Upper Limb Motion Analysis Using Haptic Interface

Aleš Bardorfer, *Student Member, IEEE*, Marko Munih, *Member, IEEE*, Anton Zupan and Alenka Primožič

Abstract— An objective test for evaluating the functional studies of the upper limbs (UL) in patients with neurological diseases (ND) is presented. The method allows assessment of kinematic and dynamic motor abilities of UL. Our methodology is based on creating a virtual environment, using a computer display for visual information and a PHANTOM haptic interface. Haptic interface is used as a kinematic measuring device and for providing tactile feedback to the patient. In virtual environment, a labyrinth in patient's frontal plane was created at the start of each test. By moving the haptic interface control stick the patient was able to move the pointer (a ball) through the labyrinth in three dimensions and to feel the reactive forces of the walls. The primary patient's task was to pass the labyrinth as quickly as possible, with as few contacts (collisions) with the walls as possible. The test makes various degrees of complexity possible; by choosing labyrinths with various track width and length, and by changing wall friction.

The new test offers a wide range of numerical and graphic results. It has so far been applied to 13 subjects with various forms of ND (e.g. Friedreich Ataxia, Parkinson's disease, Multiple Sclerosis) as well as to healthy subjects. The comparison in performance between right and left UL has been carried out in healthy subjects.

Keywords— Rehabilitation robotics, upper limb movement assessment, haptic interface.

I. Introduction

UPPER limb (UL) assessment is a qualitative and quantitative procedure, by which the quality of a patient's UL motion and motor abilities – UL functional state – is evaluated. The necessity of UL assessment arises mostly in patients with neurological diseases (ND). Functional impairment differs significantly among various ND individuals, as well as between patients with the same diagnoses. Therefore patients should be treated and followed up on an individual basis. Concise insight into UL functional state is a prerequisite for planning an optimal treatment and complex care for each individual case. A precise, objective and sensitive quantification of dysfunction of UL may also facilitate better understanding of the natural course of the disease and enable therapists to judge the effectiveness of various treatment procedures. Even though the quantification of ND has recently become more interesting to investigators, the techniques for measuring the motion and motor dysfunction remain rather primitive, and the methods of evaluation (assessment protocol) insensitive and subjective to a large extent.

Aleš Bardorfer and Marko Munih are with the Laboratory of Biomedical Engineering and Robotics, Faculty of Electrical Engineering, University of Ljubljana, SI-1000 Ljubljana, Slovenia (e-mail: alesb@robo.fe.uni-lj.si, marko@robo.fe.uni-lj.si).

Anton Zupan and Alenka Primožič are with the Institute for Rehabilitation of the Republic of Slovenia, SI-1000 Ljubljana, Slovenia (e-mail: anton.zupan@mail.ir-rs.si).

Current approaches for the assessment of functional and motor abilities of ULs are limited to subjective evaluations performed by clinicians. Functional ability tests of the UL, as described in the literature, usually employ the following 4 criteria: dexterity and speed of single-hand movements; dexterity and speed of both hands (moving hands, picking up objects, unbuttoning and buttoning etc.); ability to write; squeezing a dynamometer for measuring muscle strength [1–3]. Some authors added joint range of motion measurements [4]. These tests, however, are not specific enough to be efficiently applied in patients with different NDs that are affected by various physical impairments such as tremor and bradikinesia (slowness of movements) in Parkinson's disease, ataxia (disturbances in balance and in coordination of the muscle movements) in Friedreich Ataxia and Multiple Sclerosis, muscle weakness in Muscular Dystrophy, etc. Many subjective tests (e.g. Fugl-Meyer [5], Barthel [6] and the Rivermead [7] motor assessment score) are widely used in neurorehabilitation and have an important role in ND assessment, but lack objectivity as they produce subjective or semiquantitative results; e.g. "Parkinson's disease: Impairment Index" may vary by as much as 40 % between various observers [8]. In these tests, the physical therapist assigns the score which is in most cases in a discrete form (yes/no or mild/moderate/severe) and as such grading lacks the resolution. The trend in rehabilitation diagnosis is to provide objective and repeatable test methods to decrease subjective judgments and increase the therapist's ability to obtain reproducible findings and meaningful results.

Some work has been reported on using visual-only virtual environment (VE) technology in rehabilitation. Wilson et al. [9] presented the evidence that knowledge and skills acquired by disabled individuals in simulated environments can transfer to the real world. Despite many questions of ethics and safety, researchers have agreed that VE technology could bring benefits to the rehabilitation world, if used with caution [10–13]. According to Jones [11], it is anticipated that with VE techniques, retraining could provide accurate measures of difficulties, according to the patients' progress in a rehabilitation programme. Significant potential therefore exists for mechatronic devices to improve quantitative assessment, monitoring and treatment of individuals with movement disabilities. For example Reinkensmeyer et al. [14] used a simple robotic measurement device to identify the contribution of different motor impairments to decreased active range of motion of reaching in brain-injured subjects.

Various measurement setups for kinematic and dynamic gait analysis in rehabilitation environment exist and are widely used in laboratories and rehabilitation institutes

worldwide. Typically, such system consists of the optical position measuring device and floor mounted force/torque sensors (force plates). As in these gait analysis systems, commercially available haptic interfaces can be in future exploited for similar measurement purposes in UL motion analysis and could represent a modern kinesiologic laboratory for upper extremities. A single measuring device can acquire the UL position as well as contact forces exerted to the VE. The use of a VE as a test polygon is considered to be an advantage over the classic gait analysis systems due to freedom in creating arbitrary test polygons at various complexity levels.

