Force exertion capacity measurements in haptic virtual environments

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An objective test for evaluating functional status of the upper limbs (ULs) in patients with muscular distrophy (MD) is presented. The method allows for quantitative assessment of the UL functional state with an emphasis on force exertion capacity. The experimental measurement setup and the methodology for the assessment of maximal exertable force utilizing the Phantom 1.5 haptic interface has been developed. The measurement setup consists of a powerful virtual reality simulator, capable of providing haptic, visual and audio feedback. The patient's task in the virtual environment is goal oriented and includes stretching a virtual spring in six different directions. The Phantom 1.5 haptic interface serves as a kinematic measuring device and as a force feedback generator. By moving the haptic interface control stick the patient exerts the force in six radial directions to the best of his or her abilities. The new test offers numerical as well as graphic results. The method has been applied to 32 MD patients. Several typical force exertion capacity characteristics, affected by neuro-muscular disorders are shown in a quantitative manner. Data mining was used to demonstrate good content validity of the proposed test. The method allows for a quick, accurate, repeatable and objective measurements of the UL force exertion capability.

Vorgelegt wird ein objektiver Test für die Evaluierung der Funktionsfähigkeit der oberen Gliedmaße bei Patienten mit Muskeldystrophie. Diese Methode ermöglicht eine quantitative Beurteilung der Funktionsfähigkeit der oberen Gliedmaße mit Betonung der Kapazität des Kraftaufwands. Entwickelt wurde die experimentelle Messanordnung und die Methodik für die Beurteilung der maximal ausübbaren Kraft unter Zuhilfenahme des haptischen Interaktionsgeräts Phantom 1.5. Die Messanordnung setzt sich aus einem leistungsstarken virtuellen Realitätssimulator zusammen, der ein haptisches, visuelles und akustisches Feedback liefert. Die Aufgabe des Patienten in der virtuellen Umgebung ist zielgerichtet: Er muss eine virtuelle Feder in sechs verschiedene Richtungen dehnen. Das haptische Interaktionsgerät Phantom 1.5 dient als kinematisches Messgerät und als Kraft-Feedback-Generator. Durch Bewegen der haptischen Schnittstellen-Bedieneinheit übt der Patient so gut es geht in sechs radialen Richtungen Kraft aus. Die neuen Tests liefern numerische und graphische Ergebnisse. Die Methode wurde bei 32 Patienten mit Muskeldystrophie angewandt. Verschiedene typische Eigenschaften der Kapazität des Kraftaufwands, die von neuromuskulären Störungen beeinträchtigt werden, werden auf quantitative Weise gezeigt. Die Gültigkeit guter Inhalte bei dem vorgeschlagenen Test wurde anhand einer gezielten Datensuche (Datamining) aufgezeigt. Die Methode lässt schnelle, präzise, wiederholbare und objektive Messungen der Kapazität des Kraftaufwands der oberen Gliedmaße zu.

Se presenta aquí una prueba objetiva para evaluar el estado funcional de las extremidades superiores (ES) en pacientes con distrofia muscular. Esta prueba permite la valoración cuantitativa del estado funcional de las ES, en particular de la capacidad para ejercer fuerza. Se creó un método experimental de medición y la metodología para la valoración de la fuerza máxima ejercible utilizando la interfaz háptica Phantom 1.5. El método de medición consiste en el uso de un simulador de realidad virtual capaz de proporcionar respuestas hápticas, visuales y auditivas. La tarea dada al paciente en este ámbito de realidad virtual se basó en el cumplimiento de ciertos objetivos, entre ellos estirar un muelle virtual en seis direcciones diferentes. La interfaz háptica Phantom 1.5 sirve como instrumento de medición cinemática y como generador de cierta respuesta a la fuerza ejercida. Al desplazar la palanca de control de la interfaz háptica, el paciente ejerce la fuerza en seis direcciones radiales hasta el límite máximo de sus capacidades. Esta nueva prueba arroja resultados tanto numéricos como gráficos, y se ha aplicado a 32 pacientes con distrofia muscular. Se muestran, además, de forma cuantitativa varias características de la capacidad de aplicación de fuerza, la cual se afecta como resultado de trastornos neuromusculares. Se utilizó el método de minería de datos para demostrar la validez del contenido de la prueba propuesta. Esta prueba permite obtener valores objetivos, de forma rápida, fiable y repetible, de la capacidad de aplicación de fuerza utilizando las ES.

