Real-Time Rehabilitation System of Systems for Monitoring the Biomechanical Feedbacks of the Musculoskeletal System

Tien Tuan Dao, Philippe Pouletaut, Didier Gamet, and Marie Christine Ho Ba Tho

Abstract. Functional rehabilitation aims at recovering the locomotion dysfunction of the human body by the physical therapy. The objective of this present study was to develop a system of systems (SoS) for monitoring the biomechanical feedbacks of the musculoskeletal system during the rehabilitation exercises. Wireless sensors (Kinect camera sensor, Shimmer kinematics and Electromyography (EMG) sensors) coupled with a biomechanical model was used to supervise the joint kinematics, muscle forces and joint contact area of the musculoskeletal system of the human body. A calculation time reduction strategy for joint contact area analysis was established to reach the constraints of real time simulation. A pilot case study was applied on a patient with post-polio residual paralysis. Joint kinematics and contact area at the knee level were supervised during flexion motion using video-based non-contact Kinect sensor. For the first time, an enhanced rigid multi-bodies model integrating joint contact area behavior was used for a rehabilitation purpose. Our system would be of great interest in the supervision of physical therapy exercises in non-clinical environments (e.g. rehabilitation at home).

Keywords: Functional Rehabilitation, System of Systems, Musculoskeletal System, Markerless Motion Capture, Real-time Simulation.

1 Introduction

Functional rehabilitation aims at recovering the locomotion dysfunction of the human body by the physical therapy exercises [1], [2], [3], [4]. This involves performing controlled physical and occupational therapy interventions with or without the assistance of physiotherapist to improve musculoskeletal strength and flexibility as well as the range of motion. At the moment, functional rehabilitation has been com-

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monly realized in clinical environment under supervision of physiotherapists [5]. However, the supervision and the evaluation of a rehabilitation motion pattern remain a medical and engineering challenge due to the lack of biofeedback 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 biofeedbacks (e.g. functional measurements) during rehabilitation exercises such as motion velocity (speed), duration of motion pattern (time), ergonometric measurement, video data or joint patterns [6], [7], [8], [9], [10], [11], [12]. These quantitative biofeedbacks 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 [7]. However, these systems provided only external information (e.g. kinematics) of the musculoskeletal system during rehabilitation motion. In fact, the acquisition of internal information (muscle forces, joint contact behavior) inside the musculoskeletal system is still a challenging problem for such useful rehabilitation systems.

The kinematics of the musculoskeletal system is commonly acquired using accelerometer [13], [14] or 3D motion capture system (e.g. VICON, OptoTrack, Motion Analysis) [9], [15], [16]. These systems provide kinematical data with a good precision but the set up protocol is complex (e.g. definition of skin-based marker clusters or acquisition requirement in well-controlled environment) and time-consuming. Recently, Kinect sensor has been widely used to provide kinematics data with a quasi-similar precision as 3D motion capture systems for planar motions [9]. Moreover, this technology has been used to develop rehabilitation system for monitoring locomotion [7], [8], [9], [10] and cognitive rehabilitation exercises [17]. The main advantages of this video-based non-contact technique are the portability, the ease-to-use capacity, the cheap price and especially the possibility to develop a home-based rehabilitation system, which may lead to reduce significantly medical cost, infrastructures and human resources. However, the use of only Kinect sensor leads to limited biofeedback information as only planar kinematics was acquired and supervised. Consequently, the first objective of this present study was to couple this video-based non-contact system with Shimmer kinematics sensors to obtain 3D joint kinematics. Moreover, an enhanced musculoskeletal model integrating joint contact behavior was developed to provide EMG-driven muscle forces as well as joint contact area during the rehabilitation motions in an immersive virtual reality environment. Joint contact behavior could be accurately acquired using finite element modeling [18]. However, this modeling approach is very time-consuming and this does still not satisfy the requirement of a real time biomechanical simulation with rapid reinforced biofeedbacks. Consequently, we proposed an enhanced rigid multi-body model allowing the musculoskeletal animation and joint contact area tracking during rehabilitation motions.

Rehabilitation system is a complex system with dynamic behavior of physical therapy exercises in space and time. Moreover, the motion pattern is uncontrolled and unpredictable due to the human variations. Furthermore, the integration of a biomechanical model into a rehabilitation system leads to a computational and biological complexity [19], especially in real time simulations. Emergent events and chaos may be appeared for bad motion patterns. From system engineering point of view, rehabilitation system may be classified in the most complex systems [20], [21], [22]. The development of such a complex rehabilitation system integrating a biomechanical model needs an innovative and flexible engineering methodology. Recently, we introduced a biomechanical system of systems (SoS) to deal with the complexity of biomechanical data and models [23]. In fact, the second objective of this present study was to develop software architecture of our rehabilitation system using system of systems approach for monitoring the biomechanical feedbacks (muscle forces, joint kinematics and contact area) of the musculoskeletal system in real time conditions.

