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Interactive and Connected Rehabilitation Systems for E-Health

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Abstract

Functional rehabilitation aims at recovering the locomotion dysfunction of the human body by the physical therapy. The objective of this paper was to develop interactive and connected rehabilitation systems as a system of systems for monitoring the bio-feedbacks of the human musculoskeletal system during the rehabilitation exercises. Video-based non-contact system as Kinect sensor was used to get kinematics data of the human body. Generic and subject-specific avatar representations were integrated. Rehabilitation exercises will be designed as serious games to motivate the end users. Our first prototype was focused on the rehabilitation exercises of the lower limb. Software development and experimental aspects of our proposed solution were presented and discussed. Our system would be of great interest in the supervision of physical therapy exercises in clinical as well as in non-clinical environments (e.g. rehabilitation at home). As perspectives, multi-sensor fusion between Kinect sensor and other kinematics-based sensors like Shimmer ones will be investigated to get an accurate 3D joint motion. Electromyography (EMG) signals will be also used to monitor the muscle functions. Moreover, specific device will also be developed to facilitate the sensors set up and motion monitoring.

Keywords: Functional rehabilitation; Bio-feedback signals; System of systems; Multi-sensor fusion; Serious game; Musculoskeletal system; Real-time monitoring; Rehabilitation at home

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1. Introduction

Functional rehabilitation aims at recovering the locomotion dysfunction of the human body by physical therapy exercises [1,2]. This involves performing controlled physical and occupational therapy interventions with or without assistance of physiotherapist to improve musculoskeletal strength and flexibility as well as range of motion. Functional rehabilitation is commonly realized in clinical environment under the supervision of physiotherapists [3]. However, the supervision and the evaluation of a rehabilitation motion pattern remain a medical and engineering challenge due to the lack of feedback information about the effect of the rehabilitation motion on the human biological tissues and structures. Recently, rehabilitation systems using immersive virtual reality technologies have been developed to provide useful reinforced feedbacks (e.g. functional measurements) during rehabilitation exercises such as motion velocity (speed), duration of motion pattern (time), ergonometric measurement, video data or joint patterns [4,5]. These quantitative feedbacks may be used to identify the musculoskeletal impairments and assess the quality of the rehabilitation motion as well as to assist the patient or the physiotherapist to correct the motion patterns. Virtual simplified avatar has been usually created to represent the patient body [4]. However, these systems provided only external information (e.g. kinematics) of the musculoskeletal system during rehabilitation motion. In fact, the acquisition of internal information inside the musculoskeletal system is still a challenging problem for such useful rehabilitation systems.

Kinematics of the musculoskeletal system is commonly acquired using traditional motion capture systems (e.g. VICON) or video-based systems like KINECT sensor [6–10]. The use of video-based system has the advantage of low cost and portable

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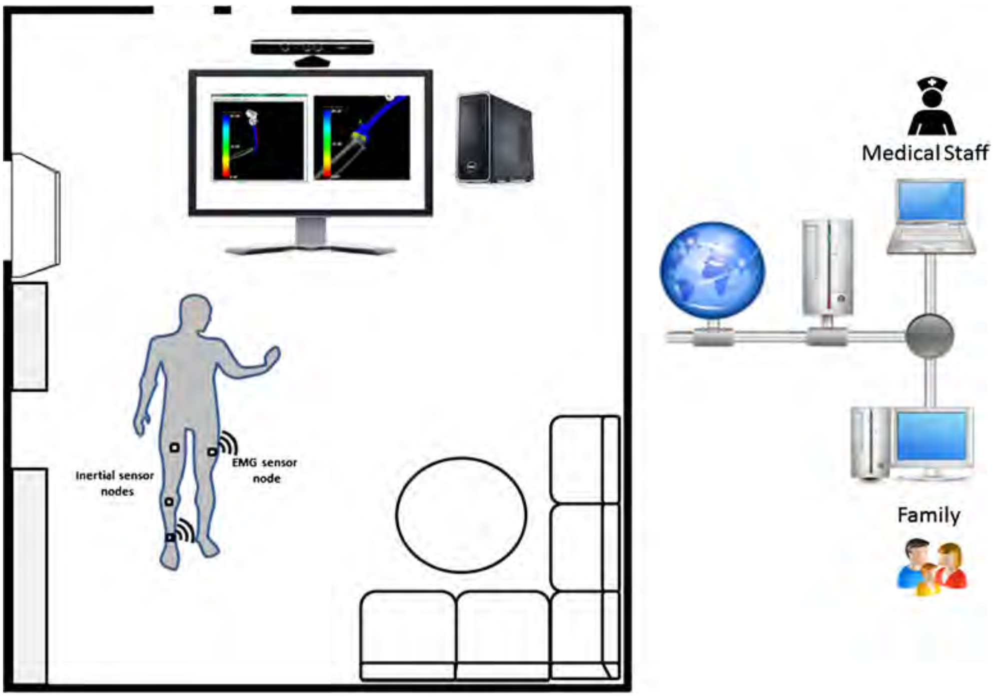