Un test objectif pour l'évaluation de l'état fonctionnel des membres supérieurs (MS) chez les patients atteints de dystrophie musculaire est présenté. Cette méthode permet une évaluation quantitative de l'état fonctionnel des MS, l'accent étant mis sur les capacités d'application de force. The experimental measurement setup and the methodology for the assessment of maximal exertable force using the Phantom 1.5 haptic interface has been developed. La configuration de mesure expérimentale et la méthodologie pour l'évaluation de la force maximale applicable à l'aide de l'interface haptique Phantom 1.5 ont été développées. La configuration de mesure consiste en un puissant simulateur de réalité virtuelle, capable de fournir un signal haptique, visuel et audio. La tâche du

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patient dans l'environnement virtuel est axée sur des objectifs spécifiques qui comprennent l'étirement d'un ressort virtuel dans six directions différentes. L'interface haptique Phantom 1.5 sert de dispositif de mesure cinématique et de générateur de retour de force. En déplaçant la manette de commande de l'interface haptique, le patient exerce une force radiale au mieux de ses capacités dans six directions. Le nouveau test propose des résultats numériques ainsi que graphiques. La méthode a été appliquée à 32 patients atteints de dystrophie musculaire. Plusieurs caractéristiques typiques de capacités d'application de force, affectées par des troubles neuromusculaires, sont présentées de manière quantitative. Des fonctionnalités d'exploration des données ont été utilisées pour démontrer la validité du contenu du test proposé. La méthode permet une mesure rapide, précise, reproductible et objective de la capacité d'effort des MS. *International Journal of Rehabilitation Research* 33:34–42 © 2010 Wolters Kluwer Health | Lippincott Williams & Wilkins.

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Introduction

For studying the movements in the human lower extremities, there are established approaches of gait measurement and analysis available. Most modern rehabilitation centers have a kinesiology department with optical measuring systems and force platforms, enabling assessment of patients' walking. Various other specialized devices enable various isometric, isotonic or isokinetic tests. The same observation is not valid when considering the upper extremities. Approaching of hand to an object, grasping, and coordination of finger movements are daily activities, which are even more important for the independent living of a person with disability than walking itself. Nevertheless, in the area of upper limb (UL) we are predominantly dealing with subjective testing of what is a completely different approach to the instrumented kinesiology department. A movement laboratory should also include instrumentation for quantitative assessment of upper extremity performance. In this context, a valuable addition to simple force measurement devices (Kurillo *et al.*, 2007) offers haptic virtual environments (VEs).

UL assessment is a quantitative procedure, by which the patient's motion and motor abilities, that is, functional states, are evaluated. The necessity of UL assessment arises not only, but mostly in persons with neuromuscular disorders (NMDs) and neurological disorders. NMDs, as hereditary chronic degenerative and progressive disorders of the motor unit, are shown with common prevalent clinical signs as is muscle weakness, gradual deterioration of muscle fibers (muscular atrophy), and eventually leads to completely or incompletely paralyzed muscle groups. A person consequently has movement problems and is gradually becoming bound to a wheelchair. Along with the primary muscle weakness, secondary signs can occur. These are muscle contractures, scoliosis, respiratory complications and cardiac deficiency in the last stage of the disease (Brooke, 1986, 2000). Functional impairments differ significantly among various disorders, as well as between patients with the same diagnosis. Therefore, patients should be treated and followed-up on an individual basis.

Current approaches for the assessment of functional and motor abilities of UL are bound to the evaluation procedures performed by clinicians. These employ the following four 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 (Smith, 1973; Bell *et al.*, 1976); some authors added joint range of motion measurements (Bear-Lehman and Abreu, 1989). These tests, however, are not catching the specifics of patients with different NMDs and neurological disorders, being affected by various physical impairments, such as muscle weakness in muscular dystrophy (MD), tremor and bradykinesia (slowness of movement) in Parkinson's disease, ataxia (disturbances in coordination of the muscle movements) in Friedreich ataxia and multiple sclerosis, etc. Many clinically accepted qualitative tests (e.g. Fugl-Meyer *et al.*, 1970; Wade and Collin, 1988; Collen *et al.*, 1990) that are widely used may vary by as much as 40% between various observers (Wade, 1992). 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 resolution. Some tests for the assessment of UL, such as the Nine-Hole-Peg-Test (Mathiowetz and Bass-Haugen, 1995), Jebsen Taylor Hand Function Test (Jebsen *et al.*, 1969), and TEMPA (Desrosiers *et al.*, 1995) measure time taken to complete the test. Some other examples, mostly in the field of activities of daily leaving include Katz Index (Guccione, 2001), Nottingham Activities of Daily Leaving Index (Wade, 1992), Frenchay Arm Test (Wade, 1992). The trend in rehabilitation diagnosis is to provide objective and repeatable test methods, to decrease subjective factors and increase the therapist's ability to obtain reproducible findings, meaningful and accurate results.

A previous study reported on using visual-only VE technology in rehabilitation. Wilson *et al.* (1997) presented the evidence that knowledge and skills acquired by disabled individuals in simulated environments can transfer to the real world. Researchers have agreed that VE technology could bring benefits to the rehabilitation world (Jones, 1998; Korpela, 1998; Latash, 1998; Ring, 1998). According to Jones (1998), it is anticipated that VE retraining techniques could provide accurate measures of the patients' progress in a rehabilitation program. Significant potential, therefore, exists for mechatronic devices to improve in particular quantitative assessment and monitoring of treatment of individuals with movement disabilities.

