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Adding Inverse Kinematics for Providing Live Feedback in a Serious Game-based Rehabilitation System

Ahmad Qamar, Mohamed Abdur Rahman, Saleh Basalamah
Advanced Media Laboratory, Computer Science Department, College of Computer and Information Systems
Umm Al-Qura University, Makkah Al Mukarramah
Kingdom of Saudi Arabia
e-mail:{ amqamar, marahman, smbasalamah}@uqu.edu.sa

Abstract— **In this paper, we present a serious game-based framework for providing live feedback to a patient performing a rehabilitation therapy for the purpose of assisting a patient in correct therapeutic steps and obtaining high quality therapy data for further analysis. The game environment uses forward kinematics to receive the live sensory data from two 3D motion tracking sensors and uses inverse kinematics to analyze the sensory data stream in real-time. A subject performs a rehabilitation therapy prescribed by the physician and using both forward and inverse kinematics the system validates the angular and rotational positions of the joints with respect to the correct therapeutic posture and provides live feedback to the subject. As a proof of concept, we have developed an open source web-based framework that can be easily adopted for in-home therapy, without the assistance of a therapist. Finally, we share our initial test result, which is encouraging.**

Keywords - Kinect; Leap Motion; physical rehabilitation; inverse kinematics

I. Introduction

Hemiplegia is the paralysis of one side of the body. It can be congenital or it can happen due to stroke. As a result of hemiplegia, a patient may suffer loss in range of motion in certain joints in the affected part of the body [1]. To improve the ability of a patient to move her limbs, a physiotherapist prescribes a number of exercises. To measure the improvement in the range of motion of a joint, physiotherapists use goniometers. A goniometer is a device that is placed on a body joint to measure the angle of rotation of a joint. Using a goniometer requires a patient to sit in a fixed position and practice the movement with the goniometer in place. This makes measuring the angle quite cumbersome and often requires the help of a trained person. Another method of measuring the range of motion is to use cameras that track passive [2, 3, 4] or active markers such as LEDs [5] attached to the patient's body. The movement of the markers is tracked by cameras while sophisticated software algorithms are applied to extract range of motion information from the images. This setup is quite expensive. It can only be performed in a clinical setting. Another method of tracking a patient's motion is through the use of robots [6]. A robot based system is much more expensive than a camera based system and is less mobile, too. In summary, existing therapy exercises are routine and boring and wearing attachments and sensors make it more difficult for a disabled child to perform the exercise efficiently. The non-invasive therapy makes the child feel comfortable with the environment. A gaming environment would make the rehabilitation process more fun for the child

To aid to non-invasiveness, Microsoft released the Kinect sensor [7] for its Xbox 360 gaming platform. The device has a video camera as well as a 3-D sensor. The Kinect can detect 20 different joints in the body at the rate of 30fps. This gives it the ability to track joint movement and range of motion in a non-invasive way. The validity of Kinect as a tool for medical rehabilitation has been thoroughly studied in [8, 9, 10]. In [11, 12], the authors have developed serious games for physical and mental rehabilitation based on the Kinect framework. As opposed to wearing sensors or markers while performing exercise, a user does not even need to be aware of the presence of a Kinect sensor. As a result, the user can perform exercise in the most natural and comfortable manner. This helps in getting more accurate results. The addition of serious games adds an aspect of entertainment to the therapy experience. This helps in improved recovery [12]. Another feature of the Kinect based setup is its low cost of ownership. This setup can be used for home-based therapy without a therapist.

In our earlier work, we used the Microsoft Kinect device [13, 18] to record and replay an exercise session performed by a hemiplegic child. Based on forward kinematics, the system tracked and displayed the movements of different joints of the subject performing therapeutic activity in front of the sensor setup. In our current work, we have extended the earlier framework by adding the inverse kinematic capability through a device called Leap Motion [14] controller to the environment. Kinect has been shown to be capable of recording joint movements with clinical accuracy. However, the measurement of hands is not accurate enough to be used for medical purposes [15]. The Leap measures hand movements with sub-millimeter accuracy [15]. We have also added an inverse kinematics component to the system. This gives our system the ability to detect the state of each joint so that it can inform the user about the validity of its position. The current framework is web-based as opposed to desktop based, requiring minimum installation steps at the user side. To the best of our knowledge, ours is the first non-invasive system with inverse kinematics based live feedback facility. This gives both the therapist and the patient

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additional information regarding the quality of improvement metrics.