2 System Description and Software Specifications

The flow chart of our system of systems for monitoring the kinematics and joint patterns of the musculoskeletal system is shown in Fig. 1. It consists of a data acquisition and management system, a multi-physical modeling system and a graphical user interface (GUI) system. The workflow of our system for a patient/subject under investigation consists of the following steps: 1) geometrical data acquisition using medical imaging at clinical center (hospital, clinics); 2) medical imaging processing to reconstruct the 3D geometrical model; 3) development of the biomechanical model derived from image-based 3D geometries; and 4) real-time monitoring of the functional rehabilitation motions.

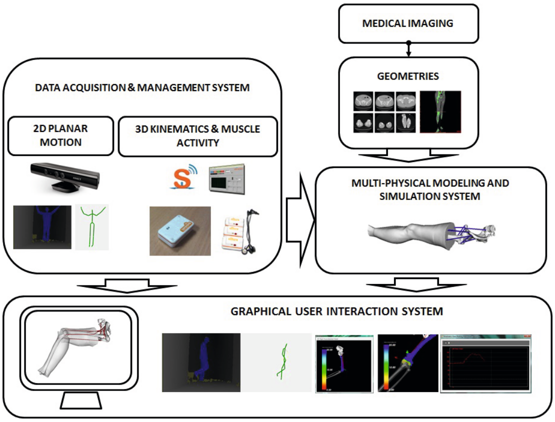

Fig. 1 Flow chart of our system of systems for the monitoring biomechanical feedbacks of the musculoskeletal system during functional rehabilitation motions

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, skeletal 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. 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 (Fig. 2).

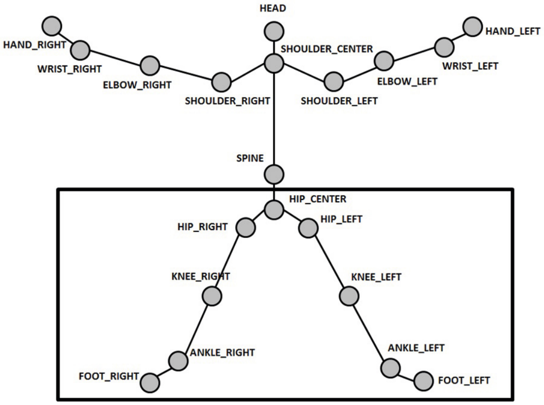

Fig. 2 Full skeleton model including 19 segments and 20 joints and focused lower limb region of interest in bold rectangle

Shimmer kinematics (accelerometer and gyroscope) and EMG sensors were used to acquire joint spatial-temporal parameter and surface EMG signals representing the muscle activity of the musculoskeletal system during functional rehabilitation motions. Based on the acceleration information, joint angles were estimated. Raw EMG signals were preprocessed (filtering, rectification) and used as muscle activation profile for forward dynamics simulation to estimate the muscle forces according to a specific rehabilitation motion. Specific device, in which sensors are embedded, is developed to facilitate the data acquisition process.

2.2 *Graphical User Interaction (GUI) System*

An enhanced virtual reality interaction system was developed using Visual C# as programming language. Three user interfaces were created (Fig. 3). The first one is the main graphical interface with a menu system and a Kinect-based 3D skeletal tracking viewer. This interface allows the user to view the result of 3D skeletal tracking process from Kinect sensors. The second one is a 3D biomechanical model viewer to display and animate the real-time simulation. This interface allows the user to view and interact with the model during real time rehabilitation motions. The third interface is the joint kinematics and muscle forces viewer to plot the biofeedbacks of the musculoskeletal system in real-time.