The aim of the present study was to devise a new test enabling objective assessment of the functional capacity (state) of the UL in patients with various forms of ND, utilizing haptic interface. The new test should be objective, reliable, easy to perform, suitable for routine use and should produce repeatable results [15]. It should be as sensitive as possible, allowing evaluation of the natural cause of the disease as well as of the effects produced by single therapeutic measures. The high sensitivity of the test should give therapists a chance to detect functional disorders of the UL in early stages of ND and to properly assess minimal functional capacities of the most severely affected individuals. In this way it would be a good indicator of the success of therapists' work in rehabilitation process. The workspace size and the exertable force range of the haptic interface should be large enough to allow the simulation of simple pick and place or writing tasks as described above. The simulated task (VE) should be simple thus none of the intelligent capabilities of the patient would influence his/her performance (e.g. finding a correct path). It should also be clear enough not to confuse even visually impaired subjects.

This paper is proposing a new objective test for clinical evaluation of UL functional state, utilizing a commercially available 3D pointing device (3 DOF haptic interface). It offers accurate, reliable and repeatable numerical information to the observer. The haptic robot is used as a position measurement and force generation device. Kinematic and dynamic information of UL movements is gathered from a pre-defined polygon – the labyrinth, which guarantees a wide range of test complexities. Acquired data proved to be an objective measure of the patient's UL functional state.

II. Methods

A. Measurement setup

The core of the measurement system is the PHANTOM Premium 1.5 haptic interface[1] ($19.5\,cm \times 27\,cm \times 37.5\,cm$ workspace size, $0.03\,mm$ 3D positional resolution increment, 3 active DOF, 6 measurement DOF, $8.5\,N$ maximal exertable force). It is used as a measuring device for positional input and as a feedback force generator. A complex and movement demanding virtual environment, representing a labyrinth is aligned with the patient's frontal plane. Randomly generated track is created by software as shown

in Fig. 1 and Fig. 2. The patient can move the pointer,
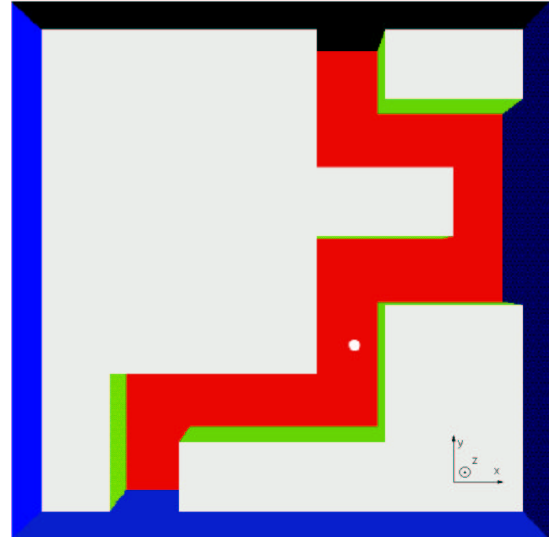

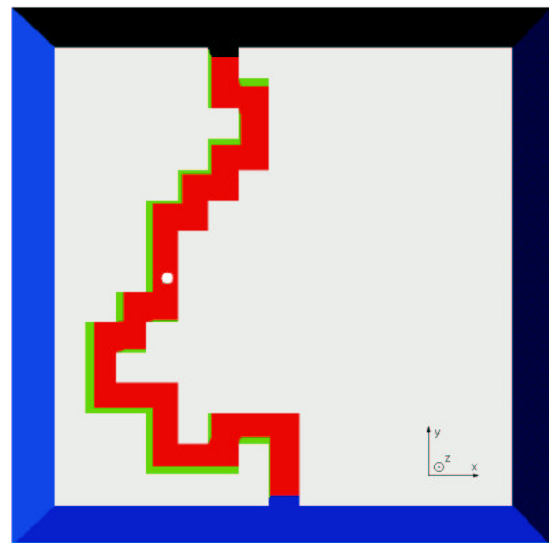Fig. 1.   Simple labyrinth.

Fig. 2.   More complex labyrinth.

represented with a ball, through the labyrinth in three dimensions by moving the haptic interface control stick. The visual and tactile information is fed back to the patient using a computer display and haptic interface. The patient can feel all the reactive forces occurring in ball contact with the labyrinth walls and can get the realistic impression as if he/she was interacting with the real environment (Fig. 3). By acquiring the 3D position and forces of the stylus, the finger dexterity, the forearm and the shoulder movement abilities are captured. However, particular contributions to the UL functional state are difficult to determine.

Initially, a wide range of labyrinth complexities were tested. Based on that, five of them were selected for further use, ranging from most simple as shown in Fig. 1 to complex shapes not presented here.
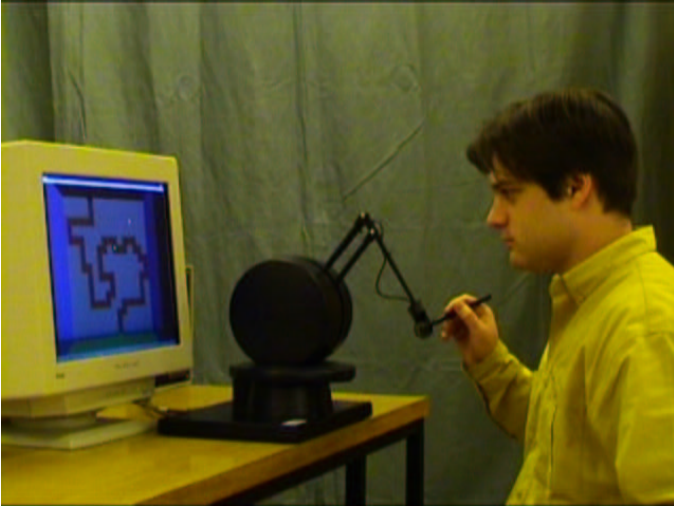
Fig. 3. The measurement setup.

