UPPER LIMB FUNCTIONAL ASSESSMENT USING HAPTIC INTERFACE

OCENJEVANJE FUNKCIJE ZGORNJEGA UDA S POMOČJO HAPTIČNEGA VMESNIKA

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Key words: *rehabilitation diagnostics; haptic interface; upper limb; medical robotics*

Abstract – *A new method for the assessment of the upper limb (UL) functional state, using a haptic interface is presented. A haptic interface is used as a measuring device, capable of providing objective, repeatable and quantitative data of the UL motion. A patient is presented with a virtual environment, both graphically via a computer screen and haptically via the Phantom Premium 1.5 haptic interface. The setup allows the patient to explore and feel the virtual environment with three of his/her senses; sight, hearing, and most important, touch. Specially designed virtual environments are used to assess the patient's UL movement capabilities. The tests range from tracking tasks – to assess the accuracy of movement – tracking tasks with added disturbances in a form of random forces – to assess the patient's control abilities, a labyrinth test – to assess both speed and accuracy, to the last test for measuring the maximal force capacity of the UL.*
A new method for the assessment of the upper limb (UL) functional state, using a haptic interface is presented. A haptic interface is used as a measuring device, capable of providing objective, repeatable and quantitative data of the UL motion. A patient is presented with a virtual environment, both graphically via a computer screen and haptically via the Phantom Premium 1.5 haptic interface. The setup allows the patient to explore and feel the virtual environment with three of his/her senses; sight, hearing, and most important, touch. Specially designed virtual environments are used to assess the patient's UL movement capabilities. The tests range from tracking tasks–to assess the accuracy of movement-tracking tasks with added disturbances in a form of random forces-to assess the patient's control abilities, a labyrinth test-to assess both speed and accuracy, to the last test for measuring the maximal force capacity of the UL.
A comprehensive study, using the developed measurement setup within the haptic virtual environment, was carried out. 19 healthy subjects and a total of 80 patients with various neurological and neuro-muscular disorders took part in the study. In this paper, only some typical characteristics of the upper limb movement, affected by Becker type muscular dystrophy are shown in a quantitave manner and compared to a healthy subject. The numerical results of the comprehensive study were analysed using data mining techniques, leading to the most important numerical parameters and revealed the content validity of the proposed tests.
The developed measurement methodology utilizing haptic interface provides objective, quantitative and repeatable method for the assesment of the upper limb functional state.

Ključne besede: *rehabilitacijska diagnostika; haptični vmesnik; gornja ekstremiteta; robotika v medicini*

