1 Introduction

The necessity of upper limb (UL) assessment arises mostly in patients with neurological or neuromuscular diseases. Current approaches for the assessment of functional and motor abilities of UL are mainly limited to subjective evaluations performed by the therapists. Several standardised scales for measuring the outcome of rehabilitation exist, such as the Barthel Index, the Functional Independence Measure (FIM), and the Functional Assessment Measure (FAM) (Wade, 1992; Wade, 1988). However, these scales are not specifically designed for the upper limbs and are subjective to a large extent, as the observer assigns the score for the (sub)test.

A concise insight into UL functional state is a prerequisite for the assessment and planning of an optimal treatment and complex care for each individual case. We believe that a precise, objective, and sensitive quantification of dysfunction of UL is needed, which may enable therapists to judge the effectiveness of various treatment procedures and also facilitate better understanding of the natural course of the disease. Haptic interfaces have the ability to measure the movement and act with software-defined forces back to the operator. The possibility of simultaneous measurement of pose (position and orientation) and tactile (force) information in an interactive environment inspired us to build a virtual reality (VR) simulator for UL assessment purposes.

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2 Method

A haptic interface technology combined with visualization techniques is introduced only for the purpose of objective UL functional assessment (Bardorfer, 2001) and not for therapeutic exercise. A VR based UL assessment system was designed, using off-the-shelf Phantom 1.5 haptic interface (Figure 1) and solely open-source code. Our VR system runs on a PC under Real-Time Linux and is capable of network distributed execution of real-time robot controller tasks and visualization processes.

The proposed instrumental UL assessment technique uses several types of virtual environments containing various accuracy, speed and force demanding tasks that are diverse in the degrees of freedom of movement (DOF). These tasks range from simple 1DOF point, line and circular tracking, 2DOF and 3DOF labyrinth passages and maximal force exertions in various directions. Special care was taken during the construction of these environments and tasks in order to be complex enough for adequate resolution/range of the results (ceiling effect), and yet simple enough to assess only the movement and motor capacity of the tested subject’s UL. The method should not assess the intellectual abilities or other impairments (e.g. visual).

In the sequel, the tasks and virtual environments that are used in the system are described. The only exception is the labyrinth test, which is described in depth in (Bardorfer, 2001), but still shown in Figure 2c.

Tracking tasks: Two position tracking tasks are available: linear tracking (Figure 2a), and circular tracking (Figure 2b). In case of linear tracking, the patient’s task is to follow the line presented on the screen as close as possible towards the red ball (from the centre out and back). The tracking takes place in 6 different directions, but only one line at a time is presented on the screen. In case of circular tracking, the task is to follow the circular line presented on the screen in the direction previously indicated by the red ball animation (counterclockwise and then clockwise). Again, the patient should follow the line as close as possible. The
next two tests are visually the same, but have added force perturbations and a gradient force field. The force perturbations are in a form of random binary signal ($F_{PRBS}$), with amplitude of $F_0=0.5$ N, acting perpendicular to the tracking line tangent (radial direction in circular tracking). The linear force field on the other hand acts along the tracking line tangent ($F_{field1} = K^*r/R$, $F_{field2} = K^*\hat{\alpha}/\hat{\beta}$, $\hat{\alpha}=(-\delta, \delta)$, $K=0.5$ N). In the circular tracking task, the angular force field opposes the movement up to the top (0 to $\delta$) and acts in the direction of movement ($-\delta$ to 0).

![Figure 2a. Linear position tracking test.](image1)

![Figure 2b. Circular position tracking test.](image2)

The maximal force task tests the capacity of exerting forces in various directions. A haptic tunnel is provided along the line segment and a relatively strong radial
force field \( F_r = K^*(r/R), K=5 \text{ N} \) is pulling the patient’s UL towards the centre. \( F_r = 8 \text{ N} \) is the limiting value of this test (ceiling effect), as the haptic interface that was used, cannot exert forces larger than 8N.

![Figure 2c. Labyrinth test.](image)

The subject is instructed to move from the centre towards the outer red ball in a continuous manner without delays to minimize fatigue, and exert a force according to his/her best abilities. The graphical representation of the test is similar to linear tracking, shown in Figure 2a.

### 3 Results and Discussion

The set of tests for objective assessment of UL functional state as described above generates a large amount of numerical and graphical data, which are in general specific for a certain task. The numerical results include: the movement velocities, maximal and average deviations, average power and average energy contributions during the robot and the patient UL movements, revealing the active role in movement (patient / haptic interface). Currently, Matlab and LaTeX are used for the off-line data analysis and automatic compilation of condensed printable reports. Presenting them all would exceed the scope of this manuscript since each of the trial generates two A4 pages of numeric and graphic output.

Figures 3a and 3b show the maximal exerted force in 6 directions for the patient with MD and healthy subject for their dominant UL, left in these cases. The reduced force capacity for the patient with MD in many directions is clearly evident, as well as is the non-even distribution of maximal forces in 6 different directions. Force capacity is higher in the right directions, meaning the flexor muscles of the left hand are stronger than the extensor muscles. The gravity effect is shown as well.
4 Conclusion

A total of 80 patients with various neuromuscular and neurological diseases were subject to UL functional assessment using this approach. The method presents a valuable diagnostic tool for objective movement and motor assessment of upper limbs, providing accurate, objective and repeatable data. The same general assessment methodology can be used with other input devices, controlling the virtual world to assess the suitability of each input device to control the same world by an individual patient.
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6 References