The aim of this study was to exploit the three degrees of freedom (DOF) haptic device Phantom with a particular software environment, as measuring device, that enables objective assessment of the motor ability of the ULs in patients with MD. For this particular group it is typical to observe a decrease of muscle force exertion with time and in various directions of movement, all in relation to particular muscle or muscle group weakening dependent on the specific person. The emphasis of the test was on the force exertion capacity, which is one of the three elements of the Elementary Resource Model by Kondraske (2000), namely, the accuracy, velocity, and force/power of movement. The force exertion capacity plays an important role in the manipulation of objects, as well as in control of many assistive devices. The new tool should be objective, reliable, easy to perform, suitable for routine use and should produce repeatable results (Zupan, 1996). It should be as sensitive as possible, allowing evaluation of the natural course of the disease as well as of the effects produced by various therapeutic measures. The high sensitivity of the test should give therapists a chance to detect functional disorders of the UL in early stages of the disease and to properly assess minimal functional capacities of the most severely affected individuals. In this way it would be a good indicator of the changes in the rehabilitation process. The workspace size and the exertable force range of the used haptic interface allow the simulation of real world force interactions in the selected group of MD population. The simulated task in VE should be simple in all aspects. It should also have computer graphics as simple as possible for clear visual perception (Bardorfer *et al.*, 2001).

The main aim of this study is to exploit haptic and VE technology for position/force measurement and force generation device for movement measurement purposes. The study brings a new objective test for clinical evaluation of UL functional state suitable for the MD population, using a commercially available three-dimensional (3D) Phantom device.

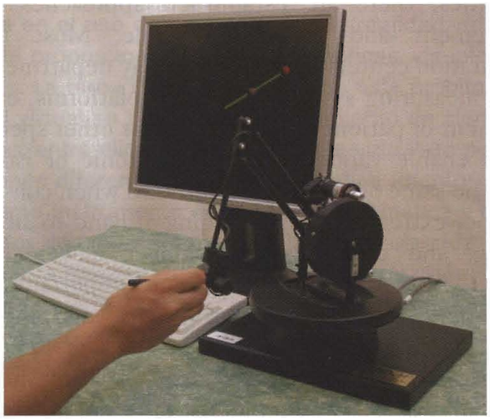
Methods

Measurement setup

The core of the measurement system is the Phantom Premium 1.5 haptic interface (*http://www.sensable.com*) with 19.5 × 27 × 37.5 cm workspace size, 0.03 mm 3D positional resolution increment, three active DOF, six measurement DOF, and 8.5 N maximal exertable force. It is used as a measuring device for positional input and as a feedback force generator. The visual and tactile information is fed back to the patient using a computer display and a haptic interface. Usually, vertical placement of the screen and the force exertion capacity tasks are performed in the patient's frontal plane (up/down, left/right) (Fig. 1).

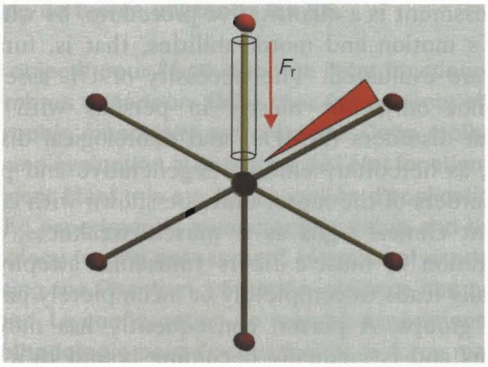
The person can move the pointer, represented with a ball in the center of the VE (Fig. 2) by moving the haptic interface control stick. Thereafter, the movement is

Fig. 1



The measurement setup with computer screen and haptic robot. The screen shows movement along the second radial segment.

Fig. 2



Six visual and haptic segments, the tunnel and force triangle are added only for this presentation. During the test only one segment is shown, (Fig. 1).

tested in one of the six directional segments. Only the selected segment is shown visually and haptically. A segment is zero-width haptic tunnel with the tunnel cross sectional stiffness of $K = 300\,\mathrm{N/m}$ as shown in Fig. 2. The haptic tunnel helps to guide the person's movements smoothly along the currently selected segment and allows the patient to concentrate on force exertion in a radial direction, from the center outward, rather than concentrating on segment tracking. Second, a relatively strong radial force field, F_r, acting towards the tunnel center, is added to the haptic scene with force being dependent on the distance r from the central starting point:

$$F_r = F_{rmax}\frac{r}{|R|} \tag{1}$$

where maximal force, F_{rmax}, is configurable, but bound to 8.5 N in case of the Phantom 1.5 haptic interface and $|R|$ is the total segment length. The effect is similar to pulling the spring along the segment. The F_{rmax} limitation represents a ceiling effect of the test being evident in healthy participants and other conditions, but is adequate for MD group. The patient's task is to apply a force in the direction of the selected segment to the best of his or her abilities without backtrack motion. By acquiring the 3D position and forces of the stylus during segment movement, the finger's dexterity, together with the forearm and the shoulder movement abilities are captured.

