Motion Capture System for Finger Movement Measurement in Parkinson Disease

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Abstract. *Parkinson's disease (PD) is a chronic neurodegenerative disorder that affects almost 1% of the population in the age group above 60 years. The key symptom in PD is the restriction of mobility. The progress of PD is typically documented using the Unified Parkinson's Disease Rating Scale (UPDRS), which includes a finger-tapping test. We created a measurement tool and a methodology for the objective measurement of the finger-tapping test. We built a contactless three-dimensional (3D) capture system using two cameras and light-passive (wireless) reflexive markers. We proposed and implemented an algorithm for extracting, matching, and tracing markers. The system provides the 3D position of spherical or hemispherical markers in real time. The system's functionality was verified with the commercial motion capture system OptiTrack. Our motion capture system is easy to use, saves space, is transportable, and needs only a personal computer for data processing - the ideal solution for an outpatient clinic. Its features were successfully tested on 22 patients with PD and 22 healthy control subjects.*

Keywords

Motion capture, bradykinesia, Parkinson's disease, marker matching, marker tracing, finger-tapping test.

1. Introduction

Parkinson's disease (PD) is a chronic neurodegenerative disorder that affects almost 1% of the population in the age group above 60 years. The key symptom in PD is the restriction of mobility in the form called Parkinson's syndrome (PS). PS manifests itself as bradykinesia, rigidity, rest tremor, and postural instability.

Bradykinesia (slowness and decrement in movement) is the leading symptom of PD [1] and is, therefore, crucial for diagnosis and for estimating the severity of the patient's functional disability. In clinical practice, bradykinesia is evaluated using clinical rating scales, most frequently the Unified Parkinson's Disease Rating Scale (UPDRS) [2]. Evaluation is subjective, based on the estimation of the severity of bradykinesia made by a qualified expert, who estimates it according to five grades on the ordinal scale. Our aim is to develop a system and methodology for objective bradykinesia measurement in clinical use.

Fig. 1. Motion capture camera system during finger-tapping test measurement.

To date, exact and objective bradykinesia monitoring has been considerably limited owing to the weight and size of the measuring equipment. Previously published scientific works refer to usage of accelerometers, gyroscopes [3], [4], [5], mechanical instruments [6], camera systems with active markers [7] or two-dimensional (2D) cameras [8] for measuring parkinsonian movements. A 2D camera system can be used to measure some movement characteristics, such as the frequency of tremor, but it is inconvenient for measuring the position of the fingers in space, the amplitude of hand opening, and the speed of movement. Accelerometers, mechanical instruments, and gyroscopes can influence the results because of their weight, their unnatural form, and the connected wires, which can be distracting. Therefore, we decided to use a contactless three-dimensional (3D) camera capture system with light-passive (wireless) reflexive markers. Commonly used motion capture camera systems, such as Vicon, OptiTrack and Motion Analysis, are optimized primarily for whole-body movement. They use several cameras, require a large laboratory, and are very expensive. We thus developed our own

3D motion capture camera system to be small, portable, and more convenient for measuring finger movements in clinical use (see Fig. 1).

2. Motion Task

Bradykinesia manifests itself as a decrease in the amplitude and speed of repetitive movements [9], [10]. These characteristics are evaluated in the UPDRS by experienced physicians. The UPDRS consists of a few motion tests, which evaluate the patient's motor abilities, including

- finger taps (the patient taps on his thumb with his index finger in rapid succession),
- hand movements (the patient opens and closes his hand in rapid succession),
- rapid alternating hand movements (pronation-supination hand movements with the widest amplitude possible using both hands simultaneously),
- leg agility (the patient taps on the ground with his heel in rapid succession while lifting his leg completely).

These tasks are very simple and they do not need a complex motion capture system intended for whole-body measurements. A motion camera system with two cameras is sufficient to determine the 3D position of a few markers placed on anatomical landmarks. Reflective markers can be placed on limbs.

In our research, we focused on the UPDRS finger-tapping test (FT) as good parameter for bradykinesia evaluation [11], [12]. In the FT test, the examiner instructs the patient to tap the index finger on the thumb as quickly as possible and with the largest amplitude possible. The examiner rates the movement by observing the speed and amplitude of the finger within a short period of time.