Fig. 1. Schematic illustration of an in-house rehabilitation scenario.

capacities. However, this provides only accurate planar kinematics for slow motion [10]. Moreover, serious game has been intensively developed to improve the user motivation during rehabilitation exercises [11,12]. Some commercial applications were also proposed like REHABILITATION FOR LOWER LIMB[1] or SEE ME[2] or JINTRONIX.[3]

Conventional/traditional rehabilitation provides a wide variety of therapy exercises with complex functional rehabilitation motions (e.g. extension/flexion, axial rotations, bending or a combination of these elementary motions). However, this deals with the limited time and non-controlled nature of the rehabilitation training for a patient due to high medical treatment cost and human resources (e.g. experimented clinicians and therapists) as well as the lack of objective and visual feedback of the rehabilitation effect. It is well known that the intensive and well-controlled use of rehabilitation program/training leads to significant improvement of musculoskeletal dysfunctions. Thus, a rehabilitation system providing an immersive virtual reality environment in which visual and quantitative feedback about the effect of rehabilitation motion on the musculoskeletal tissues and structures could be of great clinical interest. In particular, this assistive technology could be a valuable assistant to the patient to perform more precisely and accurately the exercises/motions of interest. Moreover, the system could allow the patient to perform his rehabilitation exercises at home in an intensive manner leading to motivate the practice and maximize the benefit of the rehabilitation program (Fig. 1).

The objective of this work was to develop interactive and connected rehabilitation systems as a system of systems for monitoring the bio-feedback signals of the musculoskeletal system during rehabilitation exercises in clinical as well as in non-clinical environment (e.g. home-based rehabilitation). Our proposed system of systems needs to satisfy the following challenges: 1) accurate joint kinematics by using the multi-sensor data fusion; 2) user motivation enhance using serious game technologies; 3) biomechanical modeling to provide useful bio-feedback signals; 4) innovative engineering design to facilitate the system set up; 5) system architecture development to integrate heterogeneous systems.

2. Material and methods

The flow chart of the proposed interactive and connected rehabilitation systems is shown in Fig. 2. It consists of a data acquisition and management system, a musculoskeletal simulator system and a graphical user interface (GUI) system.

2.1. Data acquisition and management system

A Kinect camera was used to acquire the kinematic data of the musculoskeletal system in real-time conditions. This marker-less motion capture system has a RGB (red, green, and blue) camera and a pair of depth sensors including an infrared laser projector and a monochrome CMOS (complementary metal–oxide–semiconductor) sensor. The Kinect system may capture the 3D geometrical data and 2D planar kinematics in ambient light conditions. The non-commercial Kinect software development kit (SDK) v1.7.0 for Windows and Visual C# (Microsoft®, USA) were used as programming languages to access into Kinect capabilities (e.g. raw sensor streams, skele-

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[1] http://applications.3d4medical.com/rehabilitation_lowerlimbs.
[2] http://www.virtual-realityrehabilitation.com/products/seeme.
[3] http://www.jintronix.com/.

