RehabFork: An Interactive Game-assisted Upper Limb Stroke Rehabilitation System

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***Abstract*— In this paper, we present the design and development of a game-assisted stroke rehabilitation system RehabFork that allows a user to train their upper-limb to perform certain functions related to the task of eating. The task of eating is divided into several components: (*i*) grasping the eating utensils such as a fork and knife; (*ii*) lifting the eating utensils; (*iii*) using the eating utensils to cut a piece of food; (*iv*) transferring the food to the mouth; and (*v*) chewing the food. The RehabFork supports the user through sub-tasks (*i*)–(*iii*). The hardware components of RehabFork consist of an instrumented fork and knife, and a 3D printed pressure pad, that measure and communicate information on user performance to a gaming environment to render an integrated rehabilitation system. The gaming environment consists of an interactive game that utilizes sensory data as well as user information about the severity of their disability and current level of progress to adjust the difficulty levels of the game to maintain user motivation. Information pertaining to the user, including performance data, is stored and can be shared with care providers for ongoing oversight.**

I. INTRODUCTION

Stroke is a common contributor to deterioration of motor function. Impairment in upper limb motor control impacts the performance of activities of daily living (ADLs), increases dependency, and reduces participation in social activities, all of which contribute to degradation in quality of life [1]. One of the most common ADLs affected is eating [2]. Some of the difficulties related to eating include *manipulating food on the plate and transporting food to the mouth* [3].

The concept of neuroplasticity has been widely studied to enhance the rehabilitation outcomes of post-stroke patients [4]. Cortical reorganization of the brain is known to play an important role in neuroplasticity, which may potentially decline due to physical inactivity associated with post-stroke disability [5]. To avoid this, it is important for patients to engage in immediate rehabilitation that follows key principles such as intensive and repetitive practice of functional and task-specific activities. Moreover, rehabilitative training that focuses on recovery of ADLs and is relevant to the needs of patients can help stroke patients regain their motor skills. Nonetheless, excessive cost [6], shortage of skilled therapists, tedious exercise routines, and lack of patient motivation [7] have been cited as reasons for low rates of successful therapeutic completion and outcomes.

The incorporation of robot-assisted interventions for rehabilitation has been deemed promising [8]. Many studies have also examined the efficacy of incorporating multimedia technology to existing rehabilitation robots for increasing patient motivation and engagement [9]. In fact, such game-assisted interventions have been shown to improve myriad aspects related to rehabilitation process and outcomes, including attention, speed, precision, and patient autonomy [10]. However, the choice of the game for rehabilitative purposes is non-trivial and may even be tricky. The gaming platform should be capable of assisting rehabilitation and supporting different rehabilitation principles such as task-oriented training, promoting functional movements, providing appropriate feedback, and encouraging motivation.

Physical rehabilitation for upper limbs has predominantly focused on unilateral activities. However, many ADLs rely on bilateral movements [11], making it essential to train for bilateral movement recovery. However, most existing rehabilitation devices that offer bilateral training are heavy and bulky [12]. In recent years, many researchers have developed various devices that can be integrated with the state-of-art game consoles such as Sony PlayStation, Nintendo Wii, Microsoft Kinect, among others, [13]. The majority of these systems adopt commercially available video games for rehabilitation purposes, and fail to ensure that users receive adequate rehabilitation [13]. Finally, the cost of rehabilitation therapy is considered a barrier to stroke rehabilitation. Hence, to address the rising cost of stroke rehabilitation, it is critical to develop low-cost devices for at-home therapy use by patients.

To address these issues, we designed and developed a rehabilitation system called RehabFork. In prior research, we have developed a task-specific upper extremity rehabilitation system, an instrumented cup, that helps post-stroke patients to perform the activity of drinking from a cup as the part of their rehabilitation [14]. Building on [14], RehabFork supports and encourages stroke patients to perform repetitive practice of functional sub-tasks of eating such as (*i*) grasping eating utensils; (*ii*) lifting eating utensils; and (*iii*) using the eating utensils to hold down and cut a piece of food as a part of their rehabilitation exercises. The activity of using a fork and knife is a bilateral task, and is a part of the Functional Task Battery [15] that lists twenty essential ADLs that require the use of the upper limb(s).