Participants

A comprehensive study, using the developed measurement setup within the haptic VE, was carried out in 19 nondisordered participants and a total of 32 persons with MD, 22 males and 10 females. The participants of the study were diagnosed with various forms of MD (Düchenne type-2, Becker type-6, Limb-Griddle type-12, Facioskapulohumeral type-9, Myotonic type-3). The age distribution of both populations was similar: 37.6 ± 15.6 years for patients with MD and 34.1 ± 11.6 years for healthy control participants. MD participants were selected on a voluntary basis after written consent when they visited their summer recreation facilities. The healthy control group was picked from the personnel in the laboratory and the rehabilitation personnel. In this study the measurements were conducted using a strict measurement protocol, approved by the ethics committee. All the disabled as well as nondisabled participants in this study were performing the described test using a wheelchair with handles for lower arm rest/fixation. The wheelchair users used their own custom designed wheelchairs, whereas nonusers always used the same wheelchair from the institution. Special attention was paid to maintain a physiologically correct sitting posture whenever possible sitting upright with backrest, feet touching the floor or wheelchair leg rests. The graphic screen was always parallel to the patient's frontal plane and positioned 50–70 cm away from the patient's eyes, depending on the patient's lower arm length. The geometrical relations between the wheelchair, the arm rests and the Phantom haptic interface were always set in a way to allow for 30° shoulder abduction, 90° elbow flexion and the lower arm being perpendicular to the frontal plane. The height of the table was 72 cm. The lighting conditions were adjusted to allow for optimal viewing of the graphic screen, without direct sunlight and screen reflections. The grip of the haptic interface stylus (end effector) varied across the patients because of their specific diagnoses and impairments or residual function, but the most prevalent grips were a three-finger grip and a cylindrical grip. Each person was tested a minimum of twice with the left arm and twice while using the right arm. In each arm, force exertion capacity was acquired first with arm resting on the wheelchair's arm support, and later with wrist being gently fixed with a wide strap to the chair rest to allow motion only below the wrist without trick movements. Trick movements are those that are learnt by somebody and (movements) executed in a different way than normal in order to do something that is otherwise prevented because of movement deficiency.

A majority of the participants acquired three such quadruple tests to gain insight into repeatability of a method or even more owing to a person's own interest.

Methods of evaluation

The 3D position of the haptic interface control stick (patient's arm partial kinematics) and the 3D force vector were sampled at a rate of $f_s = 200\,\mathrm{Hz}$. The Phantom haptic interface used in this study does not incorporate the force sensor for direct measurement of interaction forces with the environment. However, the values of the 3D force vector, F_{arm}, could be alternatively constructed from the following two components:

$$F_{arm} = F_{motor} + F_{model} \tag{2}$$

F_{motor} component represents the 3D force vector at the end effector representing the contribution from the haptic interface motors and F_{model} component is the part attributed to the dynamic properties of the haptic interface mechanism. F_{model} encompasses the dynamic interaction forces resulting from the Phantom haptic interface dynamic model, fed with the measured inputs: the filtered end effector position, velocity and acceleration. F_{motor} can be calculated from the measured driving currents generating the required joint torques. The maximal force exerted in one of the six directions represents the main numerical parameter of the test:

$$F_{RadMax} = \sup[F_{arm}(i) \times R] \tag{3}$$

These measurements and the appertaining calculated values are used for off-line data analysis and result presentation. Presentation of test results is exploiting both possible forms, graphical and numerical.

The main parameter of the force exertion task is the force itself, which is closely bound to power and energy needed to perform the movement, as well as to the exchange of energy between haptic interface and extremity under test. Corresponding power in discrete k intervals equals

$$P_{\text{subject}}(k) = [F^{\text{T}}_{\text{motor}}(k) + F^{\text{T}}_{\text{model}}(k)] \times \begin{bmatrix} v_{\text{x}}(k) \\ v_{\text{y}}(k) \\ v_{\text{z}}(k) \end{bmatrix} \tag{4}$$

$$P_{\text{robot}}(k) = -F^{\text{T}}_{\text{motor}}(k) \times \begin{bmatrix} v_{\text{x}}(k) \\ v_{\text{y}}(k) \\ v_{\text{z}}(k) \end{bmatrix} \tag{5}$$

where $P_{\text{subject}}(k)$ represents the patient's power contribution to the movement of the mechanically coupled system UL-robot, and $P_{\text{robot}}(k)$ the robot's power contribution to the movement in sample k and $v_{\text{x}}(k)$, $v_{\text{y}}(k)$ and $v_{\text{z}}(k)$ are components of the effector velocity. The average power $|\bar{P}|$ during the time/sample interval $k \in (k_1, k_2)$ is defined as

$$|\bar{P}| = \frac{1}{k_2 - k_1} \sum_{i=k_1}^{k_2} P_{\text{subject}}(i) \tag{6}$$

The time plots of power $P_{\text{subject}}(k)$ and $P_{\text{robot}}(k)$ reveal an important aspect of the patient's active role in movement. The positive person's power $P_{\text{subject}}(k)$ greater than 0 denotes the patient's active role in movement (the person leads the robot) and vise versa, the negative person's power $P_{\text{subject}}(k)$ less than 0 denotes the robot active role in movement (the robot leads the patient's UL). The power signals $P_{\text{subject}}(k)$ and $P_{\text{robot}}(k)$, as defined above, lead to mechanical energies, E_{subject} and E_{robot}, that the patient and the robot, respectively, consume for the movement in time/sample interval $k \in (k_1, k_2)$, where $T_{\text{s}} = 5$ ms is the sampling time:

$$E_{\text{subject}}(k_1, k_2) = T_{\text{s}} \sum_{i=k_1}^{k_2} P_{\text{subject}}(i) \tag{7}$$

$$E_{\text{robot}}(k_1, k_2) = T_{\text{s}} \sum_{i=k_1}^{k_2} P_{\text{robot}}(i) \tag{8}$$