3. System Construction

The velocity of finger movements and the widest distance between the fingers were measured. We placed reflexive markers on the first knuckle of the forefinger and the first knuckle of the thumb (see Fig. 2). The markers must be viewed by two cameras, which is the minimum number required for 3D vision. The maximal measurement error was determined to be 0.2 cm for the distance between the fingers in the FT test. The theoretical minimal frequency was 50 Hz, and camera resolution was 640 × 480 pixels based on the measurement error estimated. Details about the above-mentioned system requirements are described in [13]. The proposed system is designed to be able to measure other tests; therefore, it is adaptable to different areas of measurement.

Fig. 2. Hand with passive markers placed on the first knuckles of the forefinger and thumb.

3.1 Hardware

We used Imaging Source DMK 21BF04.H cameras with IR filters, 640 × 480 resolution, and 60 FPS. Each camera had its own IR emitter to increase the visibility of the reflective markers. Moreover, the movement was recorded by a common HD camera for video evaluation by an expert (see Fig. 3). The cameras were synchronized by an external signal generator. T 0412 FICS 1 lenses were used, and the distance between the cameras were set to 50 cm [13]. The camera system was placed on a tripod as shown in Fig. 3, and connected to a laptop through a USB interface. The 3D coordinates of the markers were computed on the computer based on the captured images. The application was programmed in C++ and C# languages and tested on Microsoft Windows 7.

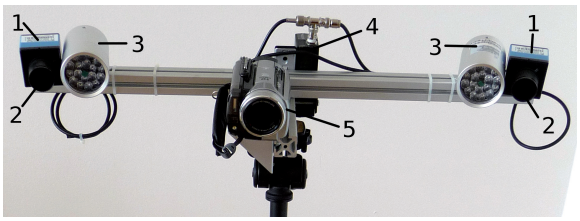

Fig. 3. Assembly of the motion capture camera system: (1) camera, (2) objective with IR filters, (3) IR emitter, (4) signal generator, (5) hand camera.

3.2 Image Capture and Marker Extraction

Images from the cameras were synchronized by the signal generator, and the computer application matched the corresponding images. The reflective markers were found to be the brightest points in the images. The images were simply selected based on a threshold, and a real-time algorithm (connected components labeling) was used to extract candidates for markers. Since some markers were hemispherical, the marker candidates were approximated with a circle and their centroids were computed (see Fig. 4).

Fig. 4. Image thresholding and approximation with circle.

3.3 Obtaining 3D Positions of Markers

Before carrying out the measurements, we calibrated the cameras using a checkerboard. The user was asked to

hold up the checkerboard to the cameras at different positions. The checkerboard was automatically detected until the calibration algorithm had enough chessboard images to compute the intrinsic and extrinsic camera parameters. We used the OpenCV library to calibrate the cameras and to eliminate image distortion [14].

The first task required to obtain the 3D positions of the markers is to match the marker in the first camera's view with the marker in the second camera's view. The fundamental matrix F is computed from the extrinsic parameters and it provides epipolar lines for each marker. If two marker candidates $u = (x_u, y_u)$ (in the first camera image) and $v = (x_v, y_v)$ (in the second camera image) matched, they lie on the corresponding epipolar line and the following equation is satisfied:

$$uFv \leq k \tag{1}$$

where the constant k is close to zero. Based on k, we obtain possible marker pairs from the first and second camera views.