The rest of the paper is organized as follows. In Section 2 we describe the system design and modeling. In Section 3 we show the implementation details and analysis of test result and in Section 4 we state the concluding remarks.

II. Description of the Proposed System

A. Framework Modelling

The human body consists of a number of joints. Every joint has a number of movements associated with it. Some movements are angular, for example, flexion/extension of the elbow that takes place when the wrist is brought near the shoulder or moved away from it [16]. Some motions are circular, like rotation, whereby a joint moves around its vertical axis, for example, rotation of the neck in a 'no' gesture. A similar kind of movement is one in which the joint moves around a single point. It is called circumduction. An example of this kind of movement is the rotary movement of the thumb e.g flexion, extension, abduction, adduction, pronation and supination [16]. Similar to the approach used in [17], we show how we model the kinematic data in terms of the joints and motions around each joint. Fig. 1 shows a snapshot how we associate each joint with a subset of actions or movements.

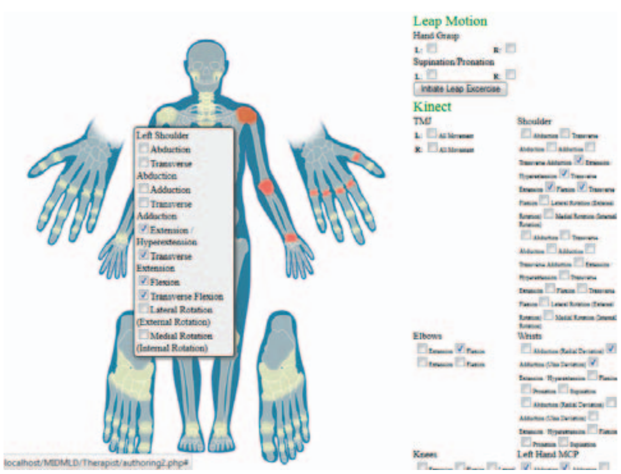

Fig. 1. Human body anatomical model where each joint of the body is associated with a subset of therapeutic motions.

For the purpose of modelling, we consider J to be the set of joints being tracked:

$$J = \{j_1, j_2, j_3, \dots j_m\} \qquad (1)$$

One instance of J can be as following:
j_1=neck, j_2=right shoulder, j_3=left shoulder, etc.

At any given temporal dimension, we consider a joint to be in a particular state and at that state the joint produces one or more movements related to that state. We define the set of states S as following:

$$S = \{s_1, s_2, s_3, \dots s_n\} \qquad (2)$$

Again, one instance of S can be as following:
s_1=flexion, s_2=extension, s_3=abduction, s_4=adduction, etc.

A primitive therapeutic context P is defined as a set of ordered pairs of joints and their respective states as following:

$$P_i = \{< j_m, s_n >\} \qquad (3)$$

An example of the above can be primitive therapeutic contexts $P_1$for wrist flexion and P_2 for wrist extension.

$$P_1 = \{j_1, s_1\} \qquad (4)$$

where j_1=wrist and s_1=flexion.

$$P_2 = \{j_1, s_2\} \qquad (5)$$

where j_1=wrist and s_2=extension.

A complete therapeutic context T is defined as a series of primitive therapeutic contexts P_1 ... P_n. As an example, the above two primitive therapeutic contexts can be combined into a complete therapeutic context T depicting the wrist bend therapy as following:

$$T_1 = \{P_1, P_2\} \qquad (6)$$

where P_1 is wrist-flexion and P_2 is wrist-extension.

B. Framework Design

Fig. 2 shows the high-level software components of our proposed system. The details of the different components of the software framework are as follows.