B. Subjects

For preliminary test of the motor abilities of UL and initial test of the method fidelity, 13 subjects with various forms of ND were assessed. Number of subjects having various ND are shown in TABLE I. The subjects were aged from 10 to 74 years, with mean value and standard deviation of 41 ± 21 years.

Form of ND	No. of subjects
Friedreich Ataxia	7
Parkinson's disease	3
Multiple Sclerosis	2
Muscular Dystrophy	1

TABLE I

SUBJECTS TESTED.

The experiments were conducted as follows. Before the test, the patient sat in front of the computer display using normal chair or in case of wheelchair bound patients, their own wheelchair. The haptic interface was positioned to the distal side, right or left side, depending on the patient's UL under test. During the haptic device home positioning, the patient's UL was placed in $45°$ abduction, $90°$ elbow flexion and forearm aligned with antero-posterior axis. This axis was perpendicular to the table edge. Each patient was asked to pass the labyrinth as quickly as possible, with as few contacts with vertical/horizontal walls as possible, or no contact at all. The contact events were accompanied with a short audio beep ($900\ Hz$, $30\ ms$).

During the examination each patient performed several equal trials. Depending on the patient's movement skill, two labyrinth complexities were selected. Each was used with slippery and friction walls. Slippery conditions imitated ice covered wall situation, while friction walls demonstrated rubber type surrounding. Including one repetition for each setting, this gives 8 trials for one UL and 208 for all 13 subjects.

To test the method sensitivity itself or the resolution of the test, three healthy subjects also participated in this study. The movement ability between their right and left UL is compared in the Results section.

C. Methods of evaluation

The 3D position of the robot control stick (patient's arm partial kinematics) and 3D force vector were sampled at a rate of $f_s = 200 Hz$. Traces were used for further numerical data processing, including calculation of:

- motion speed of the ball pointer $\overline{v_{tr}}$;
- speed of ball advancement through labyrinth $\overline{v_{lab}}$;
- the velocity/position ratio index R;
- number of collisions (contacts) encountered with vertical/horizontal walls n_{col};
- peak frequency of the UL motion during whole path f_{max};
- maximal impact duration T_{imax};
- average impact duration $\overline{T_i}$;
- maximal impact force F_{imax};
- average impact force $\overline{F_i}$;
- penalty sum G.

The *motion speed* $\overline{v_{tr}}$ and *speed of advancement through labyrinth* $\overline{v_{lab}}$ are calculated using (1) and (3) respectively.

$$\overline{v_{tr}} = \frac{1}{T_{ex}} \int_0^{T_{ex}} \dot{s}\, dt \tag{1}$$

$$\overline{v_{tr}} = \frac{1}{T_{ex}} \int_0^{T_{ex}} \sqrt{\dot{x}^2 + \dot{y}^2 + \dot{z}^2}\, dt \tag{2}$$

$$\overline{v_{lab}} = \frac{l_{lab}}{T_{ex}} \tag{3}$$

In equations (1) to (3) T_{ex} represents the execution time, $\dot{s}\, dt = ds$ the trajectory segment and l_{lab} the nominal labyrinth length. l_{lab} represents the center-of-track trajectory length, $\dot{x}$, $\dot{y}$ and $\dot{z}$ stand for ball pointer velocities in x, y and z directions.

The *velocity ratio* R in (4), is the ratio between the motion speed of the ball pointer $\overline{v_{tr}}$ and the speed of ball advancement through labyrinth $\overline{v_{lab}}$ or in other words the ratio between the measured patient's trajectory length and the nominal labyrinth length. It represents one of the important test outcomes.

$$R = \frac{\overline{v_{tr}}}{\overline{v_{lab}}} = \frac{\int_0^{T_{ex}} \dot{s}\, dt}{l_{lab}} \tag{4}$$

The R value, as defined above, offers a measure of the patient's ability to optimize the trajectory path.

Further numerical description is aimed to evaluate the *tremor characteristics*. *Tremor amplitude* and *frequency* are obtained by applying Discrete Fourier Transform (DFT) algorithm to the filtered motion signal $XYZ(t) = \sqrt{X(t)^2 + Y(t)^2 + Z(t)^2}$. The UL movements are filtered at $\frac{1}{10}$ of the peak frequency f_{max} to exclude the stationary offset value. The geometric sum $XYZ(t)$ of x, y and

z position components was chosen in order to capture all the tremor movements, since they can occur in arbitrary direction.

The following parameter definitions concern the contact situations. The *maximal impact duration T_{imax}* represents the time of the longest collision event. It is the longest time interval of the ball pointer in contact with the vertical/horizontal wall (5). $T_i(j)$ is the j-th impact duration and n_{col} represents the total number of collisions with vertical or horizontal walls during the test.

$$T_{imax} = \max_{j=1}^{n_{col}}(T_i(j)) \tag{5}$$

The *average impact duration $\overline{T_i}$* (6) represents the average time interval, when the ball pointer was in contact with the vertical/horizontal wall.

$$\overline{T_i} = \frac{\sum_{j=1}^{n_{col}} T_i(j)}{n_{col}} \tag{6}$$

The *maximal impact force F_{imax}* is the maximal force exerted by the patient to the vertical or horizontal wall during contact event (7). The friction forces are implicitly excluded (equations (8) to (11)).

$$F_{imax} = \max\{F_{imaxX}, F_{imaxY}\} \tag{7}$$

$$F_{imaxX} = \max(C_x(t)\,|F_x(t)|) \tag{8}$$

$$F_{imaxY} = \max(C_y(t)\,|F_y(t)|) \tag{9}$$

$$C_x(t) = \begin{cases} 1; & \textit{contact with sagital wall} \\ 0; & \textit{elsewhere} \end{cases} \tag{10}$$

$$C_y(t) = \begin{cases} 1; & \textit{contact with horizontal wall} \\ 0; & \textit{elsewhere} \end{cases} \tag{11}$$

