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Kinect-enabled home-based rehabilitation system using Dynamic Time Warping and fuzzy logic

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ABSTRACT

Most formal rehabilitation facilities are situated in a hospital or care center setting, which may not always be conveniently accessible for patients, especially those in geographically isolated areas. Home-based rehabilitation has potential to offer greater accessibility and thus increase consistent uptake. In addition, the exercise performed in conventional rehabilitation contexts may be insufficient to ensure the patient's speedy recovery, with complimentary rehabilitation exercises at home required to make a difference. The goal is to provide effective home-based rehabilitation offering outcomes similar to those obtained through hospital-based rehabilitation under the supervision of an occupational therapist. This paper presents the development of a Kinect-based system for ensuring home-based rehabilitation using a Dynamic Time Warping (DTW) algorithm and fuzzy logic. The ultimate goal is to assist patients in conducting safe and effective home-based rehabilitation without the immediate supervision of a physician.

1. Introduction

1.1. Research background and motivation

Many countries are experiencing a rapid aging of their populations, are faced with the need to replace increasingly scarce skilled workers with technology-based substitutes. Part of this trend is the increased use of assistive technology to provide traditionally hospital-based medical services at home.

In the case of rehabilitation, traditional therapy is generally conducted in a hospital setting and requires direct supervision by a trained caregiver. The aim of home-based rehabilitation is to provide an in-home alternative to in-hospital rehabilitation. Home-based rehabilitation allows for great flexibility, allowing patients to tailor their rehabilitation program to individual preferences and schedules. In many countries today, home-based rehabilitation services enjoy government support, and the number of patients applying for such services has increased significantly in recent years [1]. Demand for medical services will soon outstrip the supply of registered physicians, necessitating the development of a more economically-viable home-based treatment program without the presence of a health care worker.

Such home-based solutions would also reduce the inconvenience of traveling to distant clinics for regular therapy services. Patients may not have enough time to go to the clinic or lack transportation. For many patients, frequent travel to the clinic is a significant economic burden. Moreover, the rehabilitation exercises conducted in a formal clinic setting may be insufficient to ensure the patient's recovery without supplementary rehabilitation exercise at home. To address these issues, physicians frequently prescribe a personal home-based rehabilitation exercise for patients, thus increasing the rehabilitation treatment effect and reducing the frequency of clinic visits. However, without professional supervision, home-based rehabilitation exercises could be, at best, ineffective and, at worst, unsafe.

In this paper, we describe our development of a Kinect-based system – the Kinect-enabled system for ensuring home-based rehabilitation (KEHR) using a Dynamic Time Warping (DTW) algorithm and fuzzy logic to ensure the effectiveness and safety of home-based rehabilitation. Using KEHR, the patient first performs a prescribed exercise in the presence of a health care professional. The exercise is recorded as a base for evaluating the patient's rehabilitation exercise at home, and these evaluations can be used as a reference for the patient to validate his/her exercise performance and to prevent adverse events. A summary report of the outcomes may also be automatically uploaded to a cloud setting for physicians to monitor the patient's progress and adjust the prescription.

1.2. Kinect

The Kinect was launched on November 2010 as a webcam-style add-on peripheral for the Xbox 360 gaming console, enabling users

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to interact and control games without using through a natural user interface using gestures, voice or images rather than a controller or body sensors [2,3].

Since its launch, software developers began to use the Kinect for other applications, raising the possibility of using it as part of a rehabilitation tool. Currently, the Kinect is being used in conjunction with PCs in ways that its designers could not have foreseen, from helping children with autism to helping doctors in the operating room [4].

The Kinect SDK for Windows provides detailed location, position and orientation information for up to two players standing in front of the Kinect sensor array. Previous devices had difficulty tracking human motion using a camera without body sensors. The process of extracting the human figure from video images proceeds in two phases: (1) preprocessing that detects the human object silhouette and extracts silhouette descriptors and (2) pose estimation that quantitatively characterizes and localizes human limbs in each frame. The Kinect not only provides skeletal tracking capabilities without body sensors but also furnishes a low-cost mechanism for developing home-based systems to improve our daily life.

1.3. Dynamic Time Warping algorithm

Euclidean distance metrics are commonly used for comparing two time series due to their ease of calculation. In this research, however, patients may perform their recorded exercises for different durations and under varying conditions. Euclidean distance measurement between frames is generally unsuitable for comparing two sequential movements of different durations because it is sensitive to even a small distortion in time axis. A distance measurement called Dynamic Time Warping (DTW) has been widely applied in speech processing [5–7] and can be used to address the issue of time axis distortion.

