GAMEREHAB@HOME: a new engineering system using serious game and multi-sensor fusion for functional rehabilitation at home

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H. Tannous, D. Istrate, A. Perrochon, JC. Daviet, A. Benlarbi-Delai, J. Sarrazin, MC. Ho Ba Tho, TT. Dao

***Abstract*— Biomedical connected objects like kinematic sensors have been commonly used for patient monitoring in many clinical applications. Moreover, serious games have become widely used to improve patients' motivation during functional rehabilitation. In this work, we developed and evaluated a new engineering system as a solution for functional rehabilitation at home. A multi-sensor fusion between Kinect camera and inertial sensors was developed to animate a 3D avatar during rehabilitation and to estimate kinematic data of different joints for clinical monitoring. Two serious game scenarios were designed for upper and lower limb rehabilitation. The developed system was evaluated through patient kinematic data and a questionnaire-based approach with a panel of eight post-stroke patients and four clinical experts. The evaluation of the system showed that multi-sensor fusion provides useful data for clinical follow-up. The virtual game scenarios lead to a high level of immersion for patients. Feedbacks from clinical experts concerning the system's GUIs and the clinical relevance of the acquired data for each rehabilitation session are positive. The developed system paves the way to deploy recent technologies, such as multi-sensor fusion and serious games, as a solution for home-based rehabilitation, which can optimize the benefit of the involved patients and medical experts.**

***Index Terms*— Functional rehabilitation, Home-based rehabilitation, Multi-sensor fusion, Real-time biofeedback, Serious games, post-Stroke patient.**

I. INTRODUCTION

Home based rehabilitation has been studied as a complementary procedure that can benefit musculoskeletal patients between their clinical visits and treatments.

Currently, medical doctors prescribe daily physical exercises for their patients during an undergoing clinical rehabilitation program. Research findings have shown that performing appropriate exercises benefits the recovery of patients[1–4]. Moreover, home-based rehabilitation can help patients achieve an effective recovery and improve their quality of life [3, 4].

However, *Capan et al*. showed that performing home based exercises after temporomandibular joint condylar discopexy, without monitoring and coaching, yielded less significant improvements when compared to classical supervised rehabilitation programs [5]. On the other hand, *Hwang et al*. compared the differences between home-based exercise delivered twice a week via videoconference and traditional clinical rehabilitation session of the same length [6]. They showed that the clinical relevance of supervised home based rehabilitation is still similar to that of traditional rehabilitation programs. Similar results were observed by *Holmovist et al.* who reported no significant differences on the clinical relevance between supervised home based rehabilitation and traditional programs for stroke patients [7]. However, a follow up study, after 5 years of the same group, showed that the patients that were assigned home-based rehabilitation achieved better results when compared to those of the supervised rehabilitation group [8].

Thus, these studies show that home-based rehabilitation reaches at least a similar efficiency in terms of clinical relevance compared to traditional rehabilitation schemes. In particular, home-based rehabilitation showed good clinical relevance with long-term rehabilitation program. However, this concept faces some challenges related to the supervision capacities, patient motivation and quantitative indicators for monitoring and follow-up. Therefore, innovative engineering solutions should be investigated to promote home-based rehabilitation as a new clinical routine practice. In particular, a home-based rehabilitation solution needs a high level of patient motivation to be successful [9]. In addition, quantitative indicators of the effectiveness of rehabilitation need to be accurately provided, to assist clinicians in making their decision to assign rehabilitation programs. Furthermore, these systems should offer experts the ability to provide guidance and support to ensure that patients perform exercises properly and safely [10].

Serious games have established their ability to improve the patient's motivation during functional rehabilitation [11–16]. This new concept combines the motivational aspects of computer graphics and adds a primary objective in the scene. The primary objective can be either rehabilitation, military training, education and so on. In our case, this technology can also offer medical experts the ability to monitor the patient's recovery [17]. A study by *Burke et al*. on stroke survivors concluded that well suited serious games can be very engaging

H. Tannous, D. Istrate, MC. Ho Ba Tho, TT. Dao are with Sorbonne University, Université de technologie de Compiègne, CNRS, UMR 7338 Biomechanics and Bioengineering (BMBI), Centre de recherche Royallieu - CS 60 319 - 60 203 Compiègne cedex, France (tien-tuan.dao@utc.fr).

H. Tannous is with Lebanese American University, Beirut, Lebanon.

A. Benlarbi-Delai and J. Sarrazin are with Sorbonne University, Université Pierre et Marie Curie, L2E, Place Jussieu, Paris, France.

A. Perrochon and JC. Daviet are with HAVAE EA 6310, Université de Limoges, Limoges, France.

for patients [18]. Furthermore, many developed systems have shown positive impacts on patients [19].