The second task is to determine the trajectory of the 3D markers. The algorithm recognizes which markers from the current frame correspond to markers in the next frame by producing a trajectory T for each marker. We assumed that the movements are smooth, and we predicted the next $(n + 1)$ 3D position using the following equation:

$$T_{n+1} = T_n + \frac{T_n - T_{n-1}}{2}. \tag{2}$$

The proposed algorithm performs the matching and tracing tasks simultaneously. For possible marker pairs (1), 3D coordinates are computed and the following matrix D is created:

$$D_{i,j,n} = \begin{cases} d_{\max} + 1 & - \quad u_i F v_j > k \\ \left| T_n, P(u_i, v_j) \right| & - \quad u_i F v_j \leq k \\ d_{\max} + 1 & - \quad \left| T_n, P(u_i, v_j) \right| > d_{\max} \end{cases} \tag{3}$$

where $|T_n, P(u_i, v_j)|$ is the distance between the predicted and actual 3D positions of the marker; i and j are the indices of the markers from the left and the right camera views, respectively; and n is the number of the trajectory. Markers with the minimum sum of distances to corresponding trajectories are selected from matrix D. The algorithm solves the minimal pairing problem on a sparse matrix [15]. If any unassigned markers are remaining, a new trajectory is created.

3.4 Camera System Validation

The accuracy of a motion capture camera system depends on the size of the captured scene, which is determined by the motion task. This space was experimentally estimated for FT as a virtual cuboid sized 40 cm × 40 cm × 30 cm. The camera system was calibrated with a re-projection error that is less than 0.5 mm. The system was validated in three different ways.

First, we measured the accuracy of the system by capturing the mutual positions of the markers in space. This test verified the stability of the measurement. The system measured markers placed 5, 10, and 15 cm apart. The virtual cuboid was divided into small cubes 2 cm^3 in size. The examiner moved with the markers inside the virtual cuboid until 90% of the cubes were covered by the movement. The standard deviation was 0.04 cm. The results are summarized in Tab. 1.

Distance [cm]	Average distance [cm]	Standard deviation [cm]
5	5.00	0.03
10	10.01	0.04
15	14.01	0.04

Tab. 1. Marker distance measurement error.

Second, we verified the linearity and authenticity of the measured space. We compared our system with a commercial motion capture system, OptiTrack. The systems simultaneously captured the movement of one marker in the virtual cuboid until 90% of the cubes were covered by the movement. From every cube, the markers nearest to the centroid of the cube (approx. 600 marker positions) were chosen. The systems have different co-ordinates, and therefore, the algorithm described in [16] was used for computing the transformation matrix. We matched the corresponding markers and found that their average distance was 0.04 cm with a deviation of 0.03 cm.

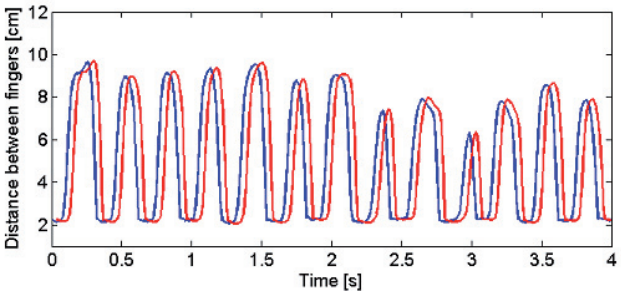

Fig. 5. Finger distance measured using our camera system and the OptiTrack system. The graphs are shifted by 0.04 s.

Finally, our tests showed that a frequency of 60 Hz is sufficient for an FT motion task. We measured the distance between the thumb and the index finger of 20 healthy people who performed rapid FT movement. The movement was captured by our system and the OptiTrack system (see Fig. 5). We compared the maximal distances between the fingers and found an average difference of 0.05 cm with a standard deviation of 0.03 cm. This error is sufficient for performing the FT test since we assumed a maximal error of 0.2 cm.

4. Motion Capture Application

The motion capture application is simple and can be used for different motion tasks.

The application window is divided into three parts. The main part (see Fig. 6) includes a 3D virtual space,

where cameras and points are depicted. The user can capture images, calibrate the system, and show the results of the measurement. The results button runs an external script that shows the results of the task. The application provides the positions of the markers in a data file to the external script. The user can change this external script and display any part of the motion capture results.