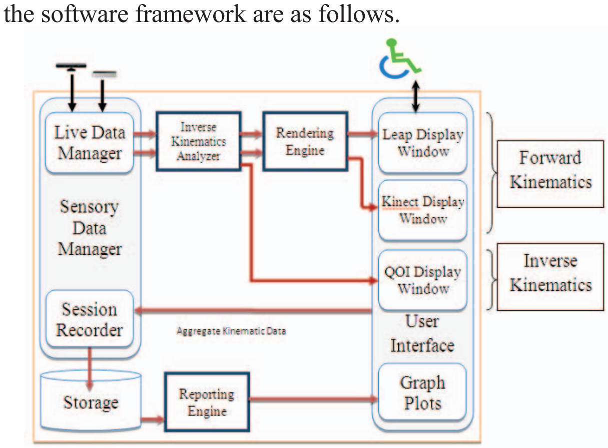

Fig. 2. System Architecture

Sensory Data Manager: Gesture Input is provided to the system through a Microsoft Kinect 3-D sensor and a LEAP Motion controller (see Fig. 3(a) and 3(b)). The sensory data manager receives the raw 3D depth data from Kinect and 3D motion data from LEAP and allocates appropriate memory to store the data stream. It employs two web sockets to receive the streams separately. It has the following two salient components: one provides online and real-time LEAP and Kinect frame analysis support while the other supports offline or delay-tolerant bulk frame analysis capability.

a. *Live Data Manager*: The live data manager processes the raw sensory data stream and converts it into JSON/BVH format. The processed data stream is then forwarded to the analysis engine.

b. *Session Recorder:* The sensory data manager also has a part that manages session data and finally stores movement data to secondary storage. This part can be controlled by the user through the system interface (see Fig. 3(i)). The user can click a button to start, stop or pause the recording. This facility has been provided to allow session control on the recorded data to the user. At the start of the session, the user may need some time to position her in front of the system. Similarly, while recording, a user may encounter garbage data due to interference from clothes or objects in the environment. In such a case, the user has the ability to pause the recording. The live stream display continues even when the recording is paused. The user can hence get a visual clue when the interference is removed and can continue with recording by pressing a button on screen. The session recorder combines the two streams and stores them in a single JSON/BVH file.

Inverse Kinematics Analyzer: The Inverse Kinematics Analyzer processes the data and detects the state of the joints and motions in the live stream. The system also provides information to the analyzer regarding the joints that need to be tracked. The analyzer calls the function required to parse the stream. The output is forwarded to the appropriate window in the user interface to inform the user about information to improve the Quality of Experience (QoE). The algorithm for the LEAP and Kinect motion analyzer is shown in Algorithm I. As shown in Algorithm I, the *Inverse Kinematics Analyzer* receives each frame from LEAP and Kinect and delegates each frame to appropriate model component that has the right therapeutic logic to parse and detect which motion is taking place in which joint. The detailed analysis of Algorithm I is portrayed in Fig. 4 as well.

ALGORITHM I

```
InverseKinematics (PatientID, TherapyID)
Get LeapStream, KinectStream;
Begin
  Read joints and movements to be tracked from the
  database for the given PatientID and TherapyID;
  Foreach LeapFrame in LeapStream
  Begin
        Foreach joint and movement tuple
        Begin
          Call appropriate function to process the
          joint and its related motion;
          Update QoE window with related metrics;
        End
  End
  Foreach KinectFrame in KinectStream
  Begin
        Foreach joint and movement tuple
        Begin
          Call appropriate function to process the
          joint and its related motion;
          Update QoE window with related metrics;
        End
  End
End
```

Rendering Engine: The rendering engine takes the two sensory data streams coming from the inverse kinematics analyzer and displays them in their respective windows. The Kinect window shows an animated stick figure with its joints represented by dots while the LEAP renderer shows a 3-D block shaped hand model complete with five fingers (see Fig. 3 (c) and 3 (d)).

Storage: In order to represent the model in the computer system, we have designed a database that holds details of joints, movements and muscles. The database contains the names of joints and the types of movements associated with each joint. Information regarding therapies is also stored in the database. Profiles for three types of users, namely, therapist, patient and caregiver are also stored in the system. Session data is stored initially to the local hard disk. The user can later on upload the data file to the cloud for post processing.

Reporting Engine: The reporting engine takes the stored motion file and processes it to extract joint-movement related data. It converts this data to graphs and plots them on the screen. For multiple joint movements, graphs are plotted for each joint and its movement from top to bottom on the page, aligned by the time stamps (see Fig. 4). This helps the therapist in extracting temporal information from the graphs. The pseudo code for the reporting engine is described in Algorithm II.