Izvleček – *Delo obravnava možnosti uporabe haptičnih vmesnikov za objektivno, kvantitativno in ponovljivo vrednotenje funkcijskih sposobnosti gornje ekstremitete. Razvito je bilo merilno okolje in metodologija za merjenje funkcije gornje ekstremitete s haptičnim vmesnikom Phantom 1.5. Haptični vmesnik omogoča simulacijo dotika z navideznim prostorom preko generiranja sil, ki jih čuti operater/pacient, obenem pa služi tudi kot merilnik pozicije in sil. Merilno okolje sestavlja zmogljiv simulator/prikazovalnik navideznega prostora s haptično, vizualno in avditorno povratno informacijo z možnostjo mrežno distribuiranega izvajanja v realnem času. Naloge pacienta v navideznem okolju so ciljno oz. funkcijsko usmerjene ter zajemajo tri dimenzije elementarnega modela virov zmogljivosti: natančnost, hitrost in silo. V nestrokovnem jeziku je pojem sile pogosto zamenjan s pojmom moči, kar pa fizikalno ni korektno. V tem duhu naloge sestojijo iz: linearnega in krožnega pozicijskega sledenja z motnjami (perturbacijami) v obliki naključnih sil in brez njih, dotikanja točk v pacientovi frontalni ravnini, prehoda labirinta z dvema stopnjama prostosti gibanja in napenjanja relativno trde vzmeti v šestih različnih smereh z namenom merjenja »mišične moči« (zmogljivosti izvajanja sile oz. pritiska). Merilno okolje oz. večmodalni simulator navideznega okolja omogoča preprosto gradnjo objektov in z njo povezano fleksibilnost in prilagodljivost naloge različnim zmogljivostim in težavnostnim stopnjam.*
Izvedena je bila obsežna študija z omenjenim merilnim sistemom v navideznem haptičnem okolju. V študijo je bilo vključenih 19 zdravih oseb in skupno 80 bolnikov z različnimi nevrološkimi in predvsem živčno-mišičnimi boleznimi, vključujoč oblike mišične distrofije (duchennova, beckerjeva, ramensko-medenična, facio-skapulo-humeralna ter miotonična oblika), spinalne mišične atrofije (tipa II in III), hereditarne motorično-senzorične nevropatije, friedreichove ataksije, parkinsonove bolezni in multiple skleroze. Prikazani pa so le nekateri izmed rezultatov nalog krožnega sledenja in merjenja maksimalne sile za pacienta z beckerjevo mišično distrofijo in primerjava teh rezultatov z zdravo osebo.
Numerični rezultati študije so obdelani z algoritmi za odkrivanje znanj iz podatkov (metodami strojnega učenja), ki privedejo do najpomembnejših numeričnih parametrov testov, ki razlikujejo paciente z različnimi živčno-mišičnimi boleznimi od zdravih oseb in razkrivajo vsebinsko veljavnost testov. Pomembne naloge s stališča merjenja natančnosti, hitrosti gibanja in mišične moči so predvsem naloge sledenja s prisotnostjo naključnih motenj in brez njih, naloga prehoda labirinta 2 DOF in naloga maksimalne sile. Ta nabor na-

log tudi ustreza trem dimenzijam elementarnega modela virov zmogljivosti: natančnosti, hitrosti in sili.
Rezultati študije so preko kvantitativnega vrednotenja karakteristik gibanja pokazali nekatere značilnosti posameznih diagnoz. Pacienti z različnimi oblikami mišične distrofije izkazujejo veliko natančnost gibanja, vendar omejeno sposobnost izvajanja sile. Motnje bistveno pripomorejo k razpoznavanju funkcionalnega stanja gornje ekstremitete pri večini živčno-mišičnih bolezni. Omenjena kvantitativno ovrednotena spoznanja so lahko koristna informacija pri snovanju vmesnikov za vodenje invalidskih vozičkov ter tudi drugih pripomočkov, ki jih uporabljajo pacienti z živčno-mišičnimi boleznimi.
Zanesljivost opazovalca in časovna zanesljivost razvite metodologije je inherentno vsebovana zaradi odsotnosti opazovalca in s tem povezanimi subjektivnimi vplivi na eni strani in zaradi časovne nespremenljivosti haptičnega sistema kot merilne naprave in konstantnosti digitalnih algoritmov obdelave izmerjenih podatkov na drugi strani. Iz podobnega razmisleka izhaja tudi objektivnost in ponovljivost razvite metode. Razvita metodologija merjenja s haptičnim vmesnikom tako predstavlja objektivno, kvantitativno in ponovljivo metodo merjenja karakteristik gibanja gornje ekstremitete in s tem njenega funkcionalnega stanja. Še vedno pa ostaja problematična (ne)eksistenca oz. težavna realizacija merilnega etalona tako kompleksnega merjenja, kot je merjenje funkcijskih sposobnosti.