The major contributions of this paper include design and

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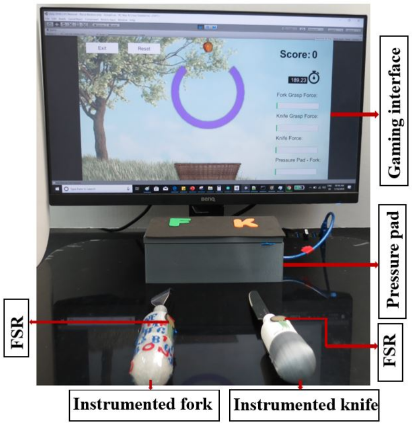

Fig. 1: Prototype of upper-extremity rehabilitation system consisting of an instrumented fork and knife, a 3D printed pressure pad, and an interactive gaming interface.

development of (*i*) an innovative rehabilitation system for the ADL of eating; (*ii*) an at-home rehabilitation system for post-stroke patients that requires only three pieces of hardware, *viz.*, an instrumented fork, an instrumented knife, and a 3D printed pressure pad; and (*iii*) an interactive game that encourages users during upper-limb rehabilitation and adapts to different severity levels of patients.

II. Design and Development

The RehabFork system (see Fig. 1) consists of an instrumented fork, an instrumented knife, a 3D printed pressure pad, and a PC-based game that provides real-time feedback to post-stroke patients (henceforth called users) regarding their performance. This system helps users to train for the complex sub-tasks of eating, namely (*i*) grasping a fork and knife, (*ii*) lifting and turning the fork to hold down food, and (*iii*) cutting food using the knife. The interactive gaming environment, designed using the Unity game engine, provides real-time sensory feedback to the user to support them in the performance of each sub-task. The sensory feedback is based on sensor data from the hardware and it includes information such as grasping, poking, and cutting forces and the angle of rotation of the forearm. Additional caps for the handles of the fork and knife were designed, 3D printed, and mounted as shown in Fig. 1. The purpose of the 3D printed caps is to support the users in successfully grasping the fork and knife, despite the severity of their condition. On each 3D printed cap handle, two force sensitive resistors (FSRs) are attached diametrically opposite to one-another to obtain the grasping force measurements. When the user grasps the instrumented utensils the average force value of the FSRs gives the grasping force. The dimension and weight parameters of instrumented fork and knife of the RehabFork system are given in Fig. 2. Each of the hardware components is briefly described below.

1) Instrumented Fork: Two Interlink 402 FSR sensors and one BNO055 Inertial Measurement Unit (IMU) are attached to the fork handle cap. The IMU, housed inside the fork handle cap, is used to obtain the rotation measurements of the user's forearm when the user manipulates the fork. A Bluno Beetle, an Arduino-based Bluetooth Low Energy (BLE)-enabled microcontroller, housed inside the fork handle cap, is used to acquire and process the FSR and IMU data of the fork and to wirelessly transmit these data to the Unity game engine.

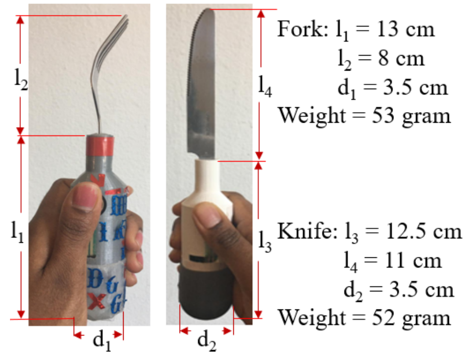

Fig. 2: Dimension and weight parameters of instrumented fork and knife.

2) Instrumented Knife: To obtain the knife grasp force value, two Interlink 402 FSR sensors are attached to the handle cap of the knife. Another Bluno Beetle microcontroller, housed inside the knife handle cap, is used to acquire and process the FSR data of the knife and to wirelessly transmit these measurements to an Arduino Nano microcontroller of the pressure pad for further transmission to the Unity game engine.

3) Pressure Pad: The pressure pad is a 3D printed box that consists of separate regions designed for fork and knife actions. Two square Interlink 406 FSR sensors are attached to the base of the fork and knife regions. The fork region is used to obtain the force that the user applies to this area of the pressure pad as they hold it down using the fork to simulate the action of holding down food. The knife region similarly consists of another FSR that obtains the force the user applies to that area of the pressure pad to simulate the action of cutting food. The pressure pad is a wired system consisting of an Arduino Nano microcontroller that processes the FSR data for the poking and cutting forces and transmits these measurements, concatenated with the measurements received from the instrumented knife, to the Unity game engine through a USB connection.

The Bluno Beetle and Arduino Nano microcontrollers obtain and transmit sensor measurements from the instrumented fork, knife, and pressure pad at a sampling rate of 60 Hz.

