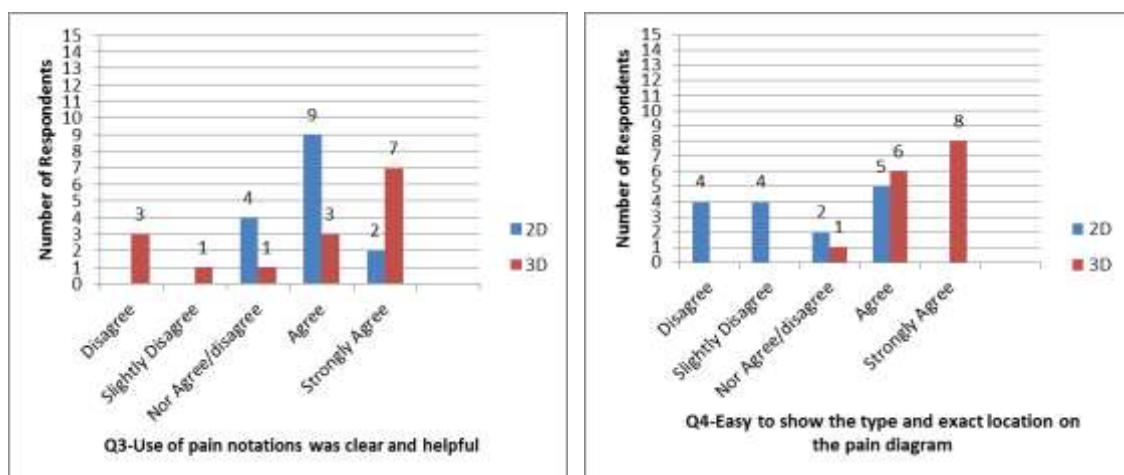


Figure 8. Histograms of Responses to Evaluation Questions 3 - 4

In fact, a comment made by a patient during the evaluation was:

“I prefer that one (3-D application) instead of the paper diagram...you can actually focus better on that one, as the area is well-defined and I can more easily indicate the location of my aches...”

Two more patients similarly remarked:

“It (3-D application) is more ‘friendly’ ... – I actually prefer this one since our different body parts are now more localized and easier to see...”

and

“This (the 3-D application) is very good and looks much easier now to show where

my discomfort is ...”

Accordingly, most comments were appreciative of the potential that the 3-D system could offer in the management of pain, and were generally in line with following comment made by another of the participant patients:

“The figure (i.e. 2-D pain drawing) was not adequate...I would definitely prefer something better.”

Moreover, positive results were similarly obtained with regards to the ability of the 3-D model to sufficiently communicate to the clinician the type of the pain experienced, through the use of a color notation that patients found to be very clear and helpful (see Figure 8). Nevertheless, patients’ perceptions suggest that there is no significant preference of using the color notation over the traditional symbol notation used in the 2-D pain drawing. On the contrary, the mean opinion score was exactly the same in both tools (see Table 3). Therefore, the small analogy that was revealed between the two different ways of pain notation seems to demonstrate the acceptance of color as a means of depicting patients’ pain type, justifying past studies [30, 31] with respect to the use of color for the intended purpose.

Accordingly, we remark that the general trend from our evaluation was that patients were enthusiastic about the system, generally disagreeing with statements regarding the insufficiency of the 3-D model to express their pain (see Figure 9). In fact, the results highlight the wide acceptability and approval of the 3-D system’s ability to sufficiently report their pain experience, as compared to the 2-D pain drawing ($p < 0.05$).