ALGORITHM II

```
PlotGraph (SessionURI, PatientID, TherapyID)
Begin
  Read json file from SessionURI;
  Split json string of LEAP and Kinect;
  JointArray=QueryDB (PatientID, TherapyID);
  Ask user which metric to plot;
  For each device in (LEAP, Kinect)
  Begin
        For each jointID in jointArray
        Begin
          Data=Parse (jointID, metric);
            Plot (Data);
        End
  End
End
```

III. IMPLEMENTATION AND TEST RESULTS

A. Experimental Setup

The framework has been implemented on a PC with 8GB RAM. A Kinect for Windows device was used to collect joint data for 20 joints. A LEAP motion controller was used to collect hand movement data. Fig. 3 (top) shows a home-based setup of the therapy environment where both Kinect and LEAP are working together.

The software runs on a Windows 8 platform. The web based interface was developed using PHP, HTML5 and three.js [1] 3D JavaScript framework. Three.js helps us rendering LEAP and Kinect frames in 3D WebGL

[1] http://threejs.org/

environment. Since Kinect did not come with any web socket, we have developed our own Web Socket for Kinect, written in Microsoft C#.net. Data from the Kinect and Leap device was collected through web sockets running on the client computer that provided the raw stream to the JavaScript code running in the web browser. At the end of each therapy session, therapy data is stored in the form of either JSON [2]or BVH[3] format. The knowledge base is stored in a MySQL database. Dynamic graph plotting is implemented using the jquery based jqplot[4] library. The animated character is drawn using the three.js library.

B. *User Interface*

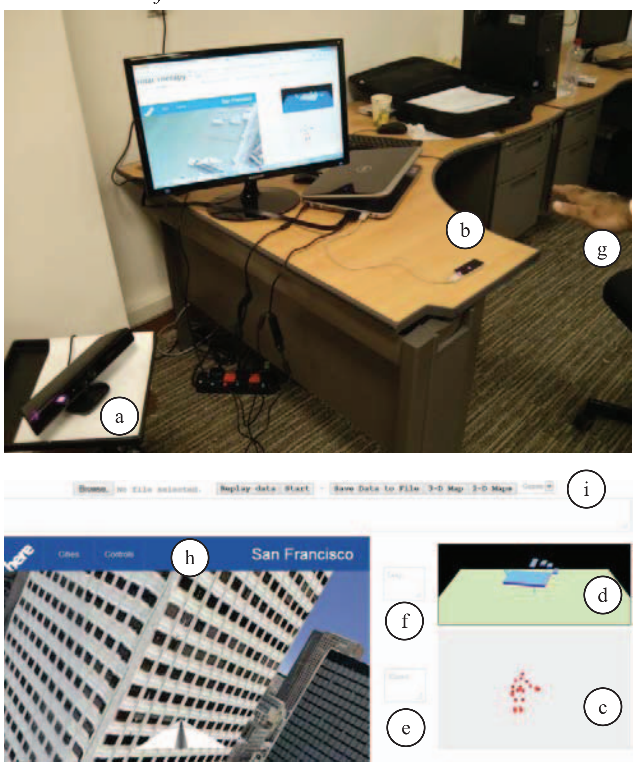

Fig. 3. Experimental setup and user interface – top image shows the experimental setup and bottom image shows the user interface (a) Kinect device (b) LEAP device (c) live 3D rendering of Kinect provided skeleton (d) live rendering of LEAP stream showing hand skeleton (e) inverse kinematic interface where feedback from Kinect stream appears (f) feedback from LEAP appears in this object (g) a user playing a 3D map browsing game which is tracked by both LEAP and Kinect to deduce rotational and angular motions from hand joints (h) 3D serious game window (i) control menus

C. *Implemented Functionality*

A therapist can add a new therapy to the therapy database by selecting the joints and movements involved in the therapy. The interactive nature of the authoring interface makes it quite easy for the therapist to design the therapy. She can also assign a therapy to a patient through the same interface. As a sample exercise we have implemented a therapy consisting of six movements for the forearm and two joints. The serious game considered in this test scenario is a map browsing session where a patient browses a map by going left (radial deviation), right (ulnar deviation), zoom in (wrist flexion), zoom out (wrist extension/hyperextension), and circling around the airplane (pronation/supination). Kinect detects the flexion and extension of the elbow while Leap is used to monitor pronation and supination of the forearm as well as flexion, extension, radial deviation and ulnar deviation for the wrist [16]. The subject starts with a flexed forearm and an open palm. A number of movements are performed in which the palm faces up or down (supination and pronation) and the tip of the fingers face straight up or down (flexion and extension of the wrist). The hand and forearm are moved forward and backward to change the angle formed at the elbow (elbow flexion and extension). The system provides live feedback through hand and skeleton animations as well as informing the user about the state of the respective joints. The user uploads the data to the server and then selects the option to view the data visually. The user can view graphs for different metrics such as joint range of motion, speed of movement of a joint and distance between two joints. The graph is plotted with time frame on the x-axis. For therapies in which multiple joints are tracked, the graphs are aligned vertically so that the therapist can see the relative movement of the joints in one glimpse.