Introduction

Upper limb (UL) functional assessment is a qualitative and quantitative procedure, by which the patient's UL motion and motor abilities – UL functional state – are evaluated. Functional impairment differs significantly among various individuals, as well as between patients with the same diagnosis. Concise insight into UL functional state is a prerequisite for planning an optimal treatment and complex care for each individual case. Current approaches for the assessment of the UL functional state are mainly limited to subjective evaluations, performed by the therapists. Many subjective tests (e. g. Fugl-Meyr [1], Barthel [2]) are widely used in rehabilitation practice and have an important role, but lack objectivity as they produce subjective or semi-quantitative results. Some of them may vary as much as 40% between various observers (3). Even though the quantification of neuro-muscular (NMD) and neurological (ND) diseases has recently become more interesting to the researchers, the techniques for measuring the motion and motor dysfunction remain rather primitive. Striving for more objective assessment, authors have devised various tests employing several functional tasks, but in most cases, the only measurable physical property that provides objectivity, is the time taken to perform some pre-defined action/task (4). All the other characteristics of the human movement, coming from the interaction with the environment, remain unexplored. However, 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 visual-only virtual reality (VR) technology in rehabilitation. Wilson et al. (5) 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 VR technology could bring benefits to the rehabilitation world, if used with caution (6–9). Significant potential therefore exists for mechatronic devices (haptic interfaces) to improve quantitative assessment, monitoring and treatment of individuals with movement disabilities.

Haptics is an emerging field in robotics. Haptic interface is a small robotic manipulator, capable of exerting controlled forces on its end effector – a property that cannot be claimed for the »usual«, industrial robots. With proper software that is controlling the robot, it is possible to create an illusion of physical contact with a virtual object for the operator holding/guiding the robot – a haptic virtual environment simulation. Traditionally human-computer interfaces have been bounded to visual and audio technology for providing the feedback to the operator. Haptic interfaces extend this traditional computer interaction paradigm by providing additional dimension, namely haptic/tactile feedback to the operator. This way, the operator receives input from more senses and experiences the virtual environment in a more realistic way.
The aim of the present study was to devise a battery of tests enabling objective instrumental assessment of the functional capacity of the UL in patients with NMD and ND, utilizing a haptic interface. The new tests should be objective, reliable, easy to perform, suitable for routine use and should produce repeatable results (10). It should be as sensitive as possible, allowing evaluation of the natural course of the disease. The high sensitivity of the test should give the therapists a chance to judge the effectiveness of various therapies. The simulated task (virtual environment) should be simple, thus none of the intelligent capabilities of the patient would influence his/her performance (e. g. finding a geometric solution). It should also be clear enough, not to confuse even visually impaired subjects.

Methods

The measurement setup consists of two personal computers running Real-Time Linux[1] and Linux[2] operating system respectively. The first one takes care of data logging and real-time control of the Phantom Premium 1.5 haptic interface[3] (19.5 ×

[1] http://www.fsmlabs.com
[2] http://www.linux.org
[3] http://www.sensable.com

27 × 37.5 cm workspace size, 0.03 mm 3D positional resolution, 3 active and 6 measurements degrees of freedom, 8.5 N maximal exertable force). The second one is a graphical workstation providing a fast 3D virtual environment scene rendering (f_g > 100Hz). They are connected via a private network segment (TCP/UDP/IP). The system allows for hard real-time haptic interface control (up to f_s = *16 kHz*) with simple collision detection and for soft real-time rendering of arbitrary 3D graphics scenes using standard VRML (Virtual Reality Markup Language). The graphics models can be exported to VRML from many available 3D modeling software packages.

The haptic interface is used as a positional measuring device and as a force feedback generator. The robots in general, and thus haptic interfaces, are active devices, meaning that they can act as a source of energy to the coupled mechanical system: human arm-haptic interface. This could be characterized as a power flow from the robot to the subject and is usually the case in robot-mediated physiotherapy (11). But with proper control strategy, haptic interfaces can be programmed to act as passive devices which could be characterized as a minimal power flow from the subject to the robot and not the other way around. This is usually the case when simulating virtual (passive) environments, and was the case in this study as well, except when using force disturbances, which will be described later.

The measurement setup is presented in Figure 1. Various virtual environments can be displayed to the subject via a com puter screen, providing visual feedback and via the Phantom 1.5 haptic interface the subject is in contact with. The subject can feel all the reactive forces occurring in contact with the virtual environment and can get the realistic impression as if he/she was interacting with the real environment. By acquiring the 3D position and force signals and their off-line analysis, it is possible to gain knowledge on the UL movement characteristics, the finger dexterity and the forearm movement abilities.