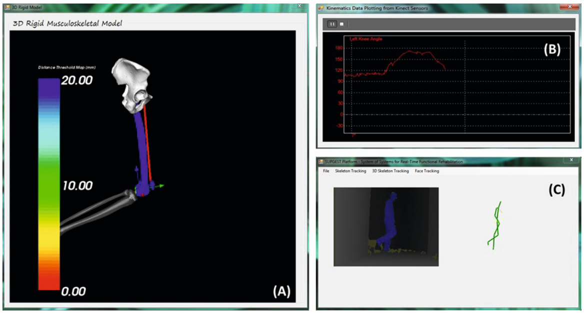

Fig. 3 Graphical user interfaces of our system of systems: (A) 3D biomechanical model viewer, (B) joint kinematics and muscle forces plot viewer and (C) Kinect-based skeletal tracking viewer within the main interface

2.3 *Multi-physical Modeling and Simulation System*

To obtain the information inside the human musculoskeletal system during functional rehabilitation motions, an advanced 3D rigid multi-bodies model was developed. Medical imaging such as computed tomography (CT) scan or magnetic resonance imaging (MRI) were used to acquire the anatomical data of the patient/subject under investigation. Then, medical imaging processing (2D segmentation, 3D reconstruction) was applied to develop 3D geometrical model. Kinematics data at specific joints of interest were extracted from Kinect sensorsand then fused with joint kinematics derived from Shimmer kinematics sensors. The recommendations of the International Society of Biomechanics were used to define the joint coordinate frame [24].

The block diagram of the modeling and simulation system in interaction with data acquisition system and graphical user system is shown in Fig. 4. First, Kinect and Shimmer sensors are activated and the biomechanical model developed from medical imaging data is generated. Second, a calibration process was set up to align the image-based geometries and the joint kinematics data. Third, musculoskeletal tracking is started to animate the musculoskelletal model as well as to provide joint kinematics and muscle forces data for plotting and contact area retrieval from a look-up table. Then the threshold-driven distance map between the two surfaces of the joint is displayed in an interactive manner. Finally, the system is looped until the user decides to quit the system. This modeling and simulation system was implemented using Visual C#.

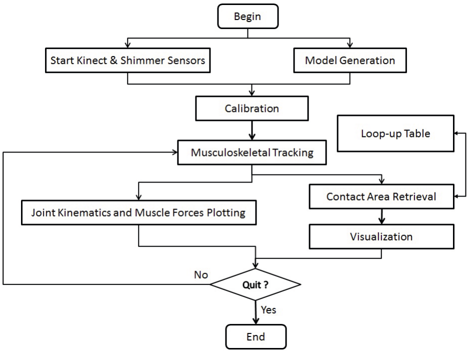

Fig. 4 Block diagram of the modeling and simulation system in interaction with data acquisition system and graphical user system

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. A point-to-point distance principle with a geometrical threshold was applied to compute the contact area according to a specific joint position [25].

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. For example, right knee angle was computed using the coordinates of the HIP_RIGHT, KNEE_RIGHT, and ANKLE_RIGHT points (Fig. 2). 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 approach [26]. Then, these information were fused with joint kinematics data derived from Shimmer kinematics sensors to provide accurate 3D joint angles for musculoskeletal simulation. Based on the pre-processed EMG signals, forward dynamics was used to estimate the muscle forces [25], [27].

3 A Pilot Case Study

To illustrate the workflow of our system, a pilot case study was designed on a patient with post-polio residual paralysis (male, 26 years old, 1m70 height, and 66kg body mass). All necessary steps are addressed in the following subsections. It is important to note that we focused only on the tracking of joint kinematics derived from Kinect sensor and joint contact area at the knee level.

3.1 Geometrical Data Acquisition Using Medical Imaging at Clinical Center

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). The subject signed an informed consent agreement before participating into this present study. The CT scan protocol included 3mm thickness and a matrix of 512 × 512 pixels leading to have 384 joint slices (Fig. 5A).

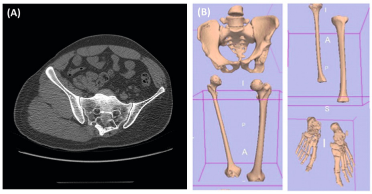

Fig. 5 (A) Raw CT image and (B) 3D reconstruction of bone tissues of the lower limbs structures

3.2 Geometrical Data Acquisition Using Medical Imaging at Clinical Center

Semi-automatic segmentation was applied using 3D Slicer software to extract the bone tissues of the lower limbs (Fig. 5B).

3.3 Biomechanical Model Development and Simulation

The enhanced 3D musculoskeletal model interating joint contact behavior of the patient was developed (Fig. 6A). We considered that the center of knee joint is located at the middle point of the epicondylar axis connected between the epicondylar peaks (Fig. 6B).

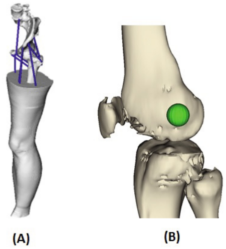

Fig. 6 (A) Enhanced 3D musculoskeletal model and (B) definition of knee joint center based on the epicondylar peaks (spheres in green color)

3.4 *Real-Time Monitoring of the Functional Rehabilitation Motions*

The calibration is needed to align the biomechanical model and the Kinect-based kinematic data (Fig. 7A). The animation of this flexion motion is shown in Fig. 7B.