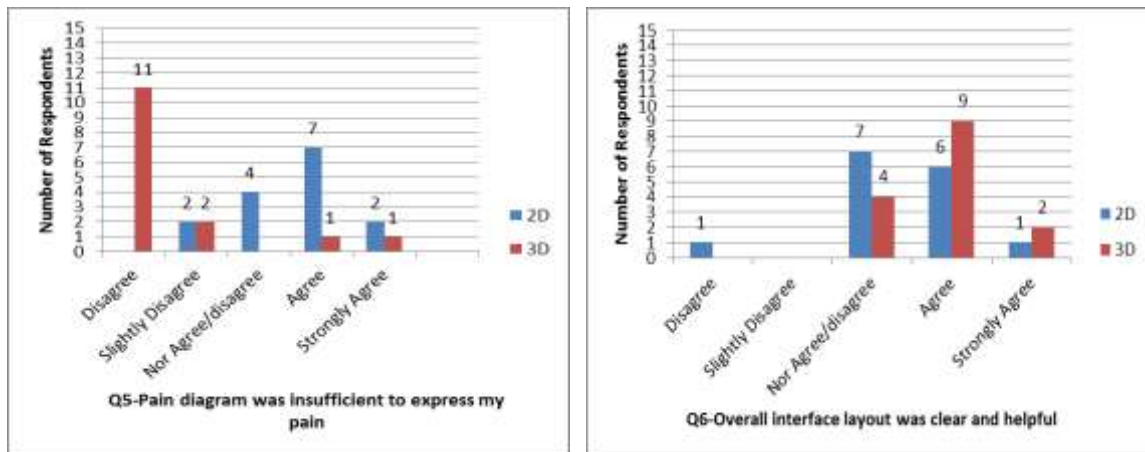


Figure 9. Histograms of Responses to Evaluation Questions 5 - 6

Overall, the majority of the SCI patients that participated in our study appreciated the advantages of the enhanced visualization ability that our 3-D model provides by indicating very positive views towards the quality of the user interface layout (see Table 3) ($p < 0.05$), as demonstrated in Figure 9.

5.2 Clinical perceptions

It is essential that clinical staff, who would potentially use the measures obtained by the system, perceive that the output of the system supported their decision making about interventions i.e. management of SCI pain. In this respect, the authors felt that, although outside the purpose of the present study, it would be beneficial and would further support our present findings if the necessary perceptions of the clinical staff were also obtained.

As such, the 3-D application was demonstrated to three participant groups, consisting of two clinicians, two nurses and to a team of four physiotherapists, all employed in the spinal cord injury unit. All had some experience of using the 2-D pain drawing, and were not exposed at the 3-D system during the evaluation period with the patients. Specifically, each group was presented with the various functionalities of the system, and was then asked to document their opinions with regards to its practicality and

usefulness in their everyday practice. These were noted and transcribed by the authors.

Their responses varied and were generally positive with respect to the system's potential. The clinicians appreciated that the system could be very useful in monitoring a patient's condition and how it progresses over time, particularly emphasizing in the enhanced precision that would be added to this progress as a result of using the 3-D model in doing so. Similar were the responses from the physiotherapist group. Specifically, they all seemed to agree that improving the visual quality of the conventional pain drawing with a 3-D model could be of important assistance to them, as they could now plan better activities/exercises to reflect the pain of their patients. Finally, from a different perspective, the two nurses were very enthusiastic about two aspects of the system: first, its ability to record patients' daily activities and whether they increase or deteriorate their pain level, and second, the possibility to show exactly where this pain is on the 3-D model. In doing so, both nurses argued that they could examine if the reported pain could be correlated with any of their daily patient care activities.

6. Hardware and software specifications

The 3-D pain application was developed using the Visual Basic .NET programming language. The 3-D model was developed from a previous model by *Cyberware, Inc.* [32]. This Cyberware model was adapted, and then manipulated and extended to meet our needs. This was then integrated in the pain application by using the functionality of Parallel Graphics Cortona Software Development Kit (SDK), an Application Programming Interface (API) that facilitates the development of 3-D-enabled applications by using the Virtual Reality Modeling Language (VRML) [33], and then displayed using the Parallel Graphics Cortona3D Viewer [34].

Accordingly, the web/database server was implemented for the Windows 2008 Server operating system, using Internet Information Server (IIS) 7.5 and the ADO.NET service to connect to the database. For the uploading functionality of the system, data could be send either wirelessly through Wi-Fi Protected Access–Pre-Shared Key (WPA-PSK) encrypted radio broadcast, or by using a standard broadband Internet connection. In both cases, the information privacy is maintained by the use of 128-bit Secure HyperText Transfer Protocol (HTTPS).