Currently, a lot of critics of this technology point out that the developed games have to be personalized and conceptualized by health professionals and engineers together, in order for the games to be adapted in specific applications [20]. Recently, we developed a series of two serious games (football and object manipulation games) with the Kinect camera for functional rehabilitation of the upper and lower limbs [21–23]. Feedback from patients and clinicians were considered to create customized rehabilitation games. In addition, many commercial home based rehabilitation systems have immerged recently [24–26]. Jintronix have recently developed a new tool that uses serious games to provide home based rehabilitation for specific patients [24]. In addition, Medimoov proposes a system for home based rehabilitation at home using the Kinect camera, where the patient can use their hands, legs or body position to navigate through a sea that contains enemy ships [25].

Many researchers have also developed serious games for home-based rehabilitation. *Martins et al*. proposed a web platform for centralized management of games for physical therapy [27]. This web platform allows the medical team to manage the games and check the results, while researchers can continuously upgrade or deploy games to be used by patients. *Chatzitofis et al*. described their approach for home based rehabilitation using different databases and components [28]. They used a Kinect camera for kinematic tracking. They tested the designed games on six patients with cardiovascular disease. Some patients responded positively to the new gaming solution, while others were not interested.

Vasconcelos et al. developed several serious games using a smartphone, EMG sensors and IMUs [29]. The games use virtual objects like balls and walls, and requires the user to contract or extend their muscles, while moving their hands, to achieve different objectives. Their system uses a Kinect camera to assess the games. *Jonsdottir et al*. proposed a system called Rehab@Home, that uses the Kinect camera to implement arm and hand exercises for multiple sclerosis [30]. The system was validated through a randomized controlled pilot study, where 10 patients tested the games and 6 patients used games implemented by Nintendo on the Wii console. However, clinicians are not always included in the conception of the games [24–26, 28].

The answer to the question of what is missing and needed to make such complex technological solutions clinically relevant remains unclear, even though many have tried to tackle this subject in previous works [31, 32]. Recently, a real-time fusion algorithm between the Kinect camera and inertial sensors was developed in our previous study to improve the joint kinematics for functional rehabilitation [33]. This algorithm can increase the accuracy of an estimated joint angle, whenever the experts requires more accuracy to analyze the motion of a specific joint. The algorithm uses kinematic data collected from the Kinect and IMU sensors, and computes a fusion output based on an extended Kalman filter in order to increase the global precision.

However, this innovative technological solution is still not coupled with serious games. The objective of the present study was to develop and evaluate an integrative system, called GAMEREHAB@HOME, using serious games and multi-sensor fusion that can lead towards a functional rehabilitation solution at home. The developed system was evaluated by patients and experts to ensure user acceptability and in game immersion.

The remaining parts of the paper are organized as follows: Section II presents the architecture of the system and its components related to the serious games and multi-sensor fusion. System evaluation studies for patients and experts were also included in this section. Section III highlights the findings of our study. Section IV discusses these results and the proposed solutions, and compares the achieved system with systems in the academic and commercial literature. Finally, Section V concludes the study.

II. Materials and Methods

A. System architecture

GAMEREHAB@HOME is a multiuser platform that includes separate user interfaces for medical experts, patients and family members (figure 1). An intermediate cloud server is implemented between these separate users, in order to visualize any update in real-time. First, the expert sets up rehabilitation programs for their patient, choosing from a database of games. At home, the patient can play the game(s) at any time. During each rehabilitation session, data describing the patient's motion is collected using inertial (Shimmer 3 sensors at 51.2 Hz) and visual sensors. Finally, the family members of the patient and the medical experts can check different kinds of results, using their user interfaces. This system also allows the users to communicate with medical staff using messages and notifications. Two main technological components were integrated into this system. The first component allows experts to customize the serious games used during rehabilitation exercises, while the second component fuses readings from multiple sensors in real time to animate a 3D patient avatar during rehabilitation, based on collected kinematic data from elbow and knee joints. The same data can be later used for expert clinical monitoring.

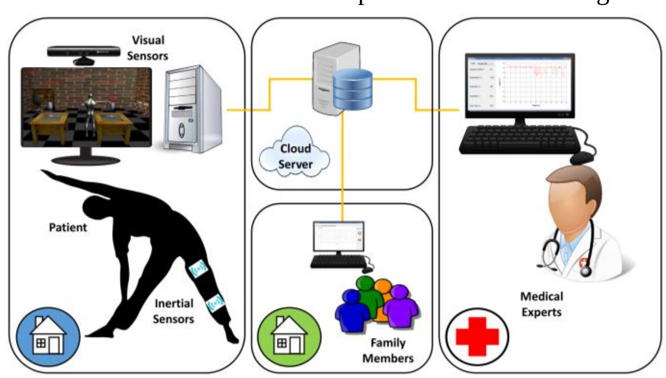

Fig. 1. Architecture of GAMEREHAB@HOME system.