Figure 1. *The measurement setup.*

The patient's tasks in virtual environments and the virtual environments themselves range from simple, such as line and circular tracking to more complex, such as the labyrinth test (11) and force exertion capacity test. In order to avoid the problem of three-dimensional perception without using a stereovision technology, which we believe is not suitable for the elderly population, most of the tasks were constructed in the patient's frontal plane. We will limit our discussion to circular tracking and force exertion capacity tests.

Circular tracking: The patient's task is to follow the circle drawn on the screen from the bottom start and end point (6 o'clock) in counter-clockwise and clockwise direction as accurate as possible. The patient tracks the line with a ball representing the current position of his/her arm. The tracking direction is indicated with the red ball animation prior to the test. Tracking in the other direction is prevented with a haptic wall in-line of the 6 o'clock direction (β = 0). The patient's movements are constrained to his/her frontal plane via a haptic device.

The second part of the circular tracking test adds the force perturbations 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) and an angular force field along the tracking line tangent ($F_{field2} = K^*(\beta/\pi)$, $\beta = (-\pi, \pi)$, K=0.5 N). The force field F_{field2} opposes the movement up to the top (0 to π) and acts in the direction of movement ($-\pi$ to 0), as indicated with arrows in Figure 2.

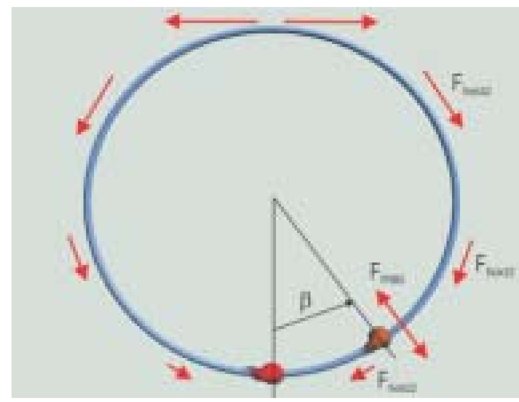

Figure 2. *Circular tracking task.*

Maximal force test: This task tests the capacity of exerting forces in six directions (one at a time) as shown in Figure 3. A »haptic tunnel« is provided along the line and a relatively strong radial force field ($F_r = K^*(r/R)$, K=5 N) is pulling the patient's UL towards the center. F_r = 8.5 N is the limiting value of this test (ceiling effect), as the haptic interface being used, cannot exert forces larger than 8.5 N. The subject is instructed to move from the center towards the outer red ball in a continuous manner without delays to minimize fatigue, and exert a force in this same direction according to his/her best abilities.

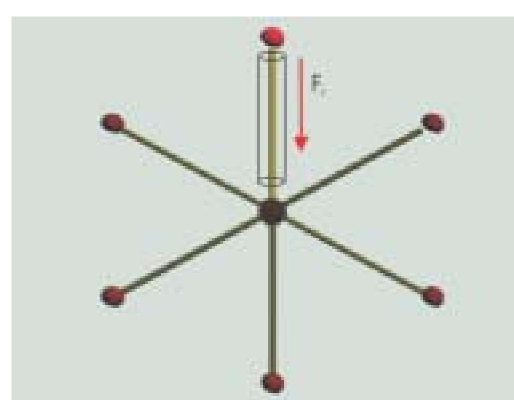

Figure 3. *Maximal force test.*

Results

During the tests described above, the 3D position and force vector signals are logged and later used for off-line data analysis. The set of tests for objective assessment of UL functional state as described above generates a large amount of numerical and graphical results, which are in general specific for a certain task. The Matlab and LaTeX were used for the off-line data analysis and automatic compilation of condensed printable reports.