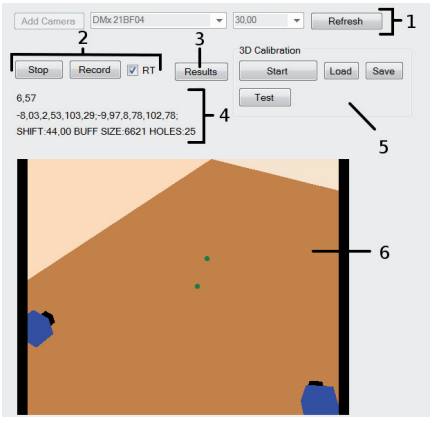

Fig. 6. Main application window showing (1) camera selection menu, (2) capture start and stop buttons, (3) results button, (4) measurement information, (5) external parameters calibration menu, and (6) 3D capture virtual space.

The other two windows (see Fig. 7) show a camera image. If the scene is overexposed, the user can change the exposure and the threshold to see all markers. The camera image can be shown in three view modes: gray scale image, marker view, and no view.

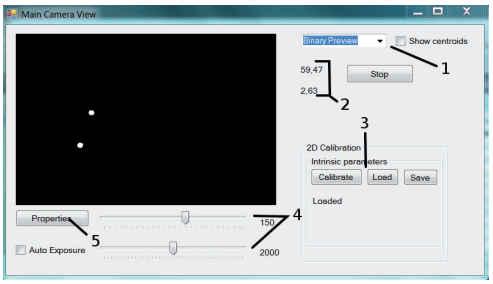

Fig. 7. Camera view window showing (1) view mode, (2) camera frame rate, (3) camera calibration menu, (4) exposure and threshold adjustment sliders, and (5) camera properties button.

5. Experiments

The system was successfully tested on 22 (12 F) patients with mild to moderate PD, mean Hoehn & Yahr stage 2.05 (range 1-2.5) [17], mean UPDRS FT rate 1.5 (range 0-3), mean age 64 (48-82), disease duration 9.3 (1-24) years, and 22 (11 F) normal controls (NC), mean age 65 (50-82) years, without history of neuropsychiatric disorders and without any impairment of upper limb function. Every subject was tested in his ON state, performing FT according to the UPDRS, each hand twice for 20 seconds. The OFF state [17] was achieved more than 12 hours after withdrawal of anti-Parkinson medication while the ON state was 1.5 hours after taking the usual medication again. UPDRS item 23 (FT rank) was rated from the video recordings for NC and PD by 2 experts. The subjects were recruited and examined at the Department of Neurology, 1st Faculty of Medicine, Charles University in Prague. The distance between the thumb and the index finger (see Fig. 8) was evaluated. Features of the movements were defined: frequency, maximal finger distance and maximal opening/closing velocity and the parameters average, the deviation and the decrement for each feature was computed. These parameters were analyzed and the parameters differentiate parkinsonian subjects from healthy control subjects were selected.

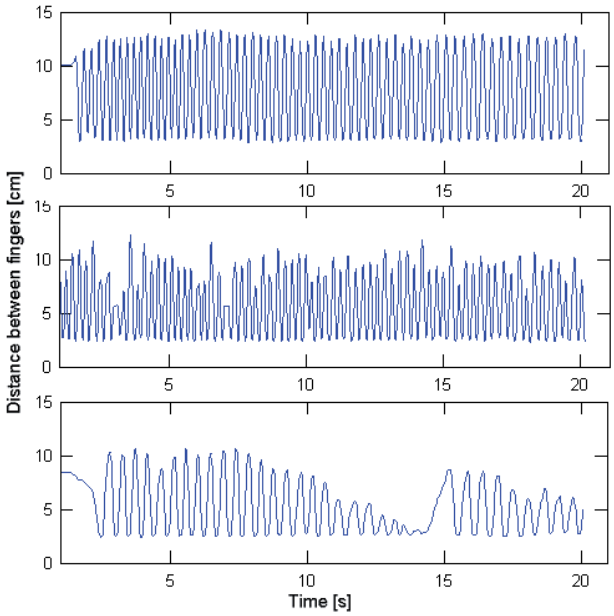

Fig. 8. Examples of markers distances of healthy control subject (top) and two parkinsonian's subjects (middle - FT rank 2; bottom - FT rank 3), who performed a 20 s FT test.

