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Quantification of Information Transfer Rate of the Human Hand during a Mouse Clicking Task with Healthy Adults and One Adult with Duchenne Muscular Dystrophy

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***Abstract*—Duchenne muscular Dystrophy (DMD) is a progressive muscle degenerative disease. Active hand assistive devices, can improve the quality of life of people with DMD. Such devices show a rejection rate due to complexity. Our hypothesis is, that a simple orthosis might prove more functional and realistic in assisting people with DMD. To investigate, we developed a portable setup that provides various visual stimuli and records the response of the subjects' fingers through a mouse clicking task. Six LEDs served as visual stimuli. The subjects' responses were obtained through mechanical interaction with two vertical mice. Different combinations of frequencies and numbers of stimuli were tested with 8 healthy subjects and one with DMD. Performance was evaluated in terms of information transfer rate (ITR), pattern accuracy and perceived workload. The outcome shows that lower complexity results in lower ITR and lower workload for all subjects. While for healthy subjects, maximum ITR was 4.3 bits/s, for DMD maximum ITR was 2.5 bits/s. Both maxima were achieved at the same trial (3 fingers at 2 Hz). This trial agrees with a pareto optimization analysis of ITR with respect to workload. The results support our hypothesis for a simple yet functional solution. Furthermore healthy subjects and the individual with DMD, in principal show similar finger control, albeit with lower absolute performance.**

Fig. 1. The subject with DMD using the portable setup with the proposed method, during a mouse clicking task. 1) Vertical mice. 2) LEDs. There is one for each index, middle and thumb of each hand. The LEDs are color coded. Green for the index, red for the middle and blue for the thumb. 3) Display board. 4) The wooden board covering all the electronics. 5) The suitcase, housing all the components of the portable setup. 6) The tablet operated by the researcher in order to choose the trial.

I. Introduction

Duchenne muscular dystrophy (DMD) is an X chromosome-linked recessive neuromuscular disease. People with DMD suffer from progressive muscle weakness which leads to physical disability and shortened life expectancy [1].

While the lifespan of men with Duchenne has increased due to improvements in health care, their hand function is limited, especially after the age of ten [2]. Currently the only hand supports for people with DMD are passive hand splints [1]. These aim at maintaining a large active range-of-motion (ROM) for the fingers and the wrist and slow the development of contractures. Nevertheless, they are not sufficient to provide dynamic rehabilitation or to assist in functional tasks. Therefore people with DMD can benefit from active hand supports that can dynamically move the hand continuously as continuous passive motion (CPM) devices or even support their hand function. In the Flextension Symbionics project [3] we have the goal of developing a wearable active hand support with an intuitive control interface for people with DMD.

Current active hand devices are getting more and more sophisticated, thus making their control challenging [4]. This leads to high rejection rates of such devices [5]. There are no long term studies on orthotic devices rejection rates.

In this study, we want to investigate the human control over the fingers. One way to quantify the capacity of the human brain to control the fingers is information transfer rate (ITR) [6]. ITR can provide a way of understanding how complex an active device should be, in order for a person to be able to accurately and intuitively control it. The perceