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Enrichment of a Kinect-based Physiotherapy and Assessment Platform for Parkinson's Disease Patients

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ABSTRACT

Our Kinect-based physiotherapy platform tailored to Parkinson's disease (PD) patients employs a Kinect sensor to extract 3D skeletal data in real-time from an exercising patient. The initial collection of five exercises served by the platform has now been enriched with an additional five exercises which are also based on traditional PD-specific physiotherapy. Each exercise has been implemented in the Unity 3d game engine and employs either a linear or a circular movement pattern with very light-weight processing demands for real-time computations. During each exercise, a trainer demonstrates correct execution and patient-provided 3D joint data obtained via the Kinect sensor are compared to exercise-specific control routines in real time, in order to assess proper posture and body control. Following completion of an exercise, performance metrics appropriate for that exercise are computed and displayed on screen as feedback to the patient. In addition, they are stored to provide a historical progress record to, e.g., enable the attending physiotherapist to fine-tune the exercise to the abilities/needs of an individual patient.

Keywords: Parkinson's disease; Rehabilitation; Augmented Reality; Microsoft Kinect.

1 Introduction

Parkinson's disease (PD) expresses the results of the damage of dopamine-producing neurons in the brain. Dopamine acts as a mediator for transferring electrical signals (messages) and helps humans retain smooth, controlled and purposeful movement. When a large percentage of those dopamine producing neurons are damaged, the motor symptoms of PD set in. At the onset of the disease and in early stages, PD affects mostly motor function, but in more advanced stages patients commonly also suffer from cognitive, behavioral and mental-related symptoms [1]. The four fundamental motor symptoms of the disease (Tremor, Rigidity, Akinesia (or bradykinesia) and Postural instability) are commonly referred to by the acronym TRAP [2] and can encumber daily activities and reduce the quality of life, especially as the disease progresses [3], [4]. The active ingredients of drugs commonly used to control PD-related symptoms and maintain body functionality at reasonable levels include levodopa, dopamine agonists, MAO-B inhibitors, COMT inhibitor, anticholinergic agents and amantadine. However, symptom variability and their severity in the lifetime of patients make standard medication paths difficult to achieve [5].

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In addition to medical treatment, physiotherapy [6], [7], [8] and [9] is highly effective in controlling and even delaying PD-related symptoms and is openly supported by a number of Parkinson clinical facilities and associations. Physical exercise such as stretching, aerobics, unweighted / weighed treadmill and strength training improves motor functionality (leg stretching, muscle strength, balance and walking) and quality of life [10]. Prominent among those approaches, the "training BIG" strategy for PD rehabilitation [11] has shown especially promising results. Training BIG advocates exercises that deploy the entire body both in seated and in standing posture (such as reaching and twisting to each side or stepping and reaching forward) that are to be performed at maximum range of motion (maximum amplitude). A recent review [12] of relevant technology-aided rehabilitation platforms gleans a number of useful design principles for physiotherapy solutions intended for the PD population.

In this work we report on enriching our existing Kinect-based, augmented reality, real-time physiotherapy platform tailored to PD patients [13]. The platform is meant to augment and not replace physiotherapy sessions and allows a patient to exercise in front of a large TV monitor - instead of in front of a mirror. Platform hosted exercises can be parametrized to cater to the individual patient abilities, This is very important for progressing diseases like PD, as they allow for tailoring of different exercises to patients as medium-term gains from exercise or medication are realized or even as the disease progresses. The present work expands the existing exercise compendium to allow physiotherapists more freedom in shaping customized exercise schedules to individual patients.

The choice to employ the Kinect sensor offers a unique opportunity to create a "closed-loop" system which facilitates patient monitoring during exercise to provide real time feedback, such as on-screen guiding artifacts and repetition counters and to alert the patient on his/her performance. Of significant importance to clinical motor assessment is the platform's ability to quantify patient mobility/dexterity on a per-exercise basis using exercise-specific performance metrics. Although such detailed "kinesiological imprints" can be affected by various factors, such as time of day, patient tiredness, effectiveness of administered drugs, on/off times, meaningful and statistically sound results over a period of a few days of using the platform are possible: for example, exercise early in the day and at the same time after taking medication. As a result, carefully customized daily exercise schedules afford the possibility to collect a time series of performance data that can be usefully correlated with e.g., detailed medication history records and disease progress.

2 Platform specifics and Exercises

The physiotherapy platform [13] relies on the Kinect sensor to supply real-time 2D (RGB camera) and depth (IR depth camera) streams. These data streams are combined by the Kinect SDK to (a) identify a patient in front of the sensor, (b) extract that person's skeleton as a hierarchy of nodes with 3D location data and (c) update that skeleton in every frame, effectively tracking the patient. The full skeletal model appears in Figure 1. The logic for each exercise has been coded in the C# programming language in the Unity3D game engine.

The existing exercise compendium has been enriched with the following five additional exercises, which are adapted from mainstream PD-specific physiotherapy exercise curricula: (1) Forearm rotations, (2) Hips rotations, (3) Rowing with a broomstick, (4) Bench presses with a broomstick and (5) Upper torso twists. Of these, the first two are executed from a standing position and the remaining three from a sitting position. These new exercises share the following traits with the original platform exercises:

a) They can be performed reasonably well by PD patients with mild to moderate symptoms (stages 1 through 3 in the Hoehn and Yahr [14] scale, i.e., without severe postural instability / motor impairment), and

b) For the entire duration of an exercise, the patient can maintain a posture that adheres to the capabilities of the Kinect sensor. Practically, this means that the Kinect sensor must at all times be able to track the patient's body to extract an accurate skeletal model for the full range of the exercise (e.g., a limb should not occlude another limb).

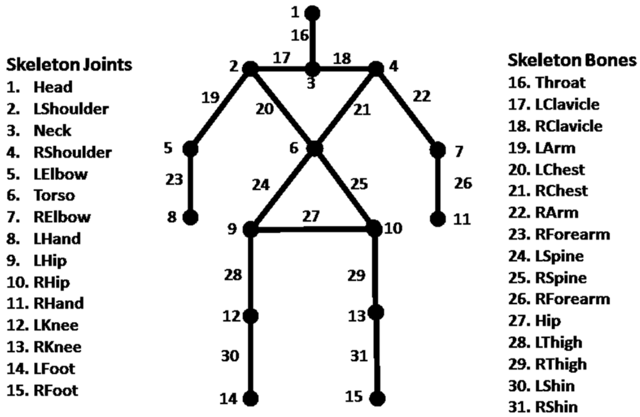

Figure 1: Joints utilized in the physiotherapy platform.

Exercises 1 through 3 employ circular movement patterns and exercises 4 and 5 employ linear movement patterns to lower the processing demands of real-time computations as far as possible. The real time joint data provided by the Kinect sensor are fed to the game engine and are checked also in real time for adherence to exercise-specific control routines in order to assess proper posture and body control for the entire duration of the current repetition. Visual feedback is provided via augmented reality artifacts showing e.g., the skeleton being tracked as well as repetition counters. When an exercise is complete, performance metrics appropriate for that exercise are computed and displayed on screen (a) to enable the attending physiotherapist to fine-tune the exercise to the abilities/needs of an individual patient and (b) to provide performance feedback to the patient.

Exercise 1 – Forearm Rotations: Facing the Kinect sensor, the patient assumes a relaxed standing stance with feet spaced apart at about shoulder width, holding the right elbow with the left hand for stabilization and extending the right forearm to his/her right at an angle of approximately 45^o to the superior (vertical) axis, as shown in the first snapshot in Figure 2. Then, from that stance, he/she has to complete N cyclic movements of the right wrist, as shown in the second snapshot in Figure 2. When the exercise for one (right) arm is complete, the patient may exercise the other (left) arm in an analogous way, as shown in the last two snapshots of Figure 2. The default value of N for each exercise is 10. During each cyclic movement, the wrist describes circles on imaginary planes that are parallel to the sagittal plane. Game code relevant to this exercise checks for correct execution as follows:

- Ideally, the elbow of the arm being exercised must remain fast for the duration of the exercise – that is the intention of the other hand holding and stabilizing the elbow of the exercising arm, in which case the distance in 3d space between the elbow being exercised and the wrist joint of the stabilizing arm must be small. Deviations of this distance from an empirically estimated maximum value imply that the exercise is not performed correctly and the current repetition is annulled.

- For the arm being exercised, the motion pattern of the wrist projected to the sagittal plane is checked for circularity, in that it must follow a superior-anterior-inferior-posterior-superior sequence (or, alternatively, a superior-posterior-inferior-anterior-and back to superior sequence). This check is meant to count only circular but not linear patterns, such as the wrist moving vertically, horizontally or even along a diagonal.

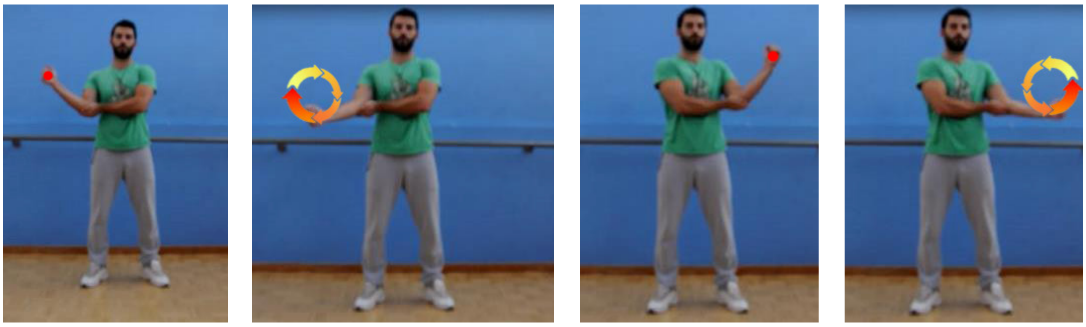

Figure 2: Exercise 1 is an arm stretching/strengthening exercise executed from a standing position. Snapshots of a trainer performing the exercise in front of a 25" monitor at a distance of approximately 2.5m from the Kinect sensor (placed to the left of the monitor). In actual deployment, a much larger 55"-58" monitor would be preferred.

A repetition is considered successful if it passes both tests described directly above, in which case an appropriate on-screen counter (Ls for the left arm or Rs for the right arm) is incremented by one. On the other hand, a repetition (for the left or right arm) is considered a failed repetition if the corresponding wrist prescribes at least half a circle but does not complete that circle, in which event a "failure" counter (Lf or Rf) is incremented accordingly. When Ls or Rs reaches N, the success and failure counters corresponding to that arm stop incrementing. The exercise is considered complete when both Ls and Rs equal N, at which point the following performance metrics are shown on screen, separately for each arm: (a) the total of number of failed repetitions Lf or Rf and (b) a circularity metric showing the ratio of the average superior-to-inferior distance divided by the anterior-to-posterior distance. Clearly, for a perfectly executed exercise, Lf=Rf=0 and circularity=1.

These metrics allow easy interpretation (a key design requirement for this collection of exercises). For example, large departures of both Lf and Rf from zero may mean that the patient has not understood the exercise or that the exercise is too hard for him/her. Alternatively, consistently disparate values for Lf and Rf (e.g., Lf close to zero but Rf significantly higher) may reveal a measurable differential in mobility control between the left and right sides. Finally, circularity metric values that deviate significantly from 1 show that the patient favors vertical or horizontal elliptical patterns for that arm. It is then up to the physiotherapist to parameterize the exercise depending on the priorities / goals set forth for a given patient as well as the capabilities of that patient. To quantitatively assess the motor function of a patient in the context of the present exercise (but also for any other exercise in the current compendium), one would explore the parameter space to "push" the patient near the limits of his/her abilities and obtain more valid results over a period of sessions. However, parameterization of the platform for home-based use should probably aim at encouraging patients to exercise more by posing less stringent demands, lest they become discouraged and cease to exercise.

Exercise 2 – Hips Rotations: Facing the Kinect sensor, the patient assumes a relaxed standing stance with hands resting (and supporting) the hips, as shown in the first snapshot in Figure 3. Starting from that stance, he/she has to complete a number of N rotations of the hips around the superior (vertical) axis (shown in the remaining snapshots in Figure 3). During each such cyclic movement, the hips are to describe circles on an imaginary plane that is parallel to the transverse (horizontal) plane. Game code relevant to this exercise is analogous to that employed in exercise 1 and checks for correct execution in the sense that the mid-hip joint must follow a superior-anterior-inferior-posterior-superior sequence or, alternatively, a superior-posterior-inferior-anterior-superior sequence. This check helps avoid linear patterns, such as vertical or horizontal wrist joint movements.

Figure 3: Exercise 2: A balance and leg-strengthening exercise executed from a standing position.

Exercise 3 – Rowing with a broomstick: At a seated position facing the Kinect sensor, the patient holds a light exercise rod / broomstick and executes a rowing motion pattern, as shown in the sequence of trainer snapshots in Figure 4. In more detail, the patient has to complete N circular patterns where the motion pattern of each wrist joint moves on a plane that is parallel to the sagittal plane and is also out of phase by 180^o with respect to the motion pattern of the other wrist joint. It is important to maintain (a) proper posture (e.g., not to let the arms drop under their own weight) and (b) proper control by forcing the exercise rod to form an angle to the vertical axis close to 45^o exactly twice during each successful repetition/cycle. Here also the game control code is a direct modification of that used in the previous two exercises.

Figure 4: Exercise 3: An arm stretching/strengthening exercise executed from a seated position.

Exercise 4 – Upright Bench Presses with a broomstick: Facing the Kinect sensor, the seated patient holds a light exercise rod / broomstick (which helps coordinate the movements of the left and right arms) with both hands at the initial upright stance where the wrist joints are located slightly higher than the shoulder joints (as shown in the first trainer snapshot in Figure 5). Then, from that stance, he/she has to complete N "upright bench presses", as shown in the remaining sequence of snapshots in Figure 5. The travel of each bench press is computed as the maximal distance D travelled vertically by the wrist joints. Relevant game code checks for correct execution by counting only presses with sufficiently large vertical travel, i.e., D > Dmin where Dmin is an exercise-specific parameter set to define the difficulty of the exercise. The default value for Dmin is (LArm+RArm)/4 (defined in Figure 1), which corresponds to an average level of difficulty. For each successful press an appropriate on-screen counter Ms is incremented by one, while each failed bench press increments a "failed rep" counter Mf. The exercise completes when Ms reaches N, at which point the following two performance metrics are computed and shown on screen: (a) the number of failed bench presses Mf and (b) the average press travel <D> as a percentage of Dmin (i.e. <D>/Dmin*100 %).

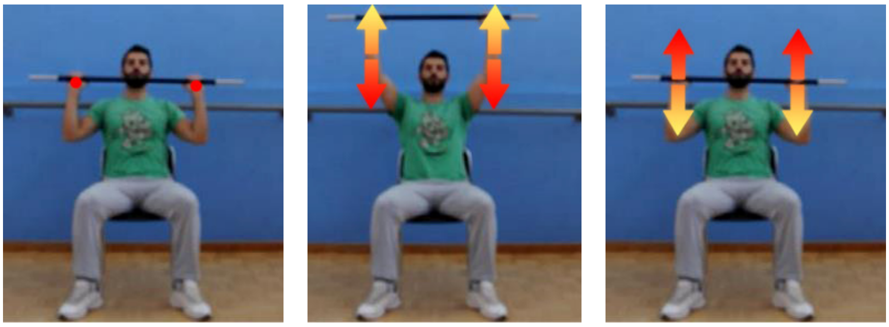

Figure 5: Exercise 4: An arm stretching/strengthening exercise executed from a seated position with the help of a short rod or light broomstick to facilitate coordinated movement of the left and right arms.

Exercise 5 – Upper torso twists: In this exercise, the patient sits facing the Kinect sensor, with feet securely planted on the ground and palms resting on the shoulders for additional control (as shown in the first trainer snapshot in Figure 6). The exercise calls for the completion of N full rotations / twists of the torso about the superior (vertical) axis from left to right, as shown in the remaining snapshots in Figure 6. Game code relevant to this exercise checks for correct execution, so that a repetition is considered successful if the line joining the shoulder joints LShoulder and RShoulder (defined in see Figure 1) monotonically prescribes an angle of at least Φmin, a parameter that defines the difficulty of the exercise. The default value for Φmin is 40^o, which corresponds to an average level of difficulty, however this value can be altered by the attending physiotherapist on a per-patient basis.

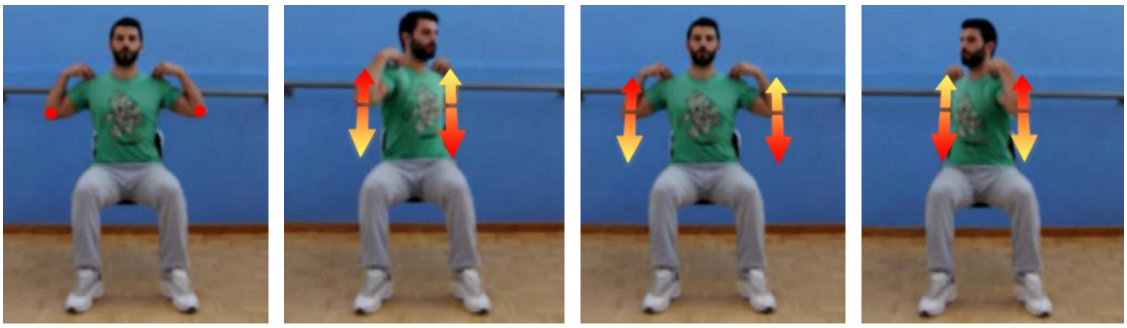

Figure 6: Exercise 5: A torso stretching/strengthening exercise executed from a seated position.

For each successful torso twist an appropriate on-screen counter Ts is incremented by one, whereas each failed repetition increments the corresponding "failure" counter Tf. The exercise is considered complete when Ts reaches N, at which point the following two performance metrics are shown on screen: (a) the total number of failed repetitions Tf and (b) the average value of the twist angle <Φ> over all successful repetitions. A perfectly executed exercise should yield Tf=0 and a value for <Φ> that exceeds the value of Φmin set by the attending physiotherapist. Patient progress may be usefully monitored from the historical values for Tf and <Φ> for the given patient. For example, if the patient consistently reaches small values of Tf and values for <Φ> that are sufficiently larger than Φmin, that fact may imply that the physiotherapist can safely increase the difficulty of the exercise for that patient.

3 Discussion and Future Work

The increased muscular strength, flexibility and balance control attained by physical practice is known to improve mobility and functional independence for Parkinson's disease patients. The present work reports on the enrichment of our existing Kinect-based, real-time assessment physiotherapy platform with an additional five exercises tailored to patients with mild to moderate symptoms (stages 1 through 3 in the Hoehn and Yahr [14] scale, i.e., without severe postural instability and motor impairment).

The enhanced platform has been demoed to local physiotherapists attending patients with neurological problems, including Parkinson's disease and are currently in the process of addressing safety issues and fine-tuning the parameter space of the complete exercise curriculum. Based on early feedback, it seems realistic to seek funding to make the platform available to PD patients who are willing to run it in their homes. This is expected to enable the collection of a time series of performance data that can be usefully analyzed and correlated with e.g., detailed medication history records and disease progress.

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