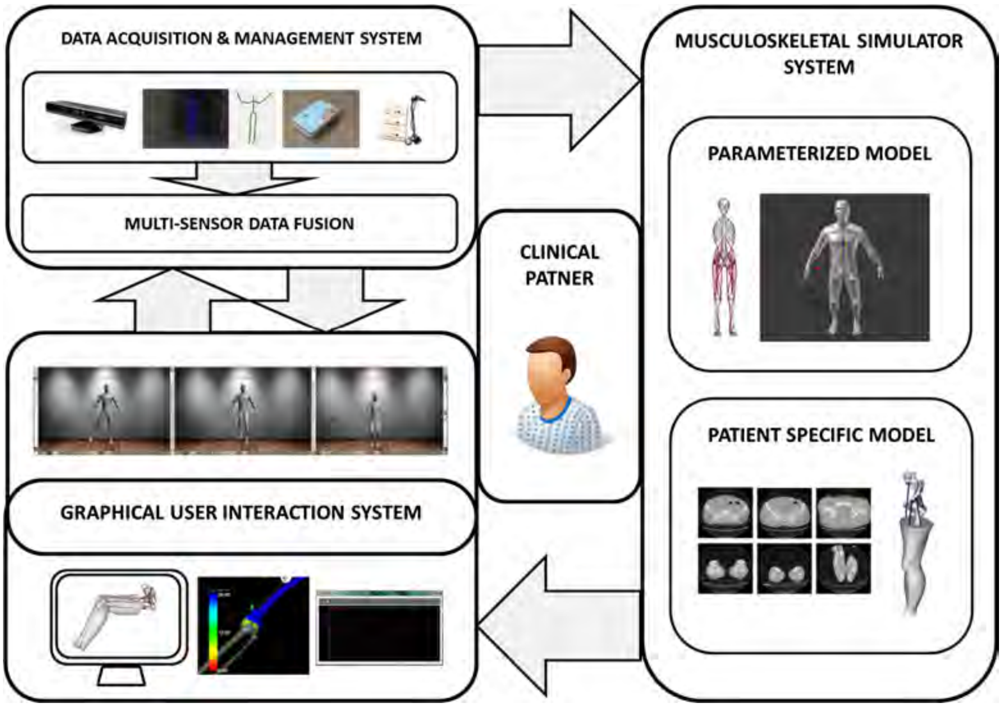

Fig. 2. Flow chart of current software architecture of interactive and connected rehabilitation systems.

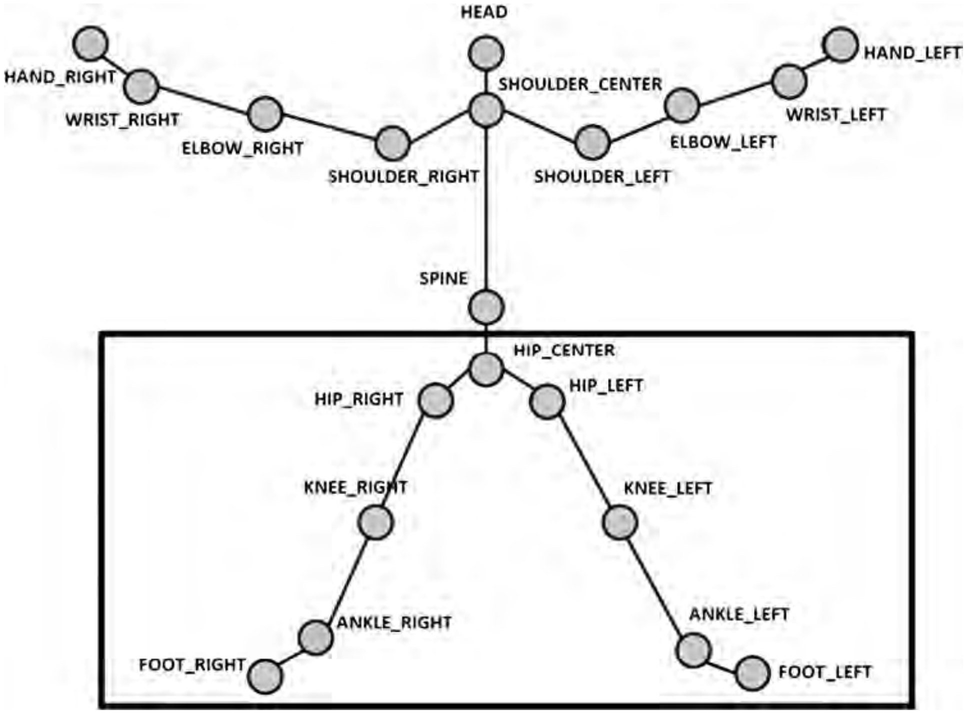

Fig. 3. Full skeleton model including 19 segments and 20 joints and focused lower limb region of interest in bold rectangle.

tal tracking) to develop our system. The 2D planar kinematics was acquired using the available skeletal tracking algorithm. The complete skeleton model has 20 joints (1 head, 3 shoulders (center, left, right), 2 elbows (left, right), 2 wrists (left, right), 2 hands (left, right), 1 spine, 3 hips (center, left, right), 2 knees (left, right), 2 ankles (left, right), 2 foots (left, right)) and 19 related segments (Fig. 3). Then, 3D coordinates of joints of interest are stored for further processing. For this present study, only lower limb region was tracked and then its kinematics was extracted for the modeling and simulation purpose.

2.2. Musculoskeletal simulator system

A model database was developed. This database covers a large range of geometrical body representations such as scaling

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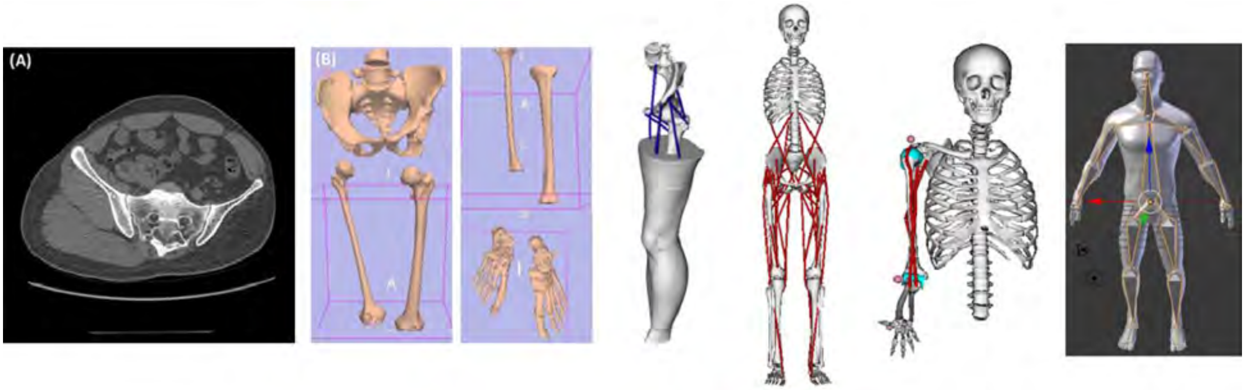

Fig. 4. Geometrical body representation database.

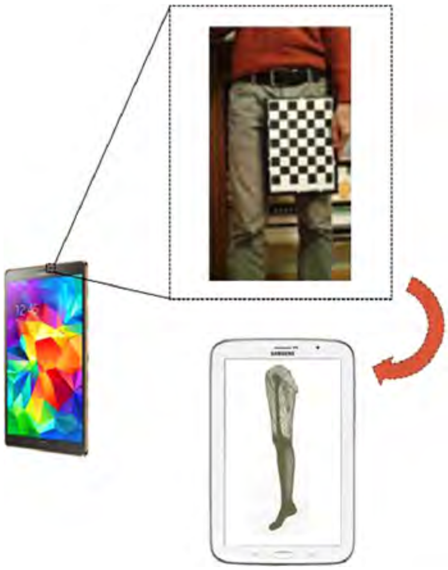

Fig. 5. Schematic illustration of the developed smart capture system for generating a subject- or patient-specific geometrical model.

geometries from generic musculoskeletal model and subject- or patient-specific geometries derived from medical images (Fig. 4). In particular, a smart capture system was developed to generate subject- or patient-specific geometries using an embedded camera in smart phone and a statistical scaling approach [13] (Fig. 5).

Kinematics data at specific joints of interest were extracted from the fusion between Kinect and Shimmer kinematics-based sensors. Inverse dynamics and static optimization are performed to describe muscle forces from a given motion. Moreover, motions under effect of modified motor control (muscle activation/contraction dynamics) are predicted using forward dynamics.

Joint contact indicators (e.g. area or pressure) are estimated using geometrical computing technique and Hertzian contact theory (fully elastic) (Fig. 6) [14]. A point-to-point distance principle based on a threshold was applied to compute the contact area according to a specific joint position.

2.3. *Graphical user interaction (GUI) system*

An enhanced virtual reality interaction system was developed. Different viewers were developed for skeletal tracking, 3D model animation, and biofeedback plotting. Rehabilitation exercises were designed as serious games (i.e. "therapeutic games"). There are two use-case scenarios as offline and online games. In the offline scenario, rehabilitation exercises were implemented a priori by the medical staff. When the user logs into the system, he (she) follows the assigned rehabilitation exercises without giving the bio-feedbacks to the system. In the online scenario, the user performs his (her) rehabilitation exercises and then the bio-feedbacks are given to the system to monitor and correct the bad motions. The interaction between the end user, his (her) evolution and medical staff is also managed. Advanced data visualization formats such as interactive reports or tree-based or graph-based structures are developed to facilitate such interaction.

2.4. *Case studies*

Two case studies were performed. The first one relates to the supervision of flexion/extension movement using a patient specific model of the post-polio residual paralysis patient in real-time conditions. The second case is the development of locomotion serious game exercises using a parametrized avatar model in offline and real-time conditions. It is important to note that only Kinect camera was used in these studies.

The first case study was designed on a patient with post-polio residual paralysis (male, 26 years old, 1 m 70 height, and 66 kg body mass). Computed tomography (CT) scanner images were acquired using a spiral-imaging scanner (GE Light Speed VCT 64) at the Polyclinique St Côme of Compiègne (France) [15]. The 3D osteoarticular model of the patient was developed. We considered that the center of knee joint is located at the middle point of the epicondylar axis connected between the epicondylar peaks.

The second case study relates to the development and evaluation of serious game designed for functional rehabilitation of the lower limbs. A basic rehabilitation exercise database was developed as serious games (Fig. 7). Exercises with three levels of difficulty were designed and implemented. For easy ex-

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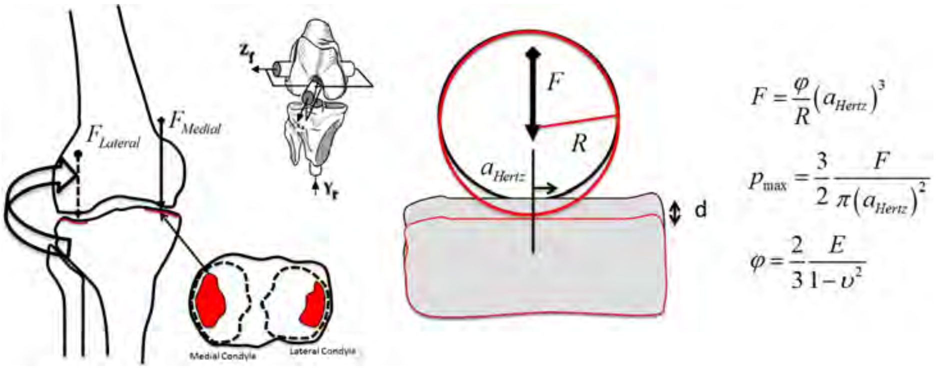

Fig. 6. Schematic representation of Hertzian contact model.

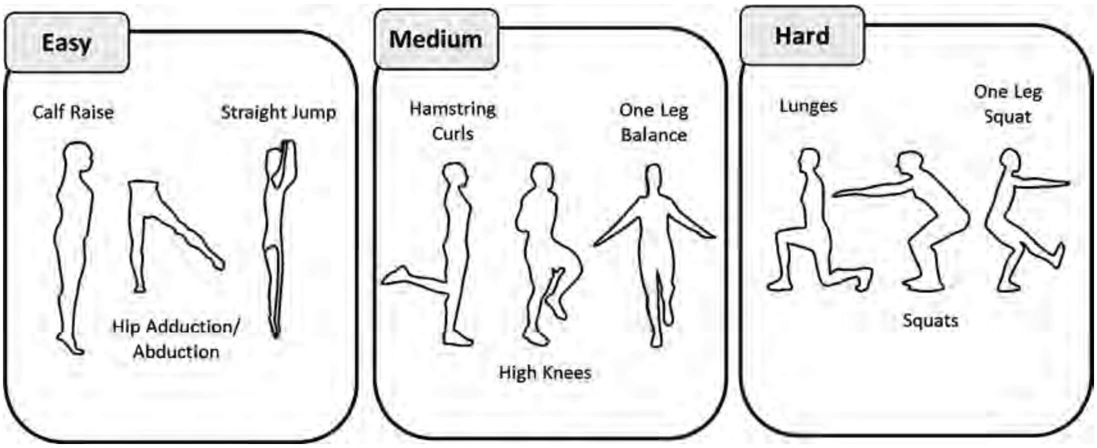

Fig. 7. Various exercises with three levels of difficulties.

ercises, jump and hip adduction/abduction were selected. For the medium exercises, hamstring curls, high knee and one leg stance were selected. Finally, squat was selected as a hard exercise. An avatar, as a simplified representation of a human body, was designed. Therefore, an available 3D human model mesh was used. This geometrical model was loaded in the 3D engine. Finally, a texture was added into the geometrical model using Blender software. For each specific subject, the avatar was linearly scaled and superposed into his (her) body size. A scoring strategy was defined and implemented to motivate the users to get higher score when they perform the rehabilitation exercises.

A graphical user interface (GUI) was developed for both experts to assign programs and monitor patient progress, and patients to explore the assigned programs and perform the required exercises. Note that password saving was accounted for by using a cryptography algorithm to ensure the connection security into our system.