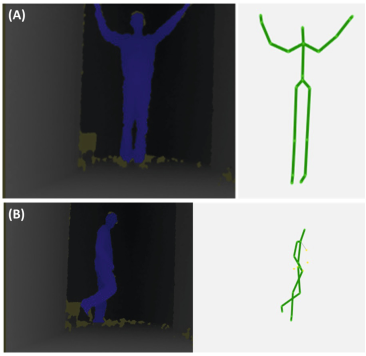

Fig. 7 (A) Calibration process and (B) a flexion motion

Contact areas at the knee joint during a flexion motion with plausible range from 0 degree (full extension) to 45 degree were computed and presented in Fig. 8 and 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. Thus, threshold-driven color map of the distance between femur and tibia revealed such evolution pattern (Fig. 8). 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 (as shown in Fig. 9).

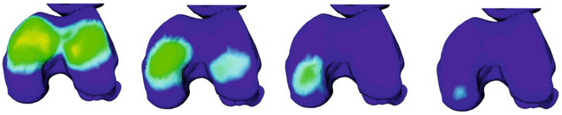

Fig. 8 Evolution of distance maps in mm for 0 to 45 degrees of flexion (left to right) of the knee joint with the threshold of 10 mm

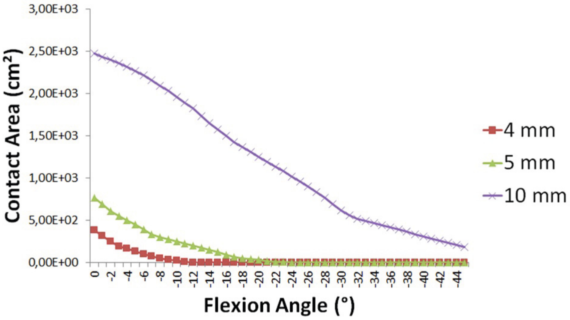

Fig. 9 Evolution of contact areas from 0 to 45 degrees of flexion with three different thresholds

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.

4 Discussion

Musculoskeletal rehabilitation is commonly prescribed for patients with musculoskeletal impairments or disabilities to optimize their functional capacities and performances as well as to reduce disability symptoms. Moreover, these physical exercises also contribute to improve the well-being nature of the patient [1]. 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 [7], [8]. Current systems allow only external visual biofeedback 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, a novel rehabilitation system of systems was developed to provide both external and internal visual biofeedback information. Thus, Kinect-based non-contact, Shimmer kinematics and EMG sensors were used to provide external and internal biofeedbacks data. An enhanced rigid multi-bodies model integrating joint contact behavior was incorporated into our system of systems to provide muscle forces as well as 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 [17], [28], [29], [30]. 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 biofeedback information. In fact, the evolution of joint contact area and muscle forces are tracked and supervised over the range of each rehabilitation motion. This gives useful information about joint behaviors and muscle activities under the effect of rehabilitation motion on the musculoskeletal tissues and structures. For the first time, such internal biofeedback information could be elucidated in a rehabilitation system.

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 biofeedback 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 objective and visual biofeedback 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 maximize the benefit of the rehabilitation program.

Internal musculoskeletal information is commonly acquired using rigid multi-bodies or continuum finite element modeling approaches [16], [31]. Joint contact behavior may be accurately provided from finite element model [32], [33], [34]. 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 calculation time reduction strategy was established to reach the constraints of real time simulation. In fact, feasible range of motion was simulated and then related joint contact areas were pre-computed and stored in a look-up table. Finally, during real time simulation, the joint contact area is retrieved and displayed from this table. This strategy reduces significantly the processing time to satisfy the computational constraints of a real time simulation.

Research topics related to system of systems have been intensively investigated in the last decade. The notion of system of systems has been recently introduced in the engineering system field. From an engineering point of view, a system is defined as a group of functionally, physically and/or behaviorally interactive, independent, material or non-material components. A system of systems (SoS) is a set of useful systems integrated into a larger system to achieve a unique set of tasks. In our present study, 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 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 [35]. In particular, the Kinect sensor provides a safely interaction with impaired patients leading to improve the clinical benefit of such useful rehabilitation system of systems.

5 Conclusions

In conclusion, we developed a novel rehabilitation system of system to provide reinforced biofeedback information of external and internal behavior of the musculoskeletal system during rehabilitation motions.

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