In case of tracking tasks, the deviation Δ from the tracking line is evaluated, as well as its mean and maximal value. Next important parameters are the speed of advancement v_{task} and the patient's trajectory speed v_{traj}, as well as the ratio of these two velocities R:

$$v_{task} = \frac{l_{track}}{T_{ex}}, \quad v_{traj} = \frac{\sum_{k=1}^{N} |p(k) - p(k-1)|}{T_{ex}}, \quad R = \frac{v_{traj}}{v_{task}}$$

where l_{track} is the nominal tracking trajectory length, T_{ex} is the tracking task execution time, and $p(k)$ is the position at sample k. Since T_{ex} is constant, the R represents the ratio of the patient's trajectory length and the nominal tracking trajectory length as well.

The last numerical parameters concern the power flow $p_{pac}(k)$, $p_{rob}(k)$ and energy contributions during the robot and the patient UL movements E_{pac}, E_{rob}, revealing the active role in movement (patient / haptic interface):

$$p_{pac}(k) = F_{pac}(k) v_{traj}(k), \quad p_{rob}(k) = F_{rob}(k) v_{traj}(k),$$

$$E_{pac} = T_s \sum_{k=1}^{N} p_{pac}(k), \quad E_{rob} = T_s \sum_{k=1}^{N} p_{rob}(k)$$

$$v_{traj}(k) = \frac{p(k) - p(k-1)}{T_s}$$

where $F_{pac}(k)$ and $F_{rob}(k)$ and are the patient and the robot force vectors at sample k respectively. T_s is the measurement sampling time ($T_s = 5\ ms$).

In this paper, only some of the results for a 32-year-old male patient with Becker type Muscular Dystrophy (BMD) in comparison to a healthy 27-year-old male subject are presented. Table 1 shows the numerical results for the circular tracking task. The R ratio differs significantly, as well as does the average deviation $\bar{\Delta}$. The mean patient movement power $\overline{p_{pac}}$ and his energy contribution E_{pac} are higher in BMD patient as well. Figure 4 and Figure 5 (top charts) show the deviations from the circular line (solid and dotted) in tracking tasks as a response to radial force perturbations (dashed) for the patient with BMD and a healthy subject respectively. Solid stands for counterclockwise and dotted for clockwise direction of movement. The middle charts represent the angular tracking position (solid and dotted) along with tangential forces (dashed). The bottom charts depict the power flow between the patient's UL and the haptic robot. When the power flow is positive, the patient's UL is playing the active role in the movement and vice versa. In Figure 5 on the right, much smaller deviations can be observed for a healthy subject and thus better responses to radial force perturbations than in Figure 4 for the patient with BMD. A similar conclusion can be drawn from Figure 6 and Figure 7 originating from the same trial.