Finally, the databases were created using Microsoft Access, which was decided to be sufficient in terms of the amount of data it can store. It has to be noted that, with regards to the 3-D functionality, the data that are saved are not pictorial, but mainly numerical/textual (location of pain—each body region had a unique text identifier, type of pain – each type had an Red Green Blue (RGB) numerical value, posture, selected mannequin body division, and time of day). As such, database sizes are kept relatively small [17] and can, therefore, be more efficiently used e.g. in uploading the information over the Internet.

All of the above were designed to run on PC machines with minimum requirements of an Intel processor, 2GB RAM and Windows Vista or later as the operating system. This study's evaluation was carried out on a Sony Vaio laptop computer consisting of an Intel Core 2 Duo Processor 2.10 GHz with Microsoft Windows 7 as the operating system, 4 GB RAM and a 250 GB hard disk. The display ability of the laptop consisted of a 15.4" Liquid Crystal Display (LCD) screen with a resolution of 1280 x 800 pixels.

7. Mode of availability of the system

The described 3-D system is not currently publicly available. Since the study presented in this paper is prototypical, the system is planned to be further evaluated, and if

necessary, refined through a number of future studies that would involve a wider range of pain-related conditions. As such, the system is in a continuing development process, currently integrating the findings revealed from the present study.

8. Concluding discussion

With the emergence of 3-D technology, clinical applications that integrate such 3-D functionality could have important benefits in the rehabilitation of people with some form of disability. Several studies [21, 23, 27] have already reported some clinical areas where 3-D visualization technology has efficiently been applied. In the anticipation that the advantages of 3-D technology could similarly benefit the visual quality of the tools currently in use to measure pain, in this paper we have described a system that provides people with SCI the ability to visualize their pain experience with the help of a digitized 3-D human model.

Our pilot findings from its evaluation with 15 patients suggest that the use of a 3-D system to support post SCI pain rehabilitation provides a significant improvement over most aspects of the conventional pain drawing currently in use. Considering that pain experience often varies between SCI patients, our results indicate that the 3-D application was significantly more efficient in capturing the type and exact location of pain, as compared to the 2-D pain drawing. Particularly encouraging were also the results with regards to the ease that patients experienced in learning to use and log pain information in the 3-D model, irrespective of age, diagnosis or pain intensity. This is a very important result considering that our system was evaluated against the already accepted and familiar conventional means of using paper and pen to carry out this activity.

Overall, our evaluation results demonstrate that the 3-D application is considerably

more sufficient than the 2-D pain drawing in more accurately reporting pain characteristics to the consulting clinical staff. This finding was also validated by a group of clinical staff members, who seemed to overly agree with the potential and advantages of the system to support pain assessment and their decision making about pain management. Nevertheless, it is essential that the clinical perspective will be explored further in a larger-scale study that would examine in more detail our system's potential in supporting quality pain management. This constitutes part of our future endeavors.

Accordingly, the small group of participants taking part in this pilot study also does not presently allow for a large-scale generalization of our results. Specifically, it was difficult to conduct a large-scale study with SCI patients due to their pain. Therefore, it is recognized that the perceptions of the present study's participants cannot be currently used to generalize the benefits of the 3-D application. However, given the limited existing research efforts in this particular area of healthcare, participants' reported perceptions may be considerable useful as they could offer a significant insight and could be used as an important point of reference for future efforts.

To this end, this study's findings could be viewed as a proof of concept towards the possibility of patients using the 3-D system in order to become better stakeholders in the management of their pain – firstly, by allowing to communicate their pain experience in a more perceivable way to the natural environment, and, secondly, by using this opportunity to better understand it and subsequently improve the quality of their life.

Author Contributions

All authors were actively involved in the conception and design of the study. Fotios Spyridonis carried out the study and performed the data collection, with the contribution of Jan Gawronski. Gheorghita Ghinea and Andrew O. Frank performed the data

analysis. All authors were involved in the interpretation of the data results, as well as in actively creating the present manuscript.

Acknowledgements

We are grateful to the patients and personnel from the Royal National Orthopaedic Hospital in London for their valuable assistance in this study. The authors would also like to acknowledge *Cyberware, Inc.* for providing a 3-D model, which was adapted and refined for the purposes of our work.