Data mining application

Given the large amount of gathered data in this study, the importance of various parameters presented in the previous section was examined using data mining techniques. Data mining is a process of searching for structural patterns in large quantities of data or large databases (Witten and Frank, 2000). By means of automatic algorithms, data mining can help in extracting meaningful information from raw data, when the information is not clearly recognizable while using manual examination. Data mining techniques were used to prove the validity of the proposed test. The results of the maximal force capacity test for 32 patients were used as input data for the supervised learning algorithm for the classification tree construction (Michalski, 1998). In a classification tree the MD group of disabled were compared with a group of healthy participants; the model prediction accuracy area under curve for this model was equal to 90%.

Results

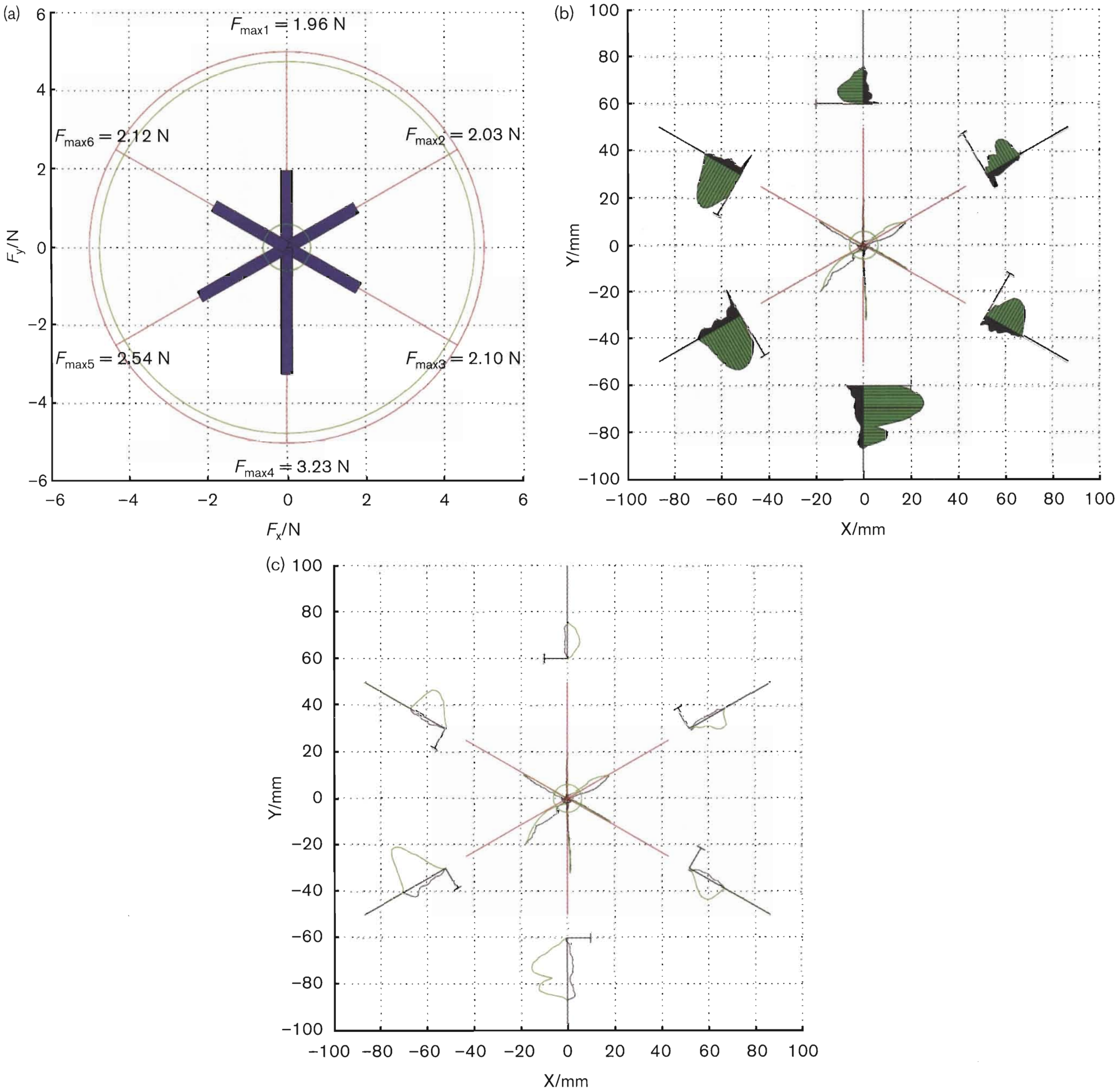
The results section gives examples for various persons tested by haptic interface, showing at first graphical measurement results, followed by demonstration of test repeatability, an example of a very weak person and two examples of MD participants not being able to produce force in some directions. Findings offer accurate and repeatable numerical information about the force exertion values and curses versus time with typical numerical parameters to the observer.