B. Serious games for functional rehabilitation of upper and lower limbs

Two customized serious games were developed for upper and lower limb rehabilitation. The first game is a football scene presented in figure 2A. In this scene, the patient needs to rotate their body to change the crosshair's position and target the cones. Then, the patient needs to verify that the triangle, at the bottom right part of the screen, is above the green square, before hitting the ball. If the ball hits the cone, the patient gets a point and they need to repeat the same movement again. Three angles are of interest in this scene: the knee flexion (α_1), the hip abduction (β_1) and the hip flexion (δ_1). These angles are tracked and saved for clinical analysis.

The second scene is an object manipulation game, shown in figure 2B. In this scene, the objective is to move the flower from vase A to vase B. The patient needs to pick up the flower from the vase, switch hands and put the flower down in the other vase. Three angles are of interest in this scene: the elbow flexion (α_2), the shoulder abduction (β_2) and the shoulder flexion (δ_2). These angles are also tracked and saved for clinical exploitation. These game scenarios were conceptualized through a co-design approach with clinicians. The scenarios allow patients to practice lower and upper limb movements with basic kinematic patterns such as knee flexion or shoulder flexion, which are commonly performed in current clinical routine practices. During the game co-design process [21], patients and clinicians participated in the design of game scenarios and user interfaces. After implementing the games, the same users performed the evaluation of the gameplay and user interfaces. Then, their feedbacks were used to improve the system and adapt it to the needs of the users.

Note that these angles are computed using the Kinect quaternion estimation algorithm to avoid errors that can occur from using Euler angles.

The algorithm computes the relative quaternion between two vectors representing the rotation of each child limb with respect to its parent (e.g. the forearm is the child of the arm, the elbow angles are the result of the algorithm's estimation). The quaternion result can be obtained using the following formulas:

$$Q_x, Q_y, Q_z = Cross(\vec{u}, \vec{v}) \quad (1)$$

$$Q_w = \|\vec{u}\| * \|\vec{v}\| + Dot(\vec{u}, \vec{v}) \quad (2)$$

where Q is the 4 dimensional quaternion $Q = (Q_x, Q_y, Q_z, Q_w)$, $\vec{u}$ and $\vec{v}$ are the parent and child unitary vectors.

C. *Multi-sensor fusion*

A network of inertial sensors, placed on different body segments, and a Kinect camera were used in the integrative system (figure 3A). The real time Kalman-based multi-sensor fusion algorithm presented in [33] was used to increase the accuracy of the joint kinematics. Note that the results from the angle computing algorithm presented in the equations (1) and (2) are fused with quaternions estimated using inertial sensors when using our fusion algorithm [33]. The fusion algorithm uses the extended Kalman filter between the different sensors, and updates the covariance matrices of measurement noise for both Kinect and inertial sensors, based on the estimated joint angles. A synchronization process was also established and the frame rate was set up at 30 frames per seconds [33].

Moreover, a system of systems approach was adopted to deploy this solution for our serious games. When Kinect and inertial sensors are both available, data fusion is performed on the data sent separately from each sensor. If the Kinect is only available, the data sent from it will be directly used by the application. The main idea of the proposed solution is to offer the opportunity to select specific joints (e.g. knee joint for lower limb rehabilitation exercises) that require more precision, in a configuration panel. Based on literature works, the required precision level to analyze the movement of the upper extremities is 6° [34] and 5.5° for the lower extremities [35]. The medical staff is responsible for this selection process. Note that the system does not require any calibration for the sensor prior to the session, and that the position of the sensor has been optimized in a previous study [33].