Conflicts of Interest Statement

There are no conflicts of interest in this paper.

References

- [1] M.Y. Wang, B. O'Shaughnessy, I. Haq and B.A. Green, Pain Following Spinal Cord Injury, *Seminars in Neurosurgery* 15 (2004) 99-105.
- [2] P.J. Siddall, R.P. Yeziarski and J.D. Loeser, Pain Following Spinal Cord Injury: Clinical Features, Prevalence, and Taxonomy, *IASP Newsletter* 3 (IASP Press, Seattle, 2000).
- [3] E.R. Felix, Y. Cruz-Almeida and E.G. Widerstrom-Noga, Chronic pain after spinal cord injury: What characteristics make some pains more disturbing than others? *Journal of Rehabilitation Research and Development* 44 (2007) 703-716.
- [4] D.D. Cardenas and E.R. Felix, Pain after spinal cord injury: a review of classification, treatment approaches, and treatment assessment, *Physical Medicine and Rehabilitation* 1 (2009) 1077-1090.
- [5] K.A. Curtis, K.E. Roach, A.E. Brooks, T. Amar, C.S. Benbow, T.D. Genecco and J. Gualano, Development of the Wheelchair User's Shoulder Pain Index (WUSPI), *Paraplegia* 33 (1995) 290-293.

- [6] M. Giner-Pascual, M. Canyis-Alberola, L. Millan, M. Guilar-Rodriguez and F. Querol, Shoulder pain in cases of spinal injury: influence of the position of the wheelchair seat, *International Journal of Rehabilitation Research* 34 (2011) 282-289.
- [7] M. Giner-Pascual, M. Canyis-Alberola, F. Querol, S. Salinas-Huertas, X. Garcia-Masso and L.M. Gonzalez, Transdermal nitroglycerine treatment of shoulder tendinopathies in patients with spinal cord injuries, *Spinal Cord*, 49 (2011) 1014-1019.
- [8] J. Gibson and A.O. Frank, Pain experienced by electric-powered chair users: a pilot exploration using pain drawings, *Physiotherapy research international: the journal for researchers and clinicians in physical therapy* 10 (2005) 110-115.
- [9] P.J. Siddall, J.M. McClelland, S.B. Rutkowski and M.J. Cousins, A longitudinal study of the prevalence and characteristics of pain in the first 5 years following spinal cord injury, *Pain* 103 (2003) 249-257.
- [10] M. Haefeli and A. Elfering, Pain assessment, *European Spine Journal* 15 (2006) 17-24.
- [11] S.J. Lee, Pain measurement: Understanding existing tools and their application in the emergency department, *Emergency Medicine* 13 (2001) 279-287.
- [12] D.D. Ohnmeiss, Repeatability of Pain Drawings in a Low Back Pain Population, *Spine* 25 (2000) 980-988.
- [13] A.O. Ransford, D. Cairns and V. Mooney, The Pain Drawing as an Aid to Psychologic Evaluation of Patients with Low-Back pain, *Spine* 1 (1976) 127-134.
- [14] A.F. Mannion, F. Balague, F. Pellise and C. Cedraschi, Pain measurement in patients with low back pain, *Nature Clinical Practice Rheumatology* 3 (2007) 610-618.
- [15] R.N. Jamison, G.J. Fanciullo and J.C. Baird, Usefulness of Pain Drawings in Identifying Real or Imagined Pain: Accuracy of Pain Professionals, Non-professionals, and a Decision Model, *The Journal of Pain* 5 (2004) 476-482.