The *average impact force $\overline{F_i}$* is the arithmetic mean of all impact forces (12).

$$\overline{F_i} = \frac{\int_0^{T_{ex}} C_x(t)\,|F_x(t)|\,dt}{2\int_0^{T_{ex}} C_x(t)dt} + \frac{\int_0^{T_{ex}} C_y(t)\,|F_y(t)|\,dt}{2\int_0^{T_{ex}} C_y(t)dt} \tag{12}$$

The last parameter, *penalty sum G*, is defined in equation (13). It represents the cumulative sum of impact forces exerted to vertical or horizontal walls in x and y directions.

$$G = \int_0^{T_{ex}} \sqrt{C_x(t)\,|F_x(t)|^2 + C_y(t)\,|F_y(t)|^2}\,dt \tag{13}$$

G shows the area under the vertical or horizontal impact force curves $C_x(t)\,|F_x(t)|$ and $C_y(t)\,|F_y(t)|$, and offers a simple measure of the patient's sensory perception. No contacts or contacts at low forces demonstrate good perception, movement coordination, and supervision. GHOST[2] C++ software library was used for real-time control, kinematic and force data acquisition. Data files were transfered to a MATLAB software for data processing and presentation.

[2]General Haptics Open Software Toolkit. `http://www.sensable.com/products/ghost.htm`

III. RESULTS

A. Subjects with ND

Fig. 4, 5, 6 and 7 show the sample trajectory paths along the labyrinth for patients with Friedreich Ataxia, Parkinson's disease, Multiple Sclerosis and a patient with Muscular Dystrophy respectively.
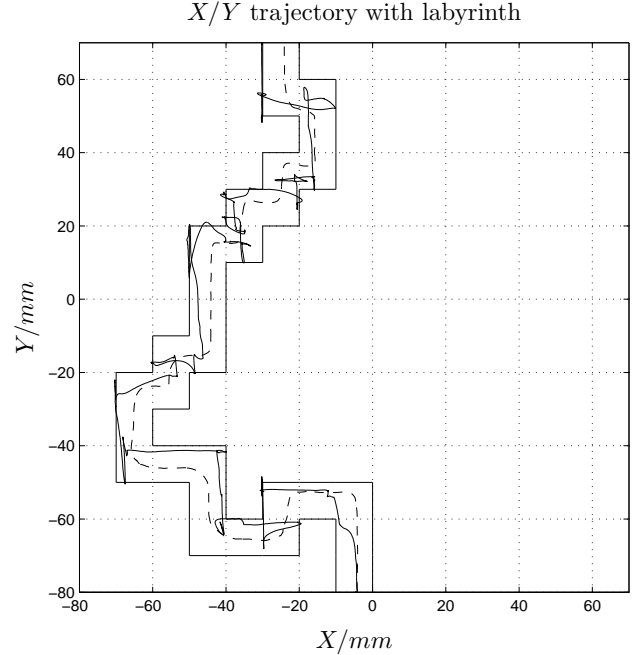
X/Y trajectory with labyrinth

Fig. 4. X/Y trajectory through labyrinth for the patient with Friedreich Ataxia (solid) and non-impaired subject (dashed). $\overline{v_{tr}} = 22.3mm/s$, $l_{lab} = 290mm$, $\overline{v_{lab}} = 10.3mm/s$, $T_{ex} = 28.1s$, $R = 2.16$, $n_{col} = 14$.

The examples in Fig. 4 and Fig. 5 were selected and will be further discussed to demonstrate individual characteristics and significant movement differences which appear and are clearly evident among Friedreich Ataxia and Parkinson's disease. In Fig. 4, the trajectory consists of several smooth regions and several knot shaped regions. The knots demonstrate absence of movement control which is typical indication for Friedreich Ataxia. The degree of trajectory complexity seems to be high for those with severe movement problems and does not exist for non-impaired subject trace in Fig. 4. As evident from the figure, in most cases the movement proceeds smoothly after evolving in desired direction.

Fig. 8 shows time courses for contact forces in x and y directions, occurring at collisions with vertical or horizontal walls for the patient with Friedreich Ataxia. Unfortunately, those forces can result from a (i) collision with a vertical or horizontal wall, or (ii) in friction wall trials due to friction with the frontal (back or front) labyrinth walls. Most frequently the subjects were sliding with a ball pointer on the back frontal labyrinth wall, although they were not suggested in any way to perform the test in such a way. The impact intervals are represented by bold lines on the chart. In Fig. 8, showing force traces for the patient with Friedreich Ataxia, all of the non-zero forces result from collision events. This particular test was performed with frictionless
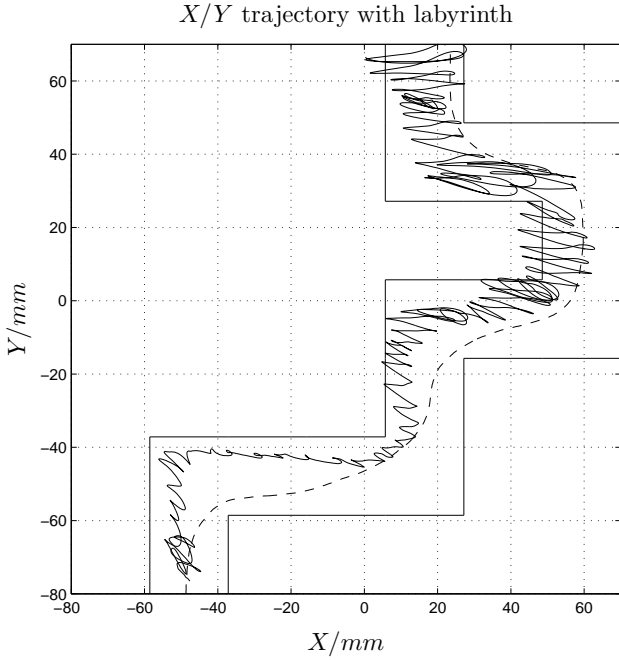
X/Y trajectory with labyrinth

Fig. 5. X/Y trajectory through labyrinth for the patient with Parkinson's disease (solid) and non-impaired subject (dashed). $\overline{v_{tr}} = 134\,mm/s$, $l_{lab} = 300\,mm$, $\overline{v_{lab}} = 23.0\,mm/s$, $T_{ex} = 13.0\,s$, $R = 5.82$, $n_{col} = 16$.