The system provides live feedback to subjects preforming exercises on the correctness of the exercise procedure in a non-invasive manner. An instructor can record an exercise therapy in front of the system. For this purpose, an authoring environment was developed. The authoring environment lets the therapist design a therapy by selecting the joints to be tracked and their associated movements in an interactive manner. After describing the therapy through the interface, the therapist records the actual movements which constitute the therapy by performing them in front of the camera and sensor setup. While recording the therapy, the therapist is given live visual feedback by the system. An on screen window receiving the live stream from the Kinect sensor shows an animated skeleton following the actions of the therapist. Another window is fed the live stream originating from the Leap controller. It shows the movements of the hands as the therapist performs the exercise. The recorded therapy can then be uploaded to the server. A child can access the therapy online and download it. The child can replay the therapy and practice performing it. The practice session of the child can also be recorded and uploaded to the server. Once a session is uploaded, the analytics component of the website can perform data analysis and draw detailed graphs to show the location of different joints as well as their speed of movement and range of motion. The framework can also provide live feedback to the user. The system has the ability to detect different states of motion for each of the 35 joints of the body that it detects. The therapies recorded by the therapist are stored in a database in the system. The system can compare the current state of the user's joints and compare them to the states stored for the prescribed therapy.

[2] http://www.json.org/
[3] http://en.wikipedia.org/wiki/Biovision_Hierarchy
[4] http://www.jqplot.com/

The system can hence suggest the user if he/she is performing the exercise in the right manner or if there is any need for correction. The system can also suggest measures to correct the exercise practice. As an example, if the user is supposed to have his hand in the pronated state whereas his hand is in the supinated state, the system can emit a warning signal or show an error message on the screen.