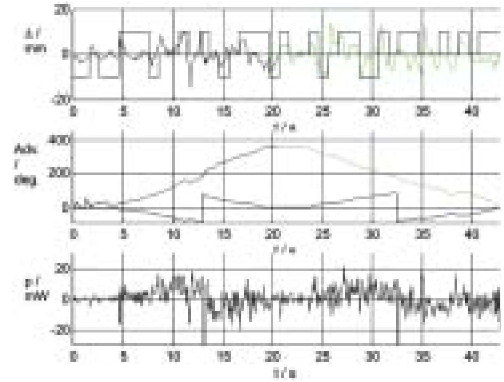

Figure 4. *Track. deviations and power (BMD).*

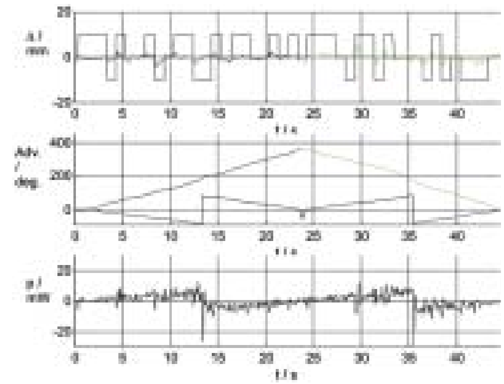

Figure 5. *Track. deviations and power (healthy).*

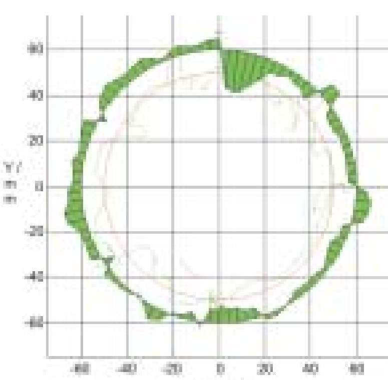

Figure 6. *Power flow and deviations (BMD).*

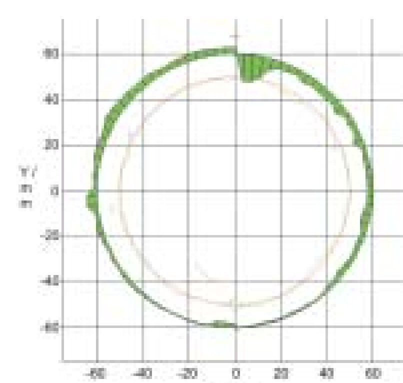

Figure 7. *Power flow and deviations (healthy).*

Table 1. *Numerical results for the patient with BMD and the healthy subject.*

Diag.	$T_{ex}[s]$	$v_{task}[mm/s]$	$v_{traj}[mm/s]$	R	$\bar{\Delta}[mm]$	$\overline{p_{pac}}[mW]$	$E_{pac}[mJ]$
BMD	22.4	14.0	29.2	2.08	3.6	8.9	1.85
healthy	21.1	14.9	15.5	1.04	0.9	3.3	0.63