The most important graph shows maximal forces obtained in six measured segments – directions (Fig. 3a). The importance of, F_{max}, is based on data mining that was conducted during analysis of the results assessed in 32 MD persons. In addition to the graphical results numerical parameters are also informative. Table 1 shows a classification tree for the MD group compared with a healthy control group for the maximal force exertion capacity test.

In the analysis of times needed for performing a test in each direction for each person and particular trial picked there were minimal and maximal times needed for the movement out and in. Some of the 32 MD patients, making more than 128 trials, needed as much as 5.2 s and as little as 1 s for one segment. The average value for the minimal time was 1.2 s and maximal time was 2.1 s with standard deviation 0.2 and 0.9 s, respectively. Considering that the real movement trajectory is never perfectly along the line even if the virtual tunnel has cross sectional stiffness of 300 N/m (this can be seen in example given in Fig. 3b) also the path velocities are not directly linked to the segment times. The minimal and maximal velocity needed for movement out and in over all the trials were found to be 6 and 294 mm/s, respectively. Average value for the minimal velocity was 34 mm/s and maximal velocity was 69 mm/s with standard deviation 21 and 49 mm/s, respectively.

Figure 3b shows kinematic parameters during the test; the end point trajectories are shown inside and velocities outside, separate for outward movement direction in black and inward movement direction in green. The lines

Fig. 3

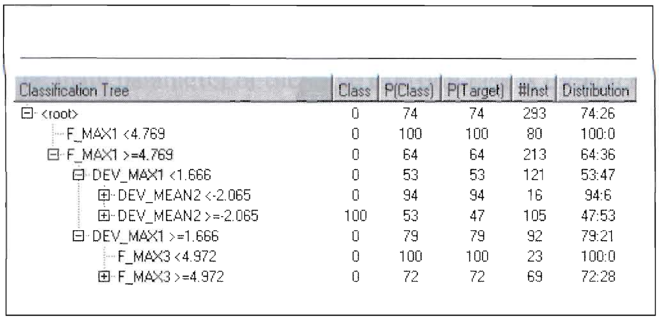


Complete graphical presentation of measurement for right hand, dominant side of a muscular dystrophy patient. (a) Obtained force values in six measured directions in frontal plane. (b) Measured traces (inside) and velocities (outside). (c) Measured traces (inside) and calculated power (outside). In both cases movement outward is denoted in black (solid) and movement inward in green color (dotted).

from the center out in six segment directions serve as axes. The full length of the line corresponds to movement of 60 mm. Force is related to the movement according to right and left of the line looking from center, according to equation (1); maximal force in this particular case was 3.2 N caused by the movement of 40 mm. The outer traces in the same graph correspond to velocities along the same movements. The second most informative parameter is DEV_{max1} (Table 1), which corresponds to maximal deviation from the haptic tunnel centerline (see Fig. 3b).

Power calculated in accordance with equation (8) is an interesting parameter shown in Fig. 3c. Owing to close

Table 1 **MD – classification model for the maximal force exertion capacity test (MD – class '0', HEALTHY – class '100'). Model prediction accuracy AUC = 90%**



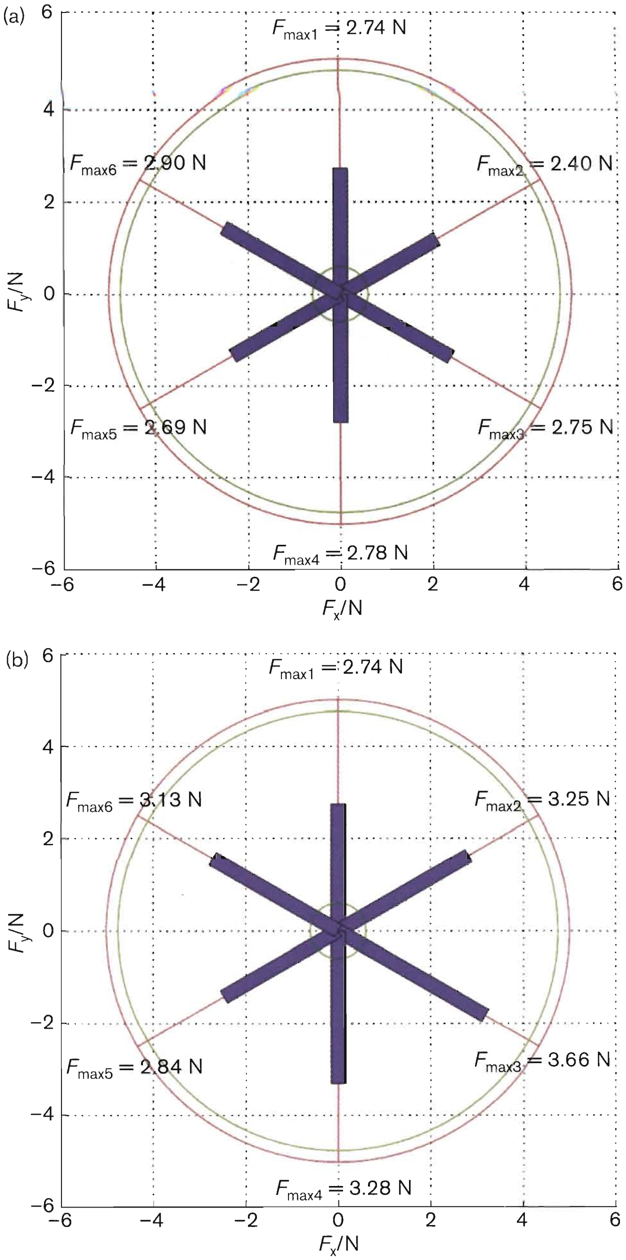
Classification Tree	Class	P(Class)	P(Target)	#Inst	Distribution
⊟ <root>	0	74	74	293	74:26
F_MAX1 <4.769	0	100	100	80	100:0
⊟ F_MAX1 >=4.769	0	64	64	213	64:36
⊟ DEV_MAX1 <1.666	0	53	53	121	53:47
⊞ DEV_MEAN2 <-2.065	0	94	94	16	94:6
⊞ DEV_MEAN2 >=-2.065	100	53	47	105	47:53
⊟ DEV_MAX1 >=1.666	0	79	79	92	79:21
F_MAX3 <4.972	0	100	100	23	100:0
⊞ F_MAX3 >=4.972	0	72	72	69	72:28