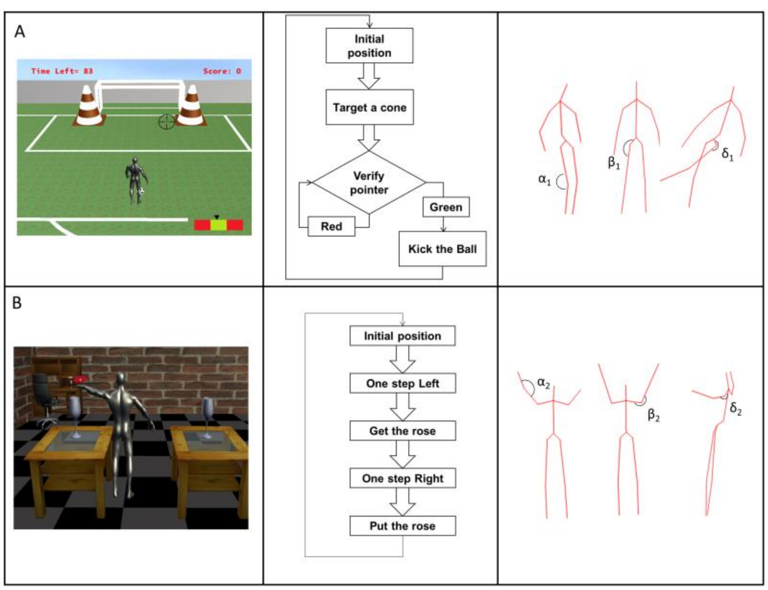

Fig. 2. A: Football game scene, scenario and angles of interest: knee flexion (α1), hip abduction (β1) and hip flexion (δ1); B: Object Manipulation game scene, scenario and angles of interest: elbow flexion (α2), shoulder abduction (β2) and shoulder flexion (δ2).

Fig. 3. A: Participant game playing with mounted inertial sensors for the elbow joint; B: GUIs for patients; C: GUIs for experts.

D. *Graphical user interfaces*

Two separate graphical interfaces for patients and experts were developed and shown in figures 3B and 3C respectively. First, the patient interface allows them to choose between the rehabilitation programs assigned by different medical experts, they can select to play a game from the selected program, and they can personalize the game by choosing an avatar from 3 available options.

The patients can also select to place sensors on their body, based on the expert's recommendation, to benefit from the sensor fusion during the session. At the end of each session, the patient can leave a comment about their performance for their expert. Finally, the patient can send messages to their supervising experts. During each trial, the patient can see feedback about specific joint behaviors and game score in real time.

The expert's interface allows the user to add a new patient profile and a rehabilitation program. They can also assign programs and/or send messages to their patients.

After that, each rehabilitation program is established by the clinician for a specific patient using his pathological state and available serious games. When the patient finished playing an assigned game scenario, related information about joint behavior and recorded motion video were stored for further analysis by the clinicians. Then, for each exercise performed from the assigned rehabilitation program, the expert can visualize statistics about the different performed trials. They can also view the achieved trials in more details, by using separate interfaces. The first one shows the angle evolution behavior for the selected joints, and the second shows the movement of the patient's joints, in three different planes (3D), as a stick avatar.

The interfaces were developed using Visual C# as programming language. A relational database was developed using MySQL. The 3D avatar model was designed and implemented using Blender software.

E. *First system evaluation*

The developed system was evaluated by both patients and clinicians to ensure the user-dependent acceptability. The evaluation was performed at the "Centre Hospitalier Universitaire de Limoges" (France) under supervision of experienced clinicians. A panel of eight stroke patients (2 females and 6 males, 66.37±7.03 years old) and four physical therapists (female, 42±11.76 years old) participated in this evaluation campaign. Subjects were chosen according to the following inclusion criteria: the absence of a musculoskeletal condition that could potentially affect the ability to balance safely; the absence of serious visual impairment or a hearing disorder. The exclusion criteria were as follows: severe dementia or aphasia; unable to follow instructions; unable to stand alone. Each participant signed an informed consent agreement before participating in the evaluation process.

1) *System evaluation by patients*

The two tested scenarios of developed serious game, using multi-sensor fusion, were evaluated with 8 post-stroke patients.

Each scenario was tested twice, with and without the use of inertial sensors attached on particular body parts. For the football game, the patient used the Kinect camera alone to play this game, then, two inertial sensors were attached on the patient's thigh and shank, to measure the knee angle with our fusion algorithm. Note that the sensors are always attached on the affected areas of the patient (either right or left knee). Regarding the object manipulation game, during each of the patients' second trial, two inertial sensors are attached on their arm and forearm, to measure the elbow angle with our fusion algorithm. Note that the data was synchronized at the first point before a joint movement (e.g. knee flexion), for a duration of 3 seconds.

At the end of the session, each participant evaluates the games using three questionnaires. Two of the questionnaires were already used in our previous study [21], with two added questions concerning the comfort/discomfort of mounting sensors on the patient's limbs (i.e. effect of sensors on the game and on the body). Moreover, one question, concerning the variation in the levels of difficulty of each scenario was removed from these two questionnaires, since we did not test different levels of difficulty for each game. Note that these two questionnaires evaluate the game interface and the level of comfort of the patients during the trials. They were conceptualized by our team composed of engineers, clinical experts and social scientists to include the major aspects related to the evaluation of a serious game for functional rehabilitation.

The third questionnaire does not focus on the different games in particular, but on the level of immersion of the patients in these games. The chosen questionnaire, referred to as the "Immersive Experience Questionnaire (IEQ)", comes from a well cited study conducted by Jennett et al. where they measured the level of immersion of people in virtual games, using 5 criteria: challenge, control, real world dissociation, emotional involvement and cognitive involvement [36].