X/Y trajectory with labyrinth

Fig. 6. X/Y trajectory through labyrinth for the patient with Multiple Sclerosis (solid) and non-impaired subject (dashed). $\overline{v_{tr}} = 27.1\,mm/s$, $l_{lab} = 300\,mm$, $\overline{v_{lab}} = 5.7\,mm/s$, $T_{ex} = 52.6\,s$, $R = 2.91$, $n_{col} = 3$.

walls with relatively small maximal impact force (1.3 N). The contact time intervals seem to be longer than in other aetiologies due to patient's inability of normal fast collision reactions. Proper reaction would be to withdraw the pointer from the wall as fast as possible. This proves to be another indication of the absence of movement control in patients with Friedreich Ataxia.

In contrast to Fig. 4, the trajectory for Parkinson's disease in Fig. 5 demonstrates fairly good overall control with superimposed oscillatory movements. As tremor increases toward the end of experiment (Fig. 5 top), this is recorded and clearly evident. The tremor amplitude and energy frequency content are further analyzed in Fig. 10 and Fig. 11. The position course is analyzed vs. time in Fig. 10. Oscillatory frequency encountered for this case seems to be constant for the whole trial. The oscillation peak frequency for integral motion f_{max} is numerically depicted in Fig. 11.

Fig. 9 shows the force traces for the patient with Parkinson's disease. This test was performed with fairly high wall friction coefficient $\mu = 1.0$ to demonstrate another extreme situation concerning friction ($F_T = \mu F_N$; F_T – tangential friction force, F_N – normal force). Most of the forces result from a friction along the frontal wall. Peak impact forces for the patient with Parkinson's disease (6.5 N, Fig. 9) are significantly larger from the patients with Friedreich Ataxia (Fig. 8). As expected, the contact time intervals are also very short and generally shorter, since they all originate from oscillations.

TABLE II shows the kinematic numerical results calculated for most frequent ND listed in TABLE I. Numbers are from one representative patient, having the ND shown in the first column. All tests, shown in TABLE II, were performed using the same labyrinth type, as in Fig. 5, with the
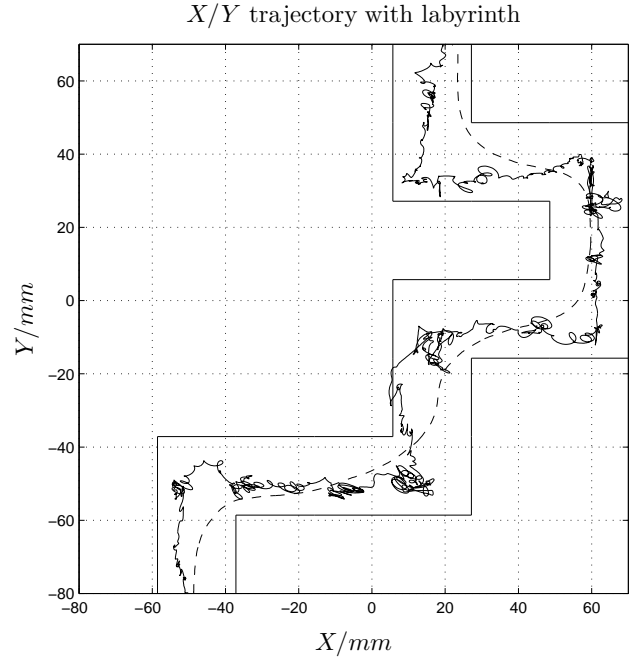
slippery walls ($\mu = 0$). For the healthy subject (A) there were no collisions and the velocity $\overline{v_{tr}}$ was even smaller than $\overline{v_{lab}}$ calculated from midline path. The numerical situation in Parkinson's disease (B) is very different, with the actual speed $\overline{v_{tr}}$ much higher than $\overline{v_{lab}}$. The number of collisions n_{col} is also very high. The next three cases (C), (D) and (E) clearly demonstrate movement impairment compared to healthy subject.

TABLE III summarizes the impact force parameters of the identical tests and the same five patients. The first two time parameters concern the impact durations. The healthy subject has been able to pass through the labyrinth without collisions with vertical or horizontal walls. Patients with Friedreich Ataxia and Multiple Sclerosis both show relatively long average and maximal impact durations, T_{imax} and $\overline{T_i}$. However, the maximal impact force F_{imax} in those two patients is much smaller, compared to the patient with Parkinson's disease. The most interesting parameters are the average impact force $\overline{F_i}$ and penalty sum G. Again the patient with Parkinson's disease demonstrates the highest G sum. The ratio $G/\overline{F_i}$ could further reveal the impact characteristics. Large $G/\overline{F_i}$ value points out long impacts with small forces (patients (C) and (D)), while small value stands for short impacts with large forces (patient (B)).

B. UL comparison in healthy subjects

Another demonstration of the high resolution of the proposed test and the method sensitivity can be found in TABLE IV, showing some of the most significant test parameters for right and left UL in three right handed healthy subjects. The results represent the average of 5 consecutive tests in each subject's UL. Since all the healthy sub-
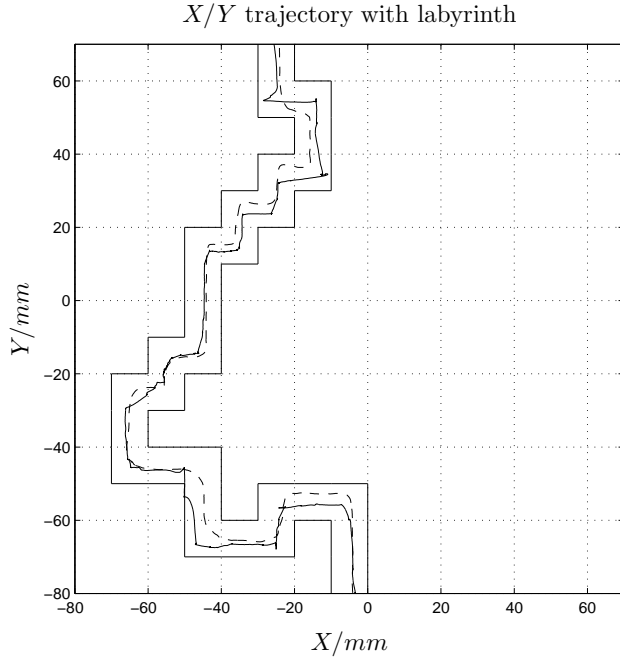
X/Y trajectory with labyrinth

Fig. 7. X/Y trajectory through labyrinth for the patient with Muscular Dystrophy (solid) and non-impaired subject (dashed). $\overline{v_{tr}} = 12.4 mm/s$, $l_{lab} = 300 mm$, $\overline{v_{lab}} = 11.0 mm/s$, $T_{ex} = 27.3 s$, $R = 1.13$, $n_{col} = 2$.

X and Y reaction forces
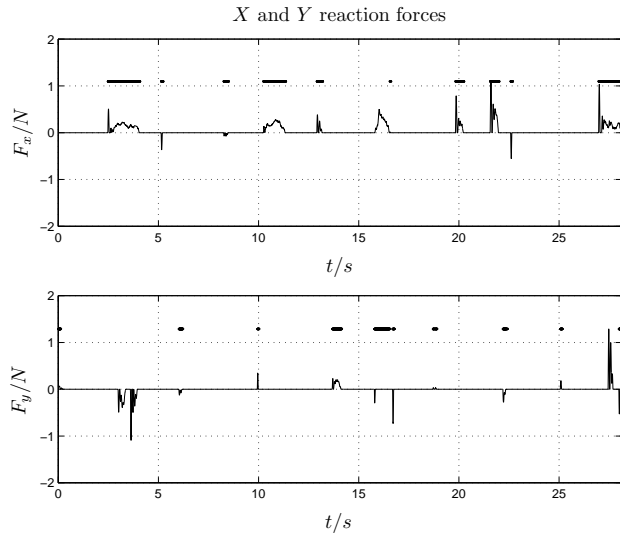

Fig. 8. Force traces for the patient with Friedreich Ataxia. Upper bold lines indicate the time when collisions occur in that direction.

X and Y reaction forces

Fig. 9. Force traces for the patient with Parkinson's disease. Upper bold dotted lines indicate the time when collisions occur in that direction.

Tremor amplitude

Fig. 10. Tremor amplitude for the patient with Parkinson's disease.

jects showed good overall performance, the graphical representations pointed out no significant differences between the right and left UL. However, as shown in TABLE IV, significant differences were revealed from numerical results proving the sensitivity of the method. To suit the relatively good movement control in these subjects, a more complex labyrinth, compared to subjects with ND, was used for the tests.

IV. DISCUSSION

Single measurement trial takes less than one minute to perform and produces kinematic and force information data. These can be 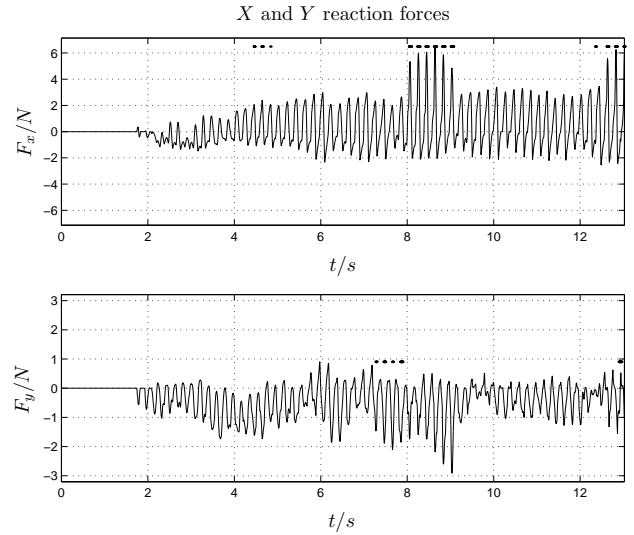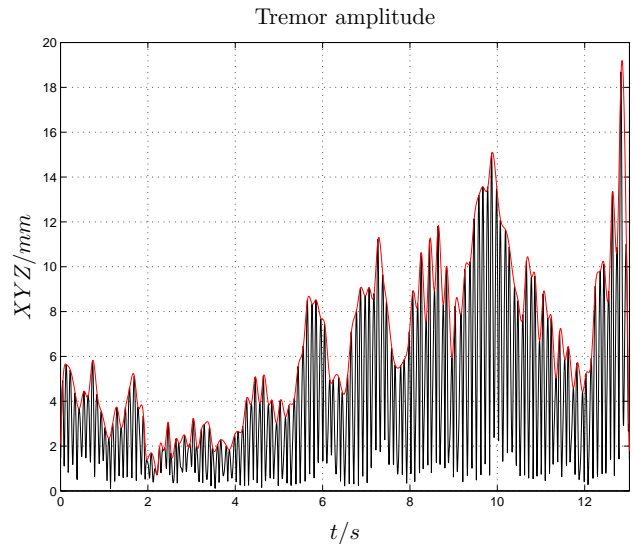presented in various domains as shown in previous section. The X/Y presentation offers rough visual estimation of movement quality/pattern with significant differences among patients with various diagnoses. For special cases, as in Parkinson's disease, the tremor amplitude and frequency analysis are important. An important finding concerning patient with Parkinson's disease was the time varying tremor amplitude during motion through the labyrinth (Fig. 10). Additional quantitative assessment is possible from the velocity/position ratio R which differs significantly regarding patients with various forms of ND (TABLE II). This suggests that R could be used as a measure of the disease state and progress. As expected, the speed of advancement through the labyrinth $\overline{v_{lab}}$ also tends to be higher in patients with less severe form of ND and good movement control. $\overline{v_{lab}}$ velocity might be considered as the most direct, very practical, reasonable and natural measure of the UL functional state.