relation with velocity presented in Fig. 3b, the power has similar course. It should be noted that the traces versus time presented in slightly different way in Fig. 3a, b and c give a clearer insight than most usual presentations.

Most meaningful are the graphs showing the forces, this is also a reason for showing more exemplary cases. One of the important questions was repeatability of the used test. Figure 4 shows two trials for the same MD person in a half hour time difference with measurements using free (a) and fixed (b) wrist.

The majority of our participants were wheelchair users, using the joystick for the control. For this purpose at least some force and movement are needed. To our surprise, their capabilities were very low in some cases, for one of the worst examples see Fig. 5. Force and movement capability in the wrist and fingers was very limited (Fig. 5a) and improved slightly when free movement of the whole arm was permitted (Fig. 5b). The inner green circle represents 0.05 N force value. Figure 6 shows an example that is common in MD disabled with fairly good force capability in some movement directions, while being inferior in others.

Fig. 4



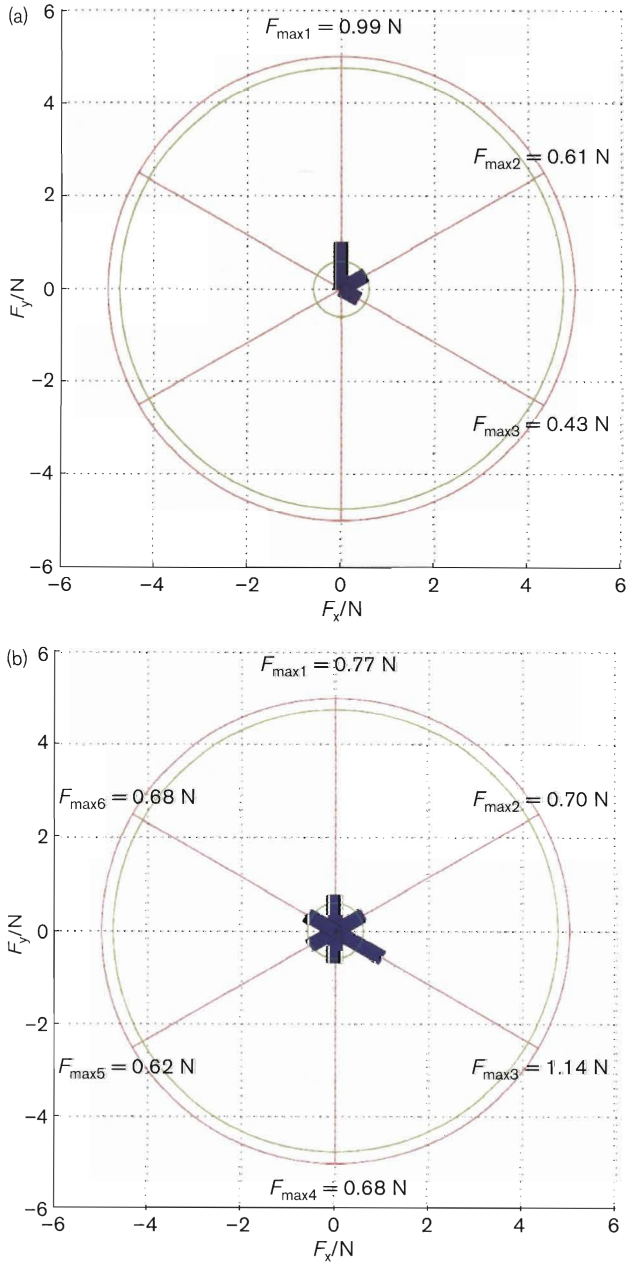
Demonstration of test repeatability. Two trials measured for the same muscular dystrophy person in half of hour time difference. Wrist was fixed in both cases.