3. Results

3.1. *Real-time supervision of flexion/extension movement using a patient specific model*

The calibration is needed to align the biomechanical model and the Kinect-based kinematic data (Fig. 8A). The animation of this flexion motion is shown in Fig. 8B. Contact areas at the knee joint during a flexion motion with plausible range from 0° (full extension) to 45° were computed and presented in Fig. 9. We observed that the evolution of knee contact area decreases over the range of flexion motion with higher values on the lateral side. Threshold-driven color map of the distance between femur and tibia revealed such evolution pattern. Moreover, the contact area is more extended on the lateral side. Furthermore, the choice of the geometrical threshold has an important impact on the range of values of the knee contact area. In fact, the increase of the threshold leads to the increase of the knee contact area.

An intelligent computing strategy was proposed to perform a real-time simulation. In fact, to track the contact area information at the joint level during the functional rehabilitation motions, a look-up table including all values of contact areas within the feasible range of motion was pre-computed and stored. Then, during real time rehabilitation motion, at each time step, one joint angle value was used to look up the corresponding contact value; this information was displayed in the graphical user interface.

At each time step, the 3D joint (point) coordinates are generated from Kinect-based skeletal tracking algorithm. Then, the law of cosines was applied to compute the angle between three joint (point) coordinates. The skeletal tracking algorithm relates to a body recognition problem using per-pixel classification algorithm. This two-step process includes a depth map computing using structured light derived from speckle pattern of infrared sensor and a body recognition using randomized decision forest

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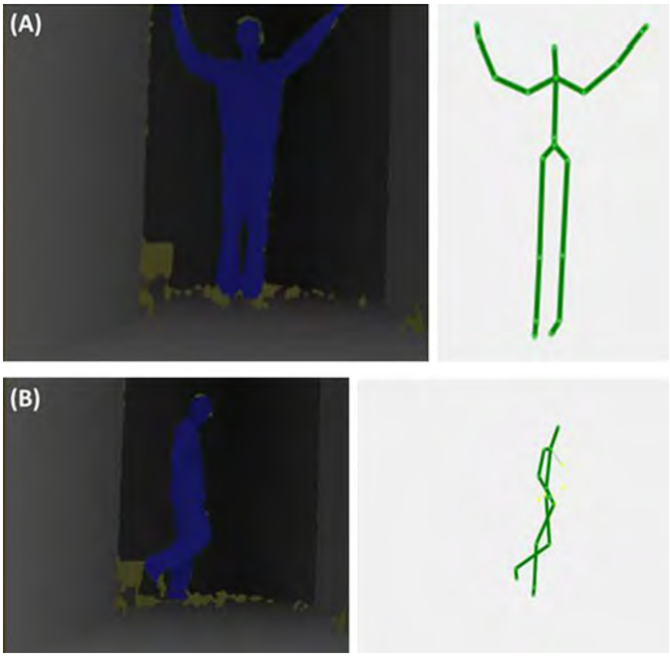

Fig. 8. (A) Calibration process and (B) a flexion motion.

approach. As concerns the runtime of the process, we can note that the computing of one contact value at one specific joint angle costs about 1.9 seconds on a 64-bits Intel® Xeon® 3.5 GHz computer while the retrieval time for one contact value at one specific angle is about 6 milliseconds.

3.2. Locomotion serious game exercises using a parametrized avatar model

When the game starts, the user needs to be distant enough so that the Kinect may capture at least the lower part of his body. At last, the game begins with a 20 seconds offline mode, where the avatar demonstrates the exercise alone. Then, the player has to repeat the offline scenario during the assigned time for the exercise. Six real time graphs are also shown on the screen with the serious game to indicate different joint angles such as right (left) knee angle, right (left) sagittal thigh angle and right (left) frontal angle (Fig. 10). The game will automatically add points to the score for every movement done correctly. Finally, after the time expiration, the game ends, indicating the score accumulated by the user, which is saved in the database along with the graphs to be visualized later and further analyzed by the expert.

The developed system for the serious game was tested on 10 healthy subjects with a mean age of 24.2 ± 3.79 year olds. The test required that every participant performs 3 exercises in different levels of difficulties. The participants were chosen based on two criteria. The first criterion is regular sport practice, which 6 out of 10 subjects confirmed. The second is previous Kinect experience, which was positive only for 2 of our subjects. It is important to emphasize that both criteria are necessary to evaluate the developed system. As results, for the Hip Adduction/Abduction, Hamstring Curls, the High Knees and Straight Jump exercises, one subject achieved a score of 51, while others achieved a score of around 30. Squats exercise seems to be the hardest challenge since the average score is smaller than those of other exercises. Indeed, the each exercise depends on the physiological profile of the testing subject. Moreover, each testing subject adapts quickly to the design concept of all developed exercises. Based on the testing and evaluation campaign, the developed system is generally accepted well by the subjects.