Thus, different steps and their time duration of the testing protocol are summarized here: 1) Place the inertial sensors on the patient's desired area. (2mins); 2) Explain the game instructions to the patient. (3mins); 3) The patient plays the Football game. (2mins); 4) The patient plays the Football game with the fusion algorithm. (2mins); 5) The patient evaluates the game using our questionnaire. (3mins); 6) Repeat steps 1 to 5 for the Object Manipulation game. (12mins); and 7) The patient evaluates their level of immersion using the questionnaire. (5mins). Note that the patients were asked to play with and without the use of the sensor fusion algorithm to identify whether they feel any difference in gameplay performance between the two setups. Therefore, a question was added at the end of each test inquiring about this particular aspect.

Finally, the total time of one rehabilitation session is around 30 minutes. During the tests, two experienced clinicians supervised the patients to ensure the safety of the patients. They also gave suggestions and comments about the tested games. Patients were also asked to choose their favorite game.

2) *System evaluation by experts*

First, the system's objective and the different graphical user interfaces were explained to participating experts. Then, each evaluation was performed individually. The testing protocol of the developed system was established with the following tasks: 1) Add a rehabilitation program; 2) Add a patient; 3) Assign a rehabilitation program to a patient; 4) Send a message to the patient; 5) Examine the patient's results (statistical results, angular results and joint position results); and 6) Evaluate the interface using a questionnaire. The selected questionnaire, referred to as the "IBM Computer Usability Satisfaction Questionnaire", to evaluate our interface is a well cited computer usability evaluation questionnaire, developed by IBM [37]. This evaluation gives indications about 4 different factors: Overall Satisfaction Score, System usefulness, Information Quality and Interface Quality. Moreover, at the end of the test, experts where asked to leave a comment about the interface in general and their interest in using it.

III. Results

A. *System evaluation outcomes by patients*

Each patient tested both games two times. During the first trial, only Kinect camera was used to estimate joint angles. Inertial sensors were added in the second trial to estimate the joint angle of one particular joint (i.e. knee angle for the football game, and elbow angle for the object manipulation game).

Figure 4 shows the estimated angles during the two different trials using the Kinect camera alone and multi-sensor fusion solution. Note that the angles estimated by the Kinect camera were subject to errors caused by object superposition and low accuracy. This could lead to some abnormal joint data behavior. On the other hand, the data estimated using the fusion algorithm is more accurate and the movement pattern can be clearly tracked and examined. Note that this higher level of accuracy when compared the Kinect camera to the sensor fusion was already described in a quantitative manner in our previous study [33].

Moreover, a statistical test (*t*-test, implemented in Matlab R2010b software [*The MathWorks Inc*.]) was performed to verify if both trials (with and without using sensor fusion solution) show significant differences in players' in-game performance (score) or not. The results confirmed that there is no difference between trial scores with and without using sensors for both rehabilitation games (P=0.581 for the football game and 0.738 for the object manipulation game). This suggested that the choice of using Kinect camera alone or the sensor fusion solution when playing the designed games does not affect the player's in-game performance.

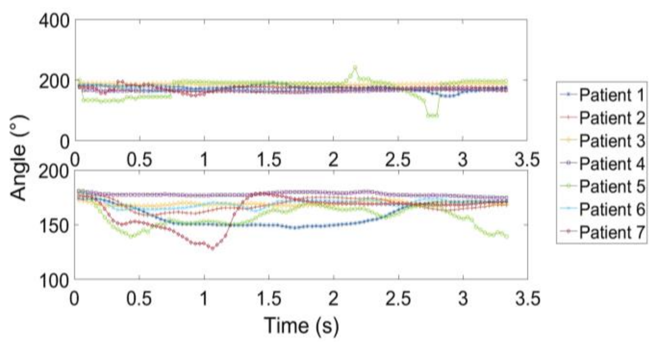

Fig. 4. Knee flexion angle estimated during the patients' first trial with football game using the Kinect camera (top), and during the second trial using the multi-sensor fusion algorithm (bottom). Note that the data was synchronized at the first point before a joint movement (e.g. knee flexion), for a duration of 3 seconds.

After completing the trials, each patient evaluated the serious games (game design, exercises, and participant perception). The answers are depicted in Table 1. The results show that most of the patients gave the highest ranks for both games (56 for football and 70 for object manipulation). The second most given rank for both games was 3 (22 for football and 11 for object manipulation). Note that 11% (11 out of 98 answers) of the participants require a significant improvement (rank 1) of the proposed solution. The main problems are the games' level of difficulties and challenges that vary between patients based on their situation, as well as the mistake permission where patients felt like they were rewarded for bad movements. Note

Table 1. Patients' Responses to the Object Manipulation (O) and Football (F) Game Questionnaires.