The maximal and average impact duration, T_{imax} and $\overline{T_i}$, hold valuable information about patient's sensory per-
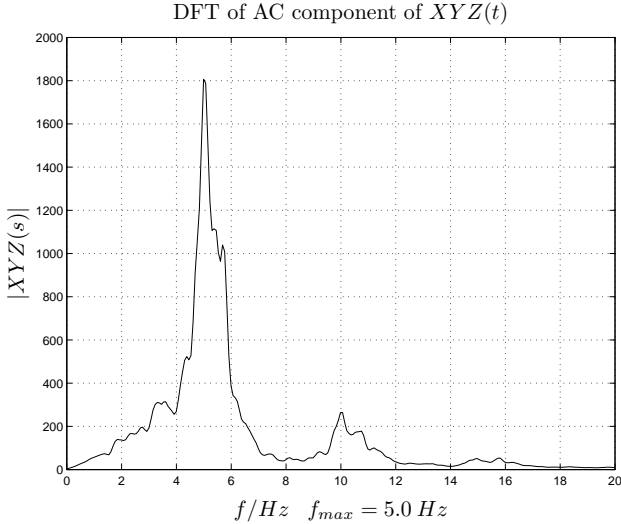
DFT of AC component of $XYZ(t)$

$f/Hz \quad f_{max} = 5.0\ Hz$

Fig. 11. Motion frequency analysis for the patient with Parkinson's disease.

	A	B	C	D	E
$\overline{v_{tr}}\ [mm/s]$	84.4	157	30.8	22.8	14.2
$l_{lab}\ [mm]$	300	300	300	300	300
$\overline{v_{lab}}\ [mm/s]$	93.8	28.6	18.1	17.5	12.9
$T_{ex}\ [s]$	3.2	10.5	16.6	17.2	23.3
R	0.9	5.5	1.7	1.3	1.1
n_{col}	0	34	10	8	1

TABLE II

AVERAGE KINEMATIC NUMERICAL RESULTS. FORM OF ND: (A) HEALTHY SUBJECT, (B) PARKINSON'S DISEASE, (C) MULTIPLE SCLEROSIS, (D) FRIEDREICH ATAXIA, (E) MUSCULAR DYSTROPHY.

	A	B	C	D	E
$T_{imax}\ [ms]$	0	60	580	1435	224
$\overline{T_i}\ [ms]$	0	38	251	204	52
$F_{imax}\ [N]$	0	6.5	1.0	1.3	0.3
$\overline{F_i}\ [N]$	0	2.69	0.18	0.13	0.2
$G\ [kgm/s]$	0	2.22	0.87	1.07	0.32
$G/\overline{F_i}\ [ms]$	/	820	4830	8230	1600

TABLE III

AVERAGE IMPACT NUMERICAL RESULTS. FORM OF ND: (A) HEALTHY SUBJECT, (B) PARKINSON'S DISEASE, (C) MULTIPLE SCLEROSIS, (D) FRIEDREICH ATAXIA, (E) MUSCULAR DYSTROPHY.

Subject	F		G		H	
UL	R	L	R	L	R	L
$\overline{v_{lab}}\ [mm/s]$	53.9	39.4	62.2	49.0	54.6	49.2
n_{col}	0	2.2	1.8	3.8	2.4	4.8
$\overline{F_i}\ [N]$	0	0.51	0.19	0.35	0.13	0.24
$G\ [ms]$	0	130	42	98	45	115

TABLE IV

AVERAGE RESULTS OF 5 CONSECUTIVE TESTS FOR EACH HEALTHY SUBJECT'S RIGHT AND LEFT UL. ALL THE SUBJECTS, (F), (G) AND (H) WERE RIGHT HANDED.

ception. However, from existing analysis it is not possible to directly draw a distinction between the patient's (in)ability of generating the desired motion on one side and the sensory impairment on the other side. The maximal and average impact duration, T_{imax} and $\overline{T_i}$, seem to be good estimations for sensoric impairment. The maximal and average impact forces, F_{imax}, $\overline{F_i}$ and G, are all considered as penalty indexes, reflecting the subject's overall UL movement performance.

The comparison of right and left UL performance in healthy subjects produced surprising results. All subjects showed significantly better movement control in their right UL, judged on the parameters shown in TABLE IV. It is interesting that all observed parameters demonstrated worse left UL performance (up to 35 % in $\overline{v_{lab}}$). The method can therefore be considered very sensitive in terms of exposing such great differences between left and right UL. However, the above shown results for impaired subjects still depict at list a rank worse movement control. Together with relatively large differences found among impaired subjects, this might be considered as an indisputable proof of high resolution of the test and high presentation value of the numerical parameters.

The patients were holding the haptic interface control stick with the fingers as described in the Methods section.