4. Discussion

Musculoskeletal rehabilitation is commonly prescribed for patients with musculoskeletal impairments or disabilities to optimize their functional capacities/performances as well as to reduce disability symptoms. Moreover, these physical exercises also contribute to improve the well-being nature of the patient. The efficiency of a rehabilitation program is evaluated using functional measurements (e.g. joint kinematics parameters) about the effect of a rehabilitation motion on the musculoskeletal system. Recently, enhanced virtual reality technologies have been used to develop immersive rehabilitation systems to provide such useful information. Current systems allow only external visual feedback information to be supervised during rehabilitation motion. The only use of external information is not sufficient to have a reliable judgment on the efficiency of a rehabilitation motion, especially for patients who suffered commonly bone deformation and muscle disabilities. In our study, both external and internal visual bio-feedback information were provided. An enhanced rigid multi-bodies model integrating joint contact behavior was incorporated to estimate internal evolution of joint contact area during rehabilitation motion. In the literature, existing rehabilitation systems provide also some kinds of virtual avatar to represent the human body in immersive virtual reality environment. However, these simplified avatar models are so far to be realistic according to the biological complexity of the musculoskeletal system. Thus, physics-based model such as the enhanced rigid multi-bodies model in our rehabilitation system needs to be integrated to improve the appearance and especially the physiological meaning of the feedback infor-

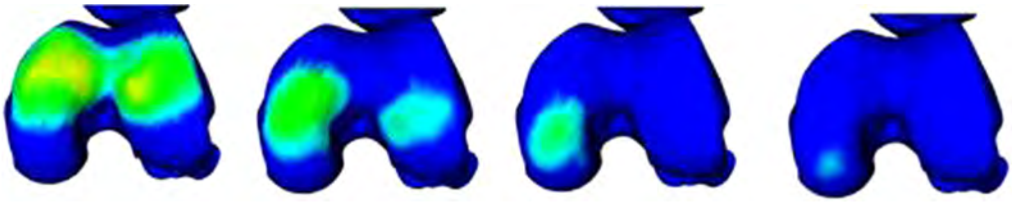

Fig. 9. Illustration of the evolution of distance maps in mm for 0° to 45° of flexion (left to right) of the knee joint with the threshold of 10 mm.