Discussion

In the data shown in Table 1, the responsibility for the first branching in the classification tree lies in parameter F_{max1}, which is the force exerted in segment 1, the vertical direction. Thus, F_{max1} can be treated as the most informative parameter in distinguishing the MD disabled from nondisabled participants. As the vertical force exertion capacity F_{max1} is closely related to muscle weakness in MD patients, this suggests good validity of the proposed test. The established reliability in conventional rehabilitation and occupational therapy evaluations ranges from 60% (satisfactory) to 80% (good) (Loeven and Anderson, 1988). The obtained prediction accuracies for F_{max1} are equal to 90%. We can claim that the classification accuracy is excellent. This establishes good content validity of the proposed haptic UL assessment methodology. The next most informative parameter is DEV_{max1}, which corresponds to maximal deviation from the haptic tunnel centerline. All the other much less informative parameters can be extracted from the decision tree in the same way.

Simply by observing the kinematic parameters, movement abilities could be recognized. For the particular case

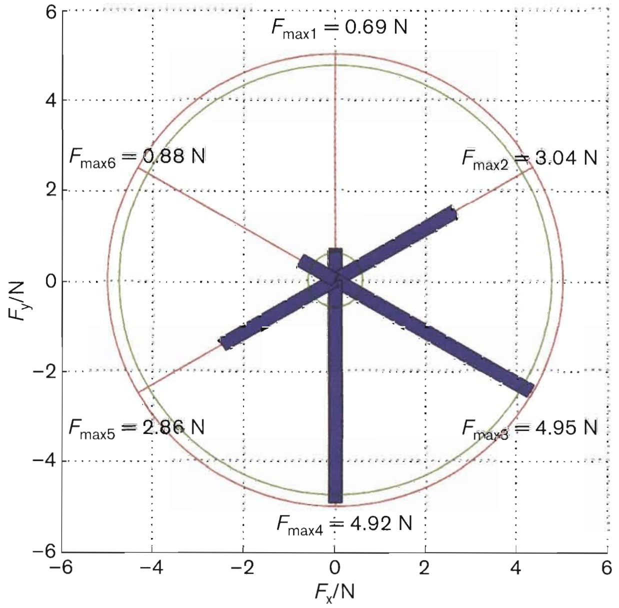
Fig. 5



An example of a very weak muscular dystrophy person, with very small force exertion. Two trials were measured: (a) fixed wrist, the person was able to produce enough minimal force marked with inner small circle equal to 0.05 N (b) using whole arm and wrist not being fixed, when the person was able to produce slightly larger forces.

shown in Fig. 3b there could be recognized slow movements in all three cases having upward direction, whereas there was less trouble with higher velocities in the downward direction. These traces can also be examined for a group of all disabled using the classification trees algorithm.

Fig. 6



Example of inability to produce force in certain directions for muscular dystrophy diagnosis. Only minor forces were measured in upward direction, but larger values in other segments.

Repeatability of presented methodology could be checked by inspection of Fig. 4. Based on visual comparison of the two figures, great similarity with only minor differences can be easily noticed. This example was also selected to show, as it looks from the figure, how little practically no difference occurs in the movement and force capability when using only wrist or whole arm for producing the movement.

Very low forces can speak for a very advanced stage of most severe MD. This is shown in clinically observable complete paralysis of the wrist in the case of fixed wrist (Fig. 5a) and some more capability induced through trick movements (Fig. 5b), and some help by proximal muscles of upper body and trunk. This kind of measured information could be very valuable to designers of various input devices such as joysticks, as well as to personnel who select, fit and adjust selected control hardware and software.

For producing force in a vertical direction there is required activity of wrist extensors, which seem to be completely weakened in case of Fig. 6, while flexor activity is still present. Radial deviation in the wrist is much more damaged than ulnar deviation, which could be understood as unproportionaly affected muscles or contractures in the wrist. The measured values speak for commencing contracture and completely weakened extensors in the wrist, leading to limited movement and force ability in ulnar deviation. In such cases use of trick movements can result in great functional advantage. In a number of other cases a comparatively well-preserved force ability for flexion and extension in the wrist was found, but with values much inferior to the healthy control group.

Conclusion

In this study a new approach to UL functional assessment through maximal force exertion capacity exercises in haptic VE was presented. Haptic interface was proposed to be used as an objective, quantitative, repeatable and sensitive measuring device. In visual and in haptic aspects, the tasks in VE were goal oriented and simple enough from the measurement methodology point of view, not to be influenced by other performance measures/impacts than the movement abilities or functional state. The new UL test was applied to a group of 32 participants with various forms of MD, resulting in UL movement impairment. The results of this study showed some typical characteristics of tested population, as well as showing limited force exertion capabilities. The quantitative findings described above might play a key role in designing and fitting optimal interfaces for various assistive technology devices. It was shown that the method meets the criteria of a good assessment test in rehabilitation environment, not as a substitution, but rather as a complementary objective measurement method. Use of some other haptic device with larger force exertion capability could extend the use of this technology to other etiology groups.

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