The receiver operating characteristic (ROC) analysis of parameters computed from a distance between two markers and its area under curve (AUC) showed that the best parameters discriminating PD patients from healthy controls were the average opening velocity (AUC = 0.77) and the decrease in the maximal opening distance (AUC = 0.87). The ROC curve and the histogram for the decrease in the maximal opening distance are shown in Fig. 10. The parameters were selected by the sequential forward selection algorithm. The Spearman's rank correlation coefficient between these two parameters was 0.2. Wilcoxon rank sum test rejected null hypothesis of equal medians of PD patients and healthy controls at the 0.1% significance level for both parameters.

Combination of the above mentioned parameters discriminates patients with PD from healthy controls better then only a single parameter (AUC = 0.94). Data distribution is shown in Fig. 11. Correlation of this parameter with mean FT rank is shown in Fig. 12 (Spearman's rho = 0.75,

$p < 0.001$). A detailed description of parameters and clinical conclusions are going to be published separately.

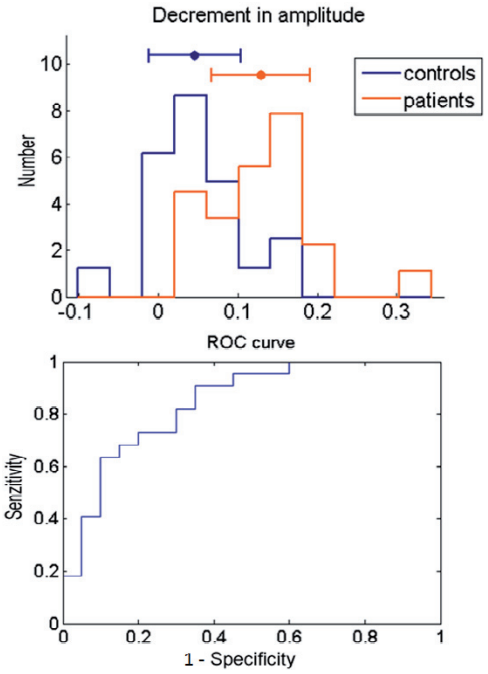

Fig. 10. Histogram and ROC curve for decrement in amplitude parameter.

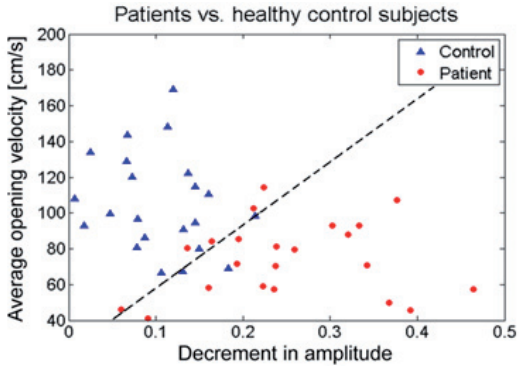

Fig. 11. FT measurement results obtained using the proposed motion capture system.

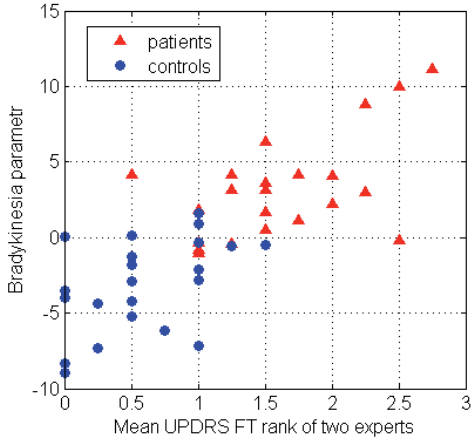

Fig. 12. Correlation of mean UPDRS FT rank of two experts with computed bradykinesia parameter consists of average opening velocity and decrease in the maximal opening distance.

6. Conclusions

We developed a motion capture system for 3D measurement of finger movements. The system consists of two cameras and two IR emitters, and it is connected to a common laptop via a USB interface. The system is transportable, uses passive markers, and can be adapted to any simple task (the markers should be visible to the cameras' views during measurement). The described motion capture system was successfully validated in three different ways as well as simultaneous video recordings were taken for visual ratings of FT by two experts. The results proved that our system is sufficient for performing the FT test for objective bradykinesia measurement in clinical use.

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