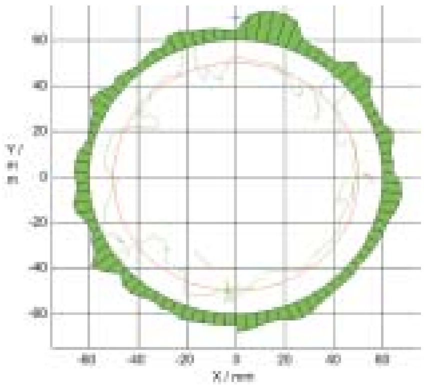

Figure 8. *Trajectory speed profile* v_{traj} *(BMD).*

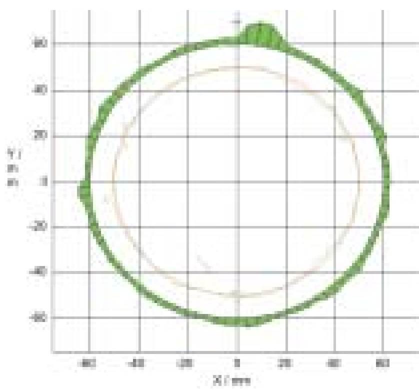

Figure 9. *Trajectory speed profile* v_{traj} *(healthy).*

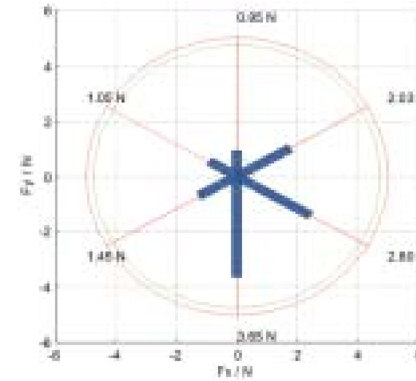

Figure 10. *Maximal force (BMD).*

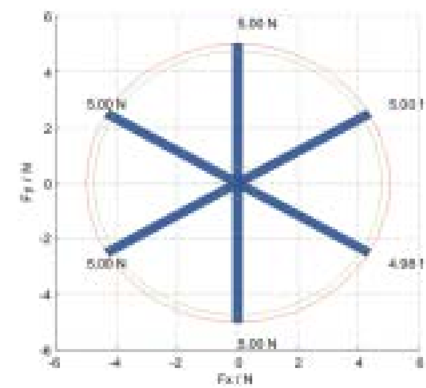

Figure 11. *Maximal force (healthy).*

The solid circular line is the (ideal) trajectory to be tracked, while the dotted line stands for the measured trajectory. The power flow, shown on the outer ring (unit at 12 o'clock = 20 mW), frequently changes the polarity in the regions with large deviations, which is not the case in healthy subject. Higher trajectory speed v_{traj} for the patient with BMD can be observed in Figure 8 (outer ring) compared to a healthy subject in Figure 9 due to poor force disturbance rejection (unit at 12 o'clock = 100 mm/s).

Figure 10 and Figure 11 show the maximal exerted force in 6 directions for the patient with BMD and healthy subject for their dominant UL, left in these cases. The reduced force capacity for the patient with BMD 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.

At such a large amount of numerical parameters for each test (12), one can be certain not all of them are relevant or significant for a particular diagnosis. To find the relevant numerical parameters, data mining techniques were used on the MD and healthy subject dataset, consisting of n = 526 measurements (137 MD, 389 healthy). The dataset consisted of the circular tracking task measurements and maximal force measurements of both hands.

Figure 12 shows a classification tree for patients with MD vs. healthy subjects. The decision tree reveals that the most significant difference when comparing patients with MD and healthy subjects in tracking tasks is the 'R1' attribute. 'R1' is the ratio of the patient's trajectory length and the tracking line length[4]. If 'R1' > 1.082, we can classify this patient to have MD with the model classification accuracy (79%), when testing for MD. However, this result might not be due to tracking inaccuracy of MD patients, but quite possibly due to their inability to reach the tracking circle in all the workspace.

Classification Tree	Class	P(Target)
⊟ <root>	0	74
⊟ R1 <1.082	0	64
⊞ T_EX2 <10.963	100	25
⊞ T_EX2 >=10.963	0	76
R1 >=1.082	0	100

Figure 12. *Classification tree for MD (circular tracking). Healthy subjects belong to a class »100«, and patients with MD to a class »0«.*

Classification Tree	Class	P(Class)
⊟ <root>	100	55
F_MAX1 <4.286	0	100
F_MAX1 >=4.286	100	100

Figure 13. *Classification tree for Duschene and Becker type of MD (maximal force task). Healthy subjects belong to a class »100«, and patients with DMD and BMD to a class »0«.*

Figure 13 shows the classification tree for patients with Duschene and Becker type of MD vs. healthy subjects for the maximal force capacity test. It is clear that the most important

[4] Thus R1 is always greater than 1.

attribute for classification is 'F_MAX1' – the capacity to exert force in vertical direction (12 o'clock). The classification accuracy of the model in Figure 13 is 99%. This makes sense, as the extensor muscles are usually weaker than the flexor ones in patients with MD. The same holds probably for healthy subjects too, but the maximal force test is unable to detect this because of its ceiling effect (F_{max} = 5 N).

Conclusions

The battery of tests for UL functional state described above provides repeatable, quantitative and objective results. The results are both in graphical and numerical form. The commercial haptic interface was used in line, circle and labyrinth tracking. In the next stage, disturbance forces and force field were added to line and circle tracking tasks. The final task included maximal force measurement in various directions.

A total of 80 patients with various neuro-muscular and neurological diseases were subject to UL functional assessment using this approach. In this paper, we have only presented sample graphical results of circle tracking and maximal force measurements for a patient with BMD and a healthy subject. Significantly better disturbance rejection as well as larger capacity to exert forces is measured quantitatively in healthy subject. Data mining techniques were employed to find relevant or typical parameters of the test for a specific diagnosis. A simple classification model was built on maximal force measurements, which quantitatively revealed that the capacity to exert force in vertical direction is the most significant parameter when distinguishing BMD patients from healthy individuals.

Acknowledgments

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