Criteria	Rank									
	O					F				
	1	2	3	4	5	1	2	3	4	5
Game: Objective/goal Unclear (1) → Clear (5)					7				2	5
Game: Level of difficulty Low (1) → High (5)	3		1	1	2	2		3		2
Game: Ignorance of achievement Unawareness (1) → Awareness (5)				1	6				1	6
Game: Environment Unattractive (1) → Attractive (5)				1	6			1	1	5
Game: User Interface Not user-friendly (1) → User-friendly (5)			2	1	4	3			1	3
Game: Beginning and end Unclear (1) → Clear (5)					7	1				6
Exercises: Instructions Unclear (1) → Clear (5)					7					7
Exercises: Suitable for game goal Low (1) → High (5)					7	1		2		4
Exercises: Feedback Unclear (1) → Clear (5)					7	1		1		5
Exercises: Effect of sensors on the game Deterioration(1) → Improvement (5)			5	1	1			7		
Participant: Effect of sensors on the body Uncomfortable (1) → Comfortable (5)					7				1	6
Participant: Challenge Low (1) → High (5)	3		1	1	2	2	1	2	1	1
Participant: Mistake Permission Impossible (1) → Possible (5)	5		2			1		6		
Participant: Security feeling Uncomfortable (1) → Comfortable (5)					7				1	6
Total	**11**	**0**	**11**	**6**	**70**	**11**	**1**	**22**	**8**	**56**

that Table 1 contains 7 answers for the football questionnaire and 7 for the object manipulation questionnaire. This is due to the fact that two different patients could not perform one of the two games based on the expert's recommendation.

As for the evaluation of the immersion level of the participant in the serious games, the responses of the patients gave ideas about six different parameters shown in figure 5. The total immersion had a median value of 0.796, maximum and minimum values of 0.935 and 0.632 respectively. First and third quartile values of 0.677 and 0.858 were noted. All of the different parameters had above average medians.

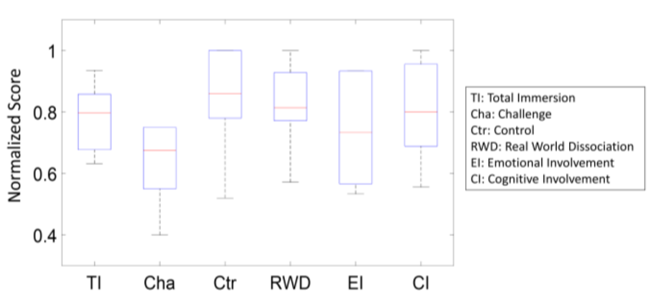

Fig. 5. Patients' responses to the immersion questionnaire.

B. *System evaluation outcomes by experts*

The results of the expert interface evaluation are shown in the figure 6. The questionnaire gave indications about four different aspects (Overall Satisfaction Score, System usefulness, Information Quality and Interface Quality) of the interface. The answers of the experts yielded above average medians. The overall satisfaction score of our interface had a median value of 0.778, maximum and minimum values of 0.849 and 0.676 respectively. The first and third quartile values of 0.721 and 0.819.

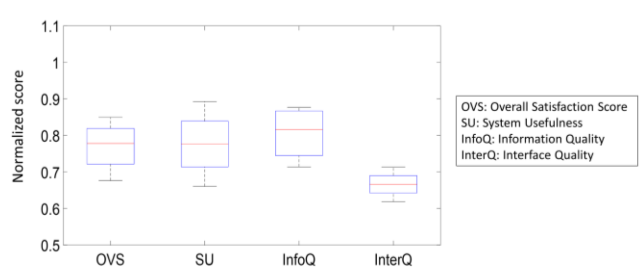

Fig. 6. Experts' responses to the interface evaluation questionnaire.

At the end of the questionnaire-based evaluation, general comments from experts were acquired for the improvement of the proposed system. 1) First recommendation relates to the design of an affordable interface (i.e. which can be deployed at home), simpler, easier to use and more fun for patients. 2) Other point deals with the adaptation of the developed interfaces for professionals with visual difficulties.

IV. Discussion

Home-based rehabilitation has many technological requirements and faces new clinical challenges when compared to traditional clinical routine practices. Novel engineering solutions need to be investigated to develop user-friendly, easy-to-install, and useful systems with motivational physical exercises. Moreover, low cost devices have to be used to bring the system into a home-based setup. However, accurate data have to be acquired and provided for clinical monitoring and follow-up purposes.

The main contribution of the present work relates to the application of a multi-sensor fusion, to achieve a high accuracy in joint angle estimation, coupled with serious game technology for functional rehabilitation. Moreover, the game scenario and graphical user interfaces of our proposed gaming system were evaluated in clinical environment by patients and clinicians to propose a suitable engineering solution for new functional rehabilitation practice.