- [16] V. Mooney, D. Cairns and J. Robertson, A system for evaluating and treating chronic back disability, *Western Journal of Medicine* 124 (1976) 370-376.
- [17] T. Serif and G. Ghinea, Recording of Time-Varying Back-Pain Data: A Wireless Solution, *IEEE Transactions on Information Technology in Biomedicine* 9 (2005) 447-458.
- [18] Bryce et al, Pain after spinal cord injury: An evidence- based review for clinical practice and research, *Journal of Spinal Cord Medicine* 30 (2007) 421-440.
- [19] M. Hickman, J.M.A. Swinburn and R. Senior, Wall thickening assessment with tissue harmonic echocardiography results in improved risk stratification for patients with non-ST-segment elevation acute chest pain, *European Journal of Echocardiography* 5 (2004) 142-148.
- [20] E. Lang, R. Naraghi, L. Tanrikulu, et al., Neurovascular relationship at the trigeminal root entry zone in persistent idiopathic facial pain: findings from MRI 3D visualization, *Journal of Neurology, Neurosurgery and Psychiatry* 76 (2005) 1506-1509.
- [21] B.S. Duerstock, C.L. Bajaj, V. Pascucci, D. Schikore, K.N. Lin and R.B. Borgens, Advances in three-dimensional reconstruction of the experimental spinal cord injury, *Computerized Medical Imaging and Graphics* 24 (2000) 389-406.
- [22] A. Mitulescu, S. Laporte, C. Boulay, J.A. De Guise and W. Scalli, 3D Reconstruction of the Pelvis Using the NSCP Technique, *Research into Spinal Deformities* 3, eds. A. Tanguy and B. Peuchot (IOS Press, Amsterdam, 2002).
- [23] W. Kakol, T. Lodygowski, M.B. Ogurkowska and M. Wierszycki, Are we able to support medical diagnosis or rehabilitation of human vertebra by numerical

- simulation? In Proceedings of the 15th International Conference on Computer Methods in Mechanics (Gliwice, Poland, June 3-6, 2003).
- [24] M. D'Amico, G. D'Amico and P. Roncoletta, A 3D parametric biomechanical skeleton model for posture and spine shape analysis, *Studies in Health Technology and Informatics* 88 (2002) 365-369.
- [25] C.Y. Greaves, M.S. Gadala and T.R. Oxland, A Three-dimensional Finite Element Model of the Cervical Spine with Spinal Cord: An Investigation of Three Injury Mechanisms, *Annals of Biomedical Engineering* 36 (2008) 396-405.
- [26] A. Ertürk, C.P. Mauch, F. Hellal, F. Förstner, T. Keck, K. Becker, N. Jährling, H. Steffens, M. Richter, M. Hübener, E. Kramer, F. Kirchhoff, H.U. Dodt and F. Bradke, Three-dimensional imaging of the unsectioned adult spinal cord to assess axon regeneration and glial responses after injury, *Nature Medicine* 18 (2012) 166-171.
- [27] A.O. Frank and L.H. De Souza, Conservative management of low back pain, *International Journal of Clinical Practice* 55 (2001) 21-23.
- [28] M.D. Tsai, Y.D. Yeh, M.S. Hsieh and C.H. Tsai, Automatic spinal disease diagnoses assisted by 3D unaligned transverse CT slices, *Computerized Medical Imaging and Graphics* 28 (2004) 307-319.
- [29] J. Brooke, SUS: a "quick and dirty" usability scale, In *Usability Evaluation in Industry*, eds. P. W. Jordan, B. Thomas, B.A. Weerdmeester and A. L. McClelland (Taylor and Francis, London, 1996).
- [30] G. Ghinea, F. Spyridonis, T. Serif and A.O. Frank, 3-D Pain Drawings-Mobile Data Collection Using a PDA, *IEEE Transactions on Information Technology in Biomedicine* 12(2008) 27-33.

- [31] P. Malliou, A. Gioftsidou, A. Beneka and G. Godolias, Measurements and evaluations in low back pain patients, *Scandinavian Journal of Medicine and Science in Sports* 16 (2005) 219-230.
- [32] Cyberware, Inc. 1999 (online) Available from: <http://www.cyberware.com/wb-vrml/index.html> Accessed: 20/05/2008.
- [33] Parallel Graphics, Ltd. 2011 (online) Available from: <http://www.parallelgraphics.com/products/sdk/> Accessed: 14/09/2008.
- [34] Parallel Graphics, Ltd. 2011 (online) Available from: <http://www.cortona3d.com/Try-Buy/Downloads.aspx> Accessed: 15/09/2008.