The framework of the RehabFork shown in Fig. 3 consists of three major pathways for the patient interaction with the gaming system, namely (*i*) through the instrumented fork, (*ii*) through the instrumented knife, and (*iii*) through the instrumented fork and knife. Regardless of the chosen pathway, the first step in the game is calibrating for the acceptable force parameters. Specifically, in the calibration step, if a user is hemiplegic, they will be prompted by the game to use their unaffected hand to grasp the instrumented fork and knife, one after the other, and simulate the action of

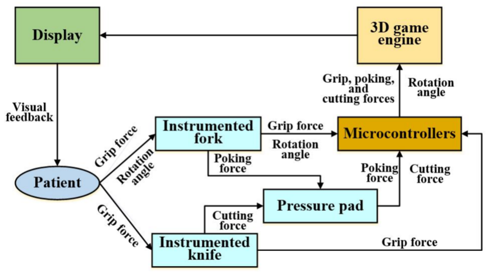

Fig. 3: Framework of upper-extremity rehabilitation system

poking and cutting on the pressure pad. Alternatively, users can select to use system default values for force parameters obtained from a healthy user.

In the first pathway, i.e., through the instrumented fork, user-specific information on grip force and forearm rotation are measured using the FSRs and IMU, respectively, embedded in the 3D printed handle cap, and the poking force is measured using the pressure pad, all of which are communicated to the game engine using the microcontrollers. In the second pathway, i.e, through the instrumented knife, the user-specific information regarding the grip force and cutting force are measured with the FSRs, embedded in the 3D printed handle cap and the pressure pad, respectively, and communicated to the game engine using the microcontrollers. Finally, the third pathway combines the actions and information of the above two pathways.

III. GAMING ENVIRONMENT

In this section, we present the details of the designed gaming interface that maintains user motivation and engagement as they train their upper-limb to perform multiple repetitions of certain sub-tasks of eating. The target population includes patients with varying severity of upper-limb disabilities and may include elderly patients at home. Keeping this in mind, the gaming environment developed using the Unity game engine is deployable on a PC or laptop and it does not require any specific gaming hardware. As the user manipulates the instrumented fork and knife along with the pressure pad, the interactive gaming interface displays a combination of game objects that respond to the user's actions. Note that the RehabFork gaming interface yields an average update rate of 60 frames per second. Moreover, it consists of three progressive levels that are described below.

A. Level 1 and Level 2

Levels 1 and 2 of the game utilize the instrumented fork pathway with the pressure pad. The instrumented knife pathway is not utilized during game play in these levels. The force bar on the screen displays the amount of force (on a linear scale) that the user needs to apply to grasp the fork. This required force corresponds to force parameter values set during the calibration step. The game scene in Levels 1 and 2 contain three objects–a Ring, an Apple, and a Basket. Once the user grasps the fork with sufficient force, the top of the 'Ring' game object opens up and the 'Apple' game object enters the ring. Once the user lifts the fork, rotates their forearm to at least 90°, and points the fork

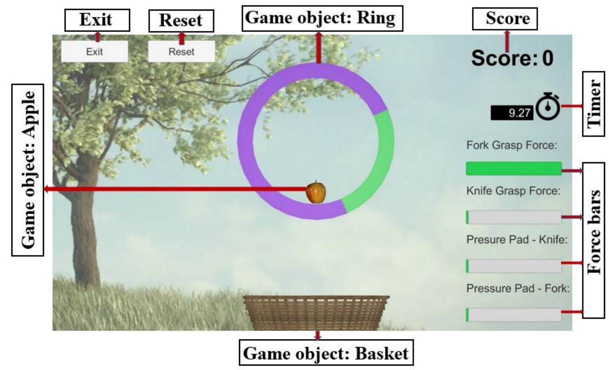

Fig. 4: Levels 1 and 2 gaming interface

towards the pressure pad, the ring closes and rotates such that the opening of the ring points towards the 'Basket' game object placed on the ground. The rotation of the ring is driven using the IMU sensor data for the angular rotation of the forearm. As the user 'pokes' down on the pressure pad with the fork, the ring opens up and the apple falls into the basket. This completes Level 1 of game and the user is shown the time taken to complete the activity and score. To progress to Level 2, the user has to successfully complete the Level 1 activity three times. Level 2 follows the same mechanism as Level 1. In Level 1, the minimum force required to grasp the instrumented fork is calculated as 50% of the average calibration force of the unaffected hand. In Level 2, this is increased to 75% of the average calibration force of the unaffected hand. The user also needs to orient the fork with respect to the fork region of the pressure pad more accurately (rotate the forearm at least 135°) to complete Level 2 successfully. To progress to Level 3, the user has to successfully complete the Level 2 activity six times.