To the best knowledge of the authors, this system is the first one providing a high level of accurate kinematics data (kinematic error is less than 5° [33]) for functional rehabilitation while keeping the low cost for the proposed solution. In fact, only one Kinect camera (around 200 €) and two inertial sensors to use on any joint (700 €) are needed for the system installation. A personal computer (costs around 500 €) is also required. Thus, the whole system now costs approximately 1400 € showing that a home-based setting is reasonably possible. Note that the use of inertial sensor is optional and this could be avoided for specific setup conditions like a home-based setup where accuracy can be compromised with portability and cost issues. Thus, the platform’s price would decrease to 500-700 euros. Moreover, the inertial sensors need to be calibrated only once before using them at home.

Finally, the questions concerning the use of sensors in the games showed that the patients did not feel that the sensors affected their in game performance, and that they felt comfortable while wearing them. This is in accordance with our objective, since we know that the increased accuracy, which the sensors can add to the game, will not necessarily be felt by the patients (not visually significant in the virtual environment). However, the sensor fusion solution will allow more accurate data to be acquired for clinical purpose. In particular, accurate joint angle estimation is of great importance for clinicians, when analyzing the exercise outcomes or validating one specific rehabilitation step during the functional rehabilitation program.

When it comes to patient immersion, we note that patients were well immersed in the games (median immersion normalized score 0.796 and mean normalized score 0.779). The challenge exhibited by the patients had the lowest median score of 0.675, which is in accordance with the finding of our questionnaire, since the games difficulty varied based on the patients’ situations. The study also shows that the patients were emotionally and cognitively involved in the game, but still felt in control. To give more significant context for these values, we compared our results to those obtained by other studies for different kinds of games. Note that the total immersion score was the only parameter comparable between the studies, since most of these studies used a different and preliminary definition by *Jennett et al* [36] in 2008 to calculate the different factors. Therefore, only total immersion value was used to compare our findings with previous studies. However, all estimated parameters were reported for future comparisons with our current findings.

Fierro et al. created a serious game for knee rehabilitation that uses the Kinect camera to move the player on a flying platform, and where the player needs to jump and clap to reload a gun and shoot the boss [38]. The study compared patient immersion for the same game, with and without using music in the scene. They found that adding music increased the mean normalized immersion score from 0.658 to 0.74. These scores are lower than the ones that we obtained without using music, which could mean that we might be able to enhance the immersion of patients if we added music to our scenes. A study by *Iacovides et al.* compared between two versions of the same commercial game (Battelfield 3), with and without giving real-time instruction to the players [39]. The results showed that, depending on the player’s experience, the mean level of immersion varied between 0.767 and 0.863, which seems to be in the same magnitude of the results that we obtained. This means that our patients are as immersed in these serious games, as players are normally immersed in commercial games.

Clinical experts who evaluated our interface were globally satisfied (median normalized overall satisfaction score of 0.778). The experts also felt that the data we present is more than enough to assess the situation of the patient with a median normalized Information quality score of 0.816. However, the interface quality score was lower than the others, but remains higher than average. This means that we need to increase the attractiveness of the interface, and take into consideration the different users (medical expert comment #2). Finally, we compared these results with studies that evaluated medial interfaces. *Kao et al*. developed a user interface to monitor patients’ blood sugar and blood levels [40]. Medical experts evaluated the interface using the same questionnaire that we used. Our system had better usefulness and information quality scores, while theirs had the better interface quality. *Ling et al*. designed serious games for patients who underwent hip replacement surgery [41]. They also developed and evaluated a monitoring interface for experts using the questionnaire designed in [42]. Our interface proved to be more useful based on the usefulness criteria of the expert evaluation questionnaire. Moreover, comments on the games from the physiotherapists suggest that their games were too difficult for patients.

Table 2. Comparison with existing home-based systems.