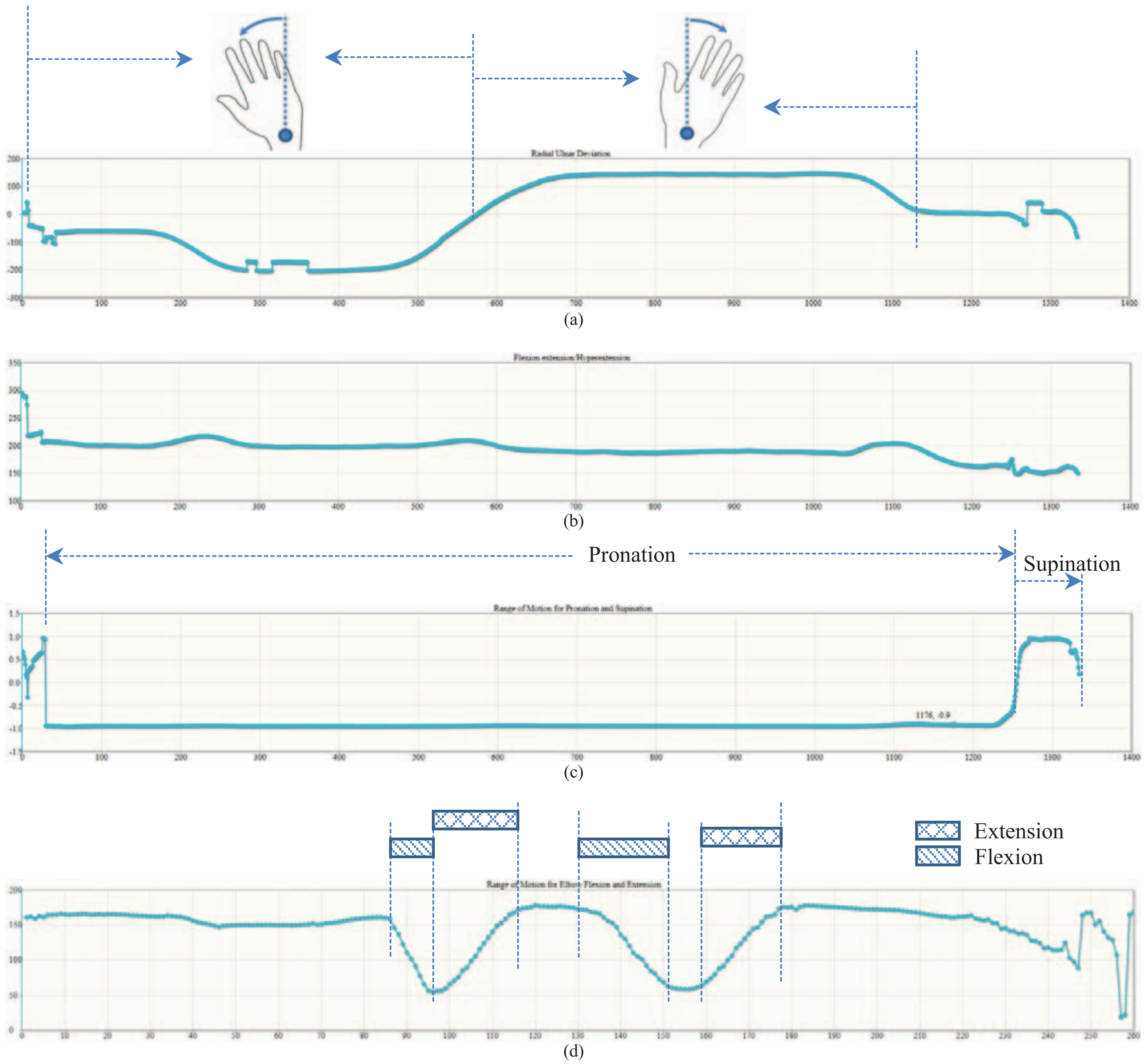

Fig. 4. Live plots showing kinematic analysis of (a) wrist radial-ulnar deviation (b) flexion extension/hyperextension of wrist (c) pronation-supination of palm surface and (d) flexion-extension of elbow joint.

D. *Analysis of Test Result*

Fig. 4 shows the result of the exercise described in Section III.C. Fig. 4(a) shows a session in which hand horizontal movement is plotted. X axis shows the number of frame while the Y axis shows normalized range of motion. As seen in Fig. 4(a), during the therapy session, the user only moved his/hand once in the right direction and once in the left direction. In other words, the +ve Y value shows ulnar deviation while the –ve Y value indicates a radial deviation. Hence, by real-time intercepting the LEAP and Kinect frames and looking at the Y value gives us a great insight about the radial/ulnar deviation movement of the wrist. Another very important data is the number of frame. Since both LEAP and Kinect can be configured to supply e.g. 60 frames per second, number of frame gives us the temporal dimension. We can use this temporal dimension to calculate, for example, speed of movement, total therapy duration, time taken to complete one unit ulnar deviation etc. These are very important parameters to decide the quality of therapy exercise. This instantaneous frame data helps us in deciding whether a motion started or not. We can employ inverse kinematic algorithms to infer whether correct motions are performed by user or not and hence, can update the subject doing the therapy in real-time.

Similarly, Fig. 4(b) shows that the wrist was initially hyperextended for a short duration and then it was in the extension state for the rest of the therapy session. Fig. 4(c) shows the subject's palm was in pronation state (palm surface facing downward) for most of the time while at the end it was in supination state (palm facing up). Finally, Fig. 4(d) shows the movement of the elbow while elbow was flexing and extending to adjust the map browsing directions.

IV. Conclusion

In this paper, we have developed a novel system that can provide live feedback in the form of inverse kinematics to a patient performing a therapy exercise. The system has the ability to detect different movements occurring at different joints. Based on this ability, it can inform the user if the performed action is the one desired or not. We have merged two state of the art gesture recognition platforms called Kinect and LEAP to be able to recognize full body gesture recognition capability. The developed system is open source and web based. Hence, any patient can do the therapy at home while sharing the therapy data with the therapist. Our developed framework is non-invasive, hence, does not require any sensors attaching to the body. We have developed serious games that can provide therapy to hemiplegic children in an entertaining way.

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