Because the wrist of the patient was unsupported during the measurements we actually evaluated the function of the upper limb as a whole, it's proximal and distal parts. The acquisition of 3 DOF pointing device seems to be sufficient for the proposed method. Based on our current experiences with the use of haptic device for this purpose and the method itself, we do not believe the acquisition of another three orientation angles, which are also supported by the device, would bring new relevant information. However, relevant estimations on sensory/force perception ability of the tested subject are unveiled from force traces.

V. CONCLUSION

The new test was applied to a group of 13 subjects with various forms of ND resulting in upper limb movement impairment as well as to three healthy subjects. This preliminary study demonstrated the suitability of the new method for the UL assessment in rehabilitation, as it gives objective, repeatable and quantitative results. The main advantage of such measuring system is the measurement objectivity, excluding the possibility of human-factor errors, which is what the rehabilitation community is looking for. The potential benefit of using this method lies not only in the measurement objectivity and high resolution, but also in the long term stability of the measure, the repeatability. Sequential tests could easily be performed over large time intervals in order to assess the disease progress or to track UL functional state changes. Due to the objectivity and repeatability of the proposed test, the results of sequential tests are comparable and useful, which could not be claimed

for many manual tests. All these characteristics make this method observer, place and time invariant. Such strict and objective approach to UL functional assessment might play a key role in evaluating various drug treatment or physical therapy effects. The method enables the therapists to make important decisions about planning an optimal treatment for each individual case based on objective and repeatable measurements.

The labyrinths as test polygons in combination with a haptic device offer simple yet efficient insight into patient's UL functional state, but lack some ability to perform more sophisticated data analysis. Labyrinths are highly complex regarding the definition of the "optimal" or reference trajectory path for the comparison with the patient's trajectory. To overcome this complexity problem, or to extend the range of tests, a simpler VE should be created, e.g. a pre-defined trajectory that should be followed by the patient. Random force perturbations via haptic device could be used to trigger and assess the patient's response to the disturbances. In this case, the patient would become involved in a feedback control loop of tracking a pre-defined trajectory. Besides the numerical parameters described in the Results section, one of the possible ways of assessing the UL functional state could be the judgment of a patient's response based on the model identified from force perturbations.

As the new test proved to be sensitive, the statistical reliability is yet to be proved by cross-validation with other UL assessment methods.

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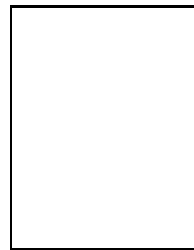
Aleš Bardorfer (S'99) received the B.Sc. degree in electrical engineering from the Faculty of Electrical Engineering, University of Ljubljana, Slovenia, in 1999. In 1998 he was with the Microsurgery Advanced Design Lab, Johns Hopkins University, Baltimore MD, USA. He was awarded first prize at the IEEE Region 8 Student Paper Contest 2000 for his work on force feedback telemanipulation entitled "Connecting Haptic Interface with a Robot". He is currently a Ph.D. student and a Research Assistant with the Laboratory of Biomedical Engineering and Robotics, Faculty of Electrical Engineering, University of Ljubljana. His research interests are directed towards haptic perception, force feedback telemanipulation and upper limb rehabilitation robotics.
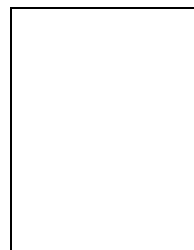
Marko Munih (M'88) received the B.Sc. in 1986 and the M.Sc. in electrical engineering from the University of Ljubljana, Slovenia, in 1989, respectively. He received the D.Sc. degree in electrical engineering in 1993 for work on controlling muscle activity with respect to the femur and tibia bone loading. From 1989 he was appointed as a Teaching Assistant at the Faculty of Electrical Engineering. From 1995 to 1996 he was a Research Assistant with the Implanted Devices Group in the Department of Medical Physics and Bioengineering at University College London, where he did research on unsupported standing of paraplegic and development of the sensory amplifier. Currently, he is Associate Professor at the Faculty of Electrical Engineering, University of Ljubljana, Slovenia. His research interests cover functional electrical stimulation of paraplegic lower extremities with surface electrode systems, including measurements, electrical circuits, control and biomechanics. The second research area is rehabilitation robotics. He is member of IEEE, IFMBE, IFESS, IFAC and IARU.
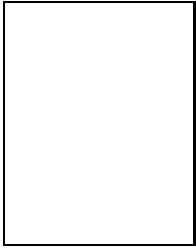
Anton Zupan, MD, PhD graduated in 1980 from the Faculty of Medicine, University of Ljubljana. He specialised in pediatrics and in physical medicine and rehabilitation. Currently he is an Associate Professor of Physical Medicine and Rehabilitation at the Faculty of Medicine, University of Ljubljana and the Head of the Unit for the rehabilitation of patients with neuromuscular diseases at the Institute for Rehabilitation of the Republic of Slovenia.
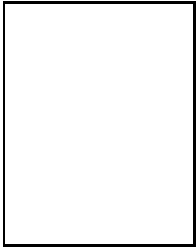
Alenka Primožič received the P.T. degree from the University of Ljubljana, Slovenia, College for Physiotherapy in 1968. She has been employed in the Institute for Rehabilitation of the Republic of Slovenia in Ljubljana since 1969. She is the Instructor for educational programmes for students of physiotherapy. In the first years of her work she was the member of rehabilitational team for spinal cord injuries, since 1988 she has been in charge of the programme of physiotherapy for patients with multiple sclerosis, Friedreich Ataxia and Parkinson's disease. She has been the co-investigator in several national and international research projects. In the years 1982 to 90 she was in charge of the post-graduate programme for physiotherapists from Kuwait and from 1988 to 96 she was the President of Slovenian Association of Physiotherapists.