System	GAMEREHAB @HOME	Medimoov [25]	Chatzitofis et al. [28]	Jintronix [24]	SeeMe [26]	Rehab@Home [30]	Vasconcelos et al. [29]
Development methodology	Co-design, co-conception	Discussion with medical experts	Not specified	Not specified	Not specified	Not specified	Conceptualized by developers
Kinematic devices	Kinect alone and/or multisensory fusion	Kinect	Kinect and/or inertial sensors	Kinect	Kinect	Kinect	Cell phone and EMG sensors
Kinematics accuracy	14° with Kinect and 3.5° with multisensory fusion	Not specified	Not specified	Not specified	Not specified	Not specified	Not specified
Types of serious games	• Football • Object manipulation • Simple task exergames	• Hammer and plank	• Exergames (jumping, running)	• Moving the ball on a ledge • Skiing • Hit the ball • Move the fish	• Clean the Window • Hit the ball • Catch the objects	• Touch the flours and avoid the bees • Move the basket on the Table • Move object in correct trajectory • Put objects on kitchen shelf	• Gates game • Bridges game • Escape the labyrinth game
Bodies of interest	Upper and lower limbs	Upper limbs	Upper and lower limbs	Upper and lower limbs	Upper and lower limbs	Upper limbs	Upper limbs
Type of rehabilitation	Functional and cognitive	Functional	Cardiovascular	Functional	Functional	Functional	Functional
Real-time feedbacks	Virtual avatar movement (joint positions and angles in 3D)	Upper body joint movement speed and angles	Virtual avatar movement (joint positions and angles in 3D)	Virtual avatar movement (joint positions and angles in 3D)	Patient movement on screen	Hand position	Hand position and EMG activity
Exercise personalization	Defined by expert	Dynamic difficulty during gameplay	Not specified	Defined by expert	Defined by expert	Not specified	Not specified
Software architecture	Standalone and cloud-based applications	Standalone application	Cloud-based application	Standalone and cloud-based applications	Standalone and cloud-based applications	Standalone application	Standalone application
System evaluation	User (patient and expert) acceptability based on questionnaires	Not specified	Not specified	Not specified	Not specified	Single-blind randomized controlled trial	Not specified
Exercise evaluation	Short-term usefulness and applicability	Not specified	Not specified	Not specified	Not specified	Long term usefulness	Not specified
Approximate cost	500-700 euros (without inertial sensors)	80 euros/ month (excluding material and licensing)	Not specified	Not specified	Not specified	Not specified	Not specified

Finally, although our system presents potential advantages for a home-based rehabilitation solution, some limitations are unavoidable. Table 2 compares our system with the currently available home-based systems to identify the enhancements that we achieved, and the limitations that need to be investigated in future works. We clearly see that there is no unified development and evaluation methodology when it comes to creating these solutions, especially for a home-based rehabilitation system. Thus, our system seems to be the only one that includes a wide variety of multidisciplinary experts involved in the conceptualization and the evaluation.

The commercial tools seem to disregard the evaluation phase, necessary to prove the clinical relevance of these rehabilitation tools. In addition, while most systems offer session report capacity for medical experts, all of the available systems do not describe the level of accuracy that their sensors offer. In particular, there are few studies performing the evaluation for the developed system. Thus further evaluations should be conducted before delivering a home-based rehabilitation solution.

In future works, data privacy problems should be investigated to avoid ethical issues within the context of a home-based rehabilitation system. In addition, long-term studies with a larger panel of patients and experts need to be conducted to confirm the clinical relevance related to patient movement improvement as well as to the reduction of medical human resources and clinical management cost. Finally, this study was conducted in a clinical environment with a limited number of patients and clinicians. Thus, this does not take into account the difficulties of playing the games at home, for example the difficulty of setting up the inertial sensors for severe stroke patients. Consequently, a home-based deployment study of the proposed system needs to be investigated in the future with a larger patient cohort, to confirm the usability, clinical relevance and possible cost benefit of implementing such a system at home. Moreover, the levels of difficulty and related game challenge will be investigated, as predefined levels cannot be used to fit large cohorts with different situations and background. In particular, our future efforts will concentrate on personalizing the games using patient data (e.g. personalized angle thresholds, time of session).

In addition to these limitations, as Microsoft has recently discontinued the manufacturing of the Kinect technology due to some problems like privacy issue (body, face, behavior tracking) or low accuracy with noisy environment for public applications like traditional games. In our present system, this technology allows us to track the human body for functional rehabilitation with dedicated Kinect camera and associated API. We still think that this technology has its place in the functional rehabilitation therapy. To deal with this issue, in the present study, we designed our serious gaming system using a system of systems approach. This allows us to add any new sensor and to remove any obsolete one in order to update the platform, without the need to change our system architecture immensely. However, more data processing efforts need to be performed to replace the available body recognition and tracking capacities of the Kinect camera technology in the future version of our system.

V. Conclusions and Perspectives

In this work, we presented GAMEREHAB@HOME system as a new engineering tool using serious game technology for functional rehabilitation at home. The system was evaluated by a reduced panel of stroke patients and clinical experts using different questionnaires and quantitative methods. The outcomes showed that this system could be implemented in a home-based setting in the future for the benefit of the patients and experts. It is important to note that, before using our system in a home-base setup, a trial period needs to be performed in controlled clinical environment with clinicians. Thus, movement patterns and patient security are ensured by the clinicians to make a decision for a home-base setup. New monitoring capacities related to these issues are currently studied to improve our proposed system.

Moreover, we will investigate the possibility to correct patients' movements in real-time, and estimate the muscle forces to provide new indicators to optimize the rehabilitation program [43]. In addition, the graphical aspects of the games will be improved with a specialized team of graphic designers and game programmers aiming towards a user-friendly gaming system.

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