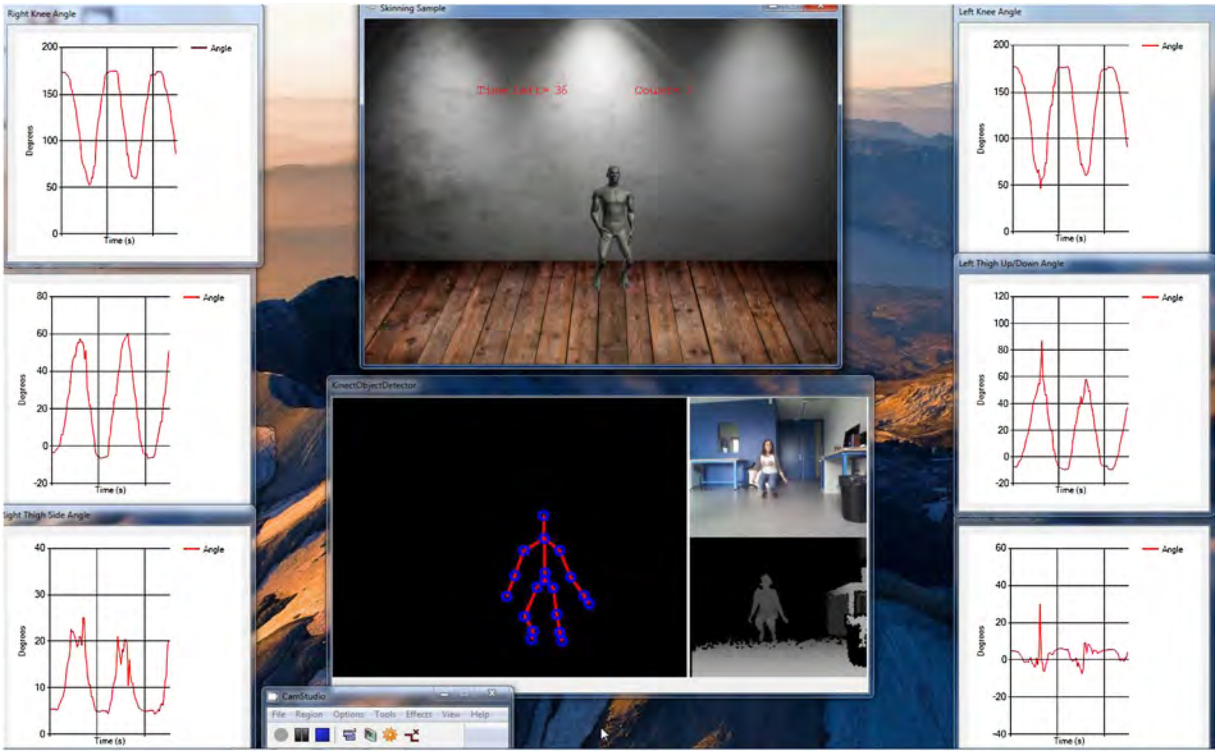

Fig. 10. Developed serious gaming interface (top), Kinect interface (bottom) and joint angle plotting (left and right).

mation. In fact, the evolution of joint contact area is tracked and supervised over the range of each rehabilitation motion. This gives useful information about joint behavior under the effect of rehabilitation motion on the musculoskeletal tissues and structures. Moreover, rehabilitation exercises were designed as serious games to motivate the end user.

Internal musculoskeletal information is commonly acquired using rigid multi-bodies or continuum finite element modeling approaches. Joint contact behavior may be accurately provided from finite element model. However, the finite element simulation is very time-consuming and this does still not satisfy the computational requirement of a real time simulations. In fact, we proposed an enhanced rigid multi-bodies model integrating geometrical joint contact behavior to provide contact area information at the joint level. Moreover, a computing reduction strategy was established to reach the constraints of real time simulation.

Research topics related to system of systems have been intensively investigated in the last decade. In this achievement, we developed a comprehensive rehabilitation system of systems, which is a combination of software and hardware systems for data acquisition, model development and user interaction purposes. The benefit from the coordination of these complex systems is to achieve a common healthcare goal with higher clinical significance and relevance for functional rehabilitation purpose. In fact, each constituent system such as data acquisition and management system or multi-physical modeling system or graphical user interface (GUI) system may work independently without a common goal but only their integration into a system of systems provides an innovative solution for functional rehabilitation. Moreover, the use of low-cost and portable Kinect sensor provides a potential solution of enhanced virtual reality games tailored for a specific rehabilitation program in clinical or home-based settings leading to reduce significantly the medical cost and infrastructures. In particular, the Kinect sensor provides a safely interaction with human body leading to improve the benefit of such useful rehabilitation system of systems. According to the state of the art [6–10], the use only Kinect device for rehabilitation is not original. However, our case studies presented a coupling between the Kinect device and the biomechanical modeling for providing bio-feedbacks. It is important to emphasize that this coupling does not exist in the literature. Indeed, this study opens new perspectives to improve the quality of the functional rehabilitation.

Kinect-based kinematic measurement may lead to precision problem according to 3D motion capture systems like VICON [16–19]. As reported in the literature, Kinect camera provides good movement pattern for trunk segment and hip joint [16, 19] and a high variance (30%) in hand and foot segments [16]. However, the compromise between the precision and the portability criteria may be acceptable when using Kinect device [17]. The present system used Microsoft Kinect 1.0 and we noted that the generated skeleton from the Kinect images had occlusion at some limbs and joints. As perspective, Kinect 2.0 will be used for a better accuracy and resolution. Moreover, the fusion between Kinect camera and other kinematics and EMG sensors like Shimmer sensors will be investigated for more complex movement patterns. Finally, a new evaluation campaign with more subject categories (e.g. different age and population type) will be performed to reinforce the benefits of the proposed system.

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5. Conclusion

We proposed interactive and connected rehabilitation systems as a system of systems to provide reinforced bio-feedback information of external and internal behavior of the musculoskeletal system during rehabilitation movements. Thus, our rehabilitation system of systems would be of great interest in the supervision of physical therapy exercises in clinical as well as in non-clinical environments (e.g. rehabilitation at home). As perspectives, kinematics-based and EMG Shimmer sensors will be used to get the complementary kinematics and muscle activities. A multi-rate Kalman filter will be implemented to get accurate 3D kinematics from the fusion of Kinect and Shimmer sensors.

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