The nonlinear dynamic time-warped alignment allows for the calculation of a more intuitive distance measurement. A method which does not suffer from the abovementioned shortcoming of Euclidean distance is needed to determine the similarity between the standard and the patient's actual exercise performance.

DTW algorithm is an extremely efficient time-series similarity measurement which minimizes the effects of shifting and distortion in time by allowing the elastic transformation of time series to detect similar shapes. These advantages are used here to compare two sequences of different durations to determine the similarity between the standard and the patient's exercise performance.

1.4. Fuzzy logic

Physicians evaluate the trajectory and speed of rehabilitation exercise mainly based on their experience and subjective criteria without using more precise and measurable computer-based values. Therefore, we cannot set a value of trajectory and speed to evaluate results using traditional logic theory. In contrast with traditional logic theory, where traditional binary sets have a two-valued logic (i.e., true or false), fuzzy logic variables may have a truth value that ranges between 0 and 1.

The proposed approach collects the physician's subjective evaluation and uses the DTW algorithm to collect trajectory and speed data to build a fuzzy inference model of the physician's subjective evaluation.

2. Literature review

2.1. Device-assisted rehabilitation

Many studies have used industrial motion sensors [7] and the Nintendo Wii Remote [8] to assist physicians and patients. Video games or virtual reality (VR) environments have been used to divert the patient's attention during the rehabilitation process, thus relieving feelings of discomfort and boredom, and physicians have used the rehabilitation data collected by the devices to better understand and monitor the patient's rehabilitation process. These studies have shown that motion sensors are useful as physical rehabilitation tools and confirm feasibility of device-assisted rehabilitation. However, to be effective, motion sensors need to be securely fastened in place, held or worn, which can cause discomfort and inconvenience.

Launched on November 2010, the Kinect provides full-body control of animated virtual characters without the use of body sensors. Sports and fitness games for the Kinect [9] let users to do exercise in their home but, in terms of evaluating the correctness of the user's motions, most of these games simply just check the user's final pose. Nevertheless, these games raise the possibility of Kinect-based exercise applications and PC-connected Kinect units have considerable potential as tools for physical rehabilitation.

2.2. Kinect applications

The Kinect is a low-cost device which can track human movement with its camera. Among the recent academic studies involving the device, many focus on real-time gesture classification and motion recognition systems [10,11]. Chang et al. [12] used the Kinect to train individuals with cognitive impairments to engage in vocational tasks, and later built a Kinect-based rehabilitation system for young adults with motor disabilities [13]. Researchers at Taiwan's National Central University and the Taipei Veterans General Hospital [14] integrated the Kinect in a VR environment to increase patient motivation for physical rehabilitation. Lange et al. [15] used the Kinect to develop an interactive game-based rehabilitation tool to provide balance training for adults with neurological injuries.

These papers showed that using Kinect could improve patient motivation and rehabilitation outcomes. However, these rehabilitation systems were designed to address specific cases through the development of one-off games, and do not allow physicians to design or modify personalize rehabilitation exercises for different patients. This is a key issue given the different rehabilitation needs among different patients, even among those with identical diseases or conditions.

Wu [16] established a motion matching model called View-Invariant that uses 3D coordinates of the key pose to calculate the distance between 15 joints of live motion skeletons, and integrated the Kinect with OpenNI [17] software to recognize human motion. Basing comparing on the frame of key pose reduces computational requirements, but loses information from one key pose to the next. This method is not appropriate for rehabilitation exercise tracking because of the need to compare all frames during the exercise to detect and improve incorrect motions.

Our research uses skeletal information to evaluate the exercise. The Dynamic Time Warping (DTW) algorithm is used to compare all frames between the patient's rehabilitation exercise and physician's model exercise.

2.3. Dynamic Time Warping (DTW)

DTW is basically a sequence matching algorithm that can adapt to sequences that vary in speed and time. The algorithm has been applied to video, audio and graphics – indeed, any data which can be turned into a linear representation can be analyzed with DTW. It is currently used in many areas including gestures recognition [18], handwriting [19], time series clustering and data mining [20–22].

Bobick and Wilson [23] used DTW to match an input signal to a deterministic sequence of states. Muscillo et al. [24] used