B. Level 3

In Level 3, both the instrumented fork and knife pathways are utilized *via* the pressure pad and a fourth game object, an Apple box, is included. The first stage of Level 3 resembles the previous levels, i.e., the user grasps the fork, lifts it, rotates it, and positions it with respect to the pressure pad. In response, the apple game object on the screen moves in the ring, the ring rotates, the ring opens up, and the apple falls into the 'Apple box' game object floating above the basket. In the second stage of Level 3, the user grasps the knife by applying at least the minimum force as displayed on the corresponding force bar on the screen. The bars in Level 3 display 100% of the calibrated force value of the unaffected hand. Once the user has successfully grasped the knife, they lift and place it on the designated knife region of the pressure pad and simulate the cutting motion. This force value from the action is transmitted to the game engine by the microcontroller and it triggers the apple to slide down into the basket. At this stage, the user needs to perform the task nine times to complete the activity.

A timer records and displays the task completion time, serving as a metric of user performance in addition to other game metrics, namely, (*i*) scores and (*ii*) progression in

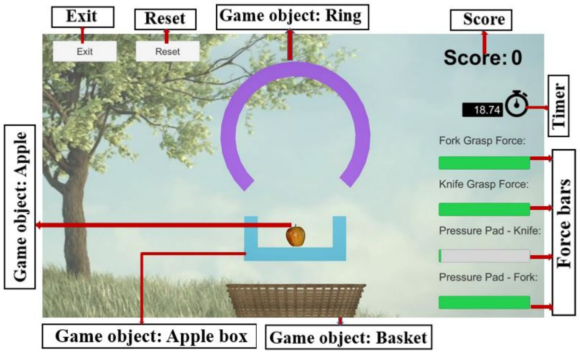

Fig. 5: Level 3 gaming interface

levels. Finally, all the user information and their performance data (including scores, levels of game completed, time taken to complete each activity, grasp quality, and poking/cutting force values, etc.) are stored in a database and the therapist can access this information to monitor the user's progress.

IV. USER STUDY

To perform a subjective assessment on the usability of RehabFork, and its potential to assist with eating, a user study was conducted with 10 healthy subjects (six males and four females). The subjects were asked to perform Level 3 of the game with RehabFork since this level consists of all sub-tasks of using RehabFork. Once subjects completed the activity, a device usability questionnaire (DUQ), inspired by [16], and a user motivation test (UMT), inspired by [17], were given to obtain their responses. See http://engineering.nyu.edu/mechatronics/embc2020.htm to access DUQ and UMT. Both DUQ and UMT contain 10 questions (odd and even questions with negative and positive statements, respectively) on a five-point Likert scale (1 indicating strong disagreement and 5 indicating strong agreement). The average response for each survey question is shown in Fig. 6. All subjects agreed or strongly agreed that various movements of fork and knife are well integrated. Seven of the 10 subjects disagreed or strongly disagreed that it took long time for them to become comfortable with the device. All subjects disagreed or strongly disagreed that the game objects did not move based on the movements of fork and knife. Nine subjects indicated that they would recommend this device for upper-limb rehabilitation.

V. CONCLUSION AND FUTURE WORK

A task-specific, game-assisted upper limb rehabilitation system, RehabFork, is designed and developed. The system consists of an instrumented fork, an instrumented knife, and a 3D printed pressure pad. To improve the motivation of users, a gaming interface is developed. To assist the users depending on the severity of their disability, different game levels are provided. This rehabilitation system is designed for at-home rehabilitation settings. Since stroke patients are vulnerable population, preliminary tests are carried out with healthy subjects. In future research, additional activities will be considered for inclusion with the device. Moreover, user

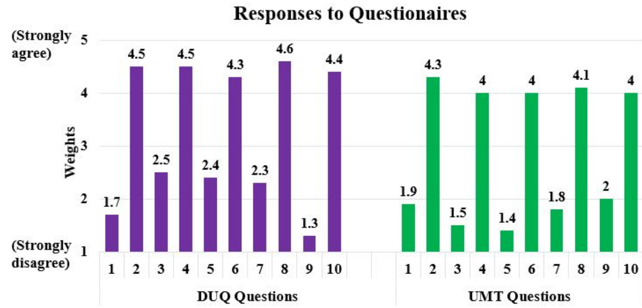

Fig. 6: Subjects' responses to DUQ and UMT questions

studies will be conducted with disabled individuals/stroke patients to test the efficacy of RehabFork.

DECLARATION

This study was approved by the Institutional Review Board and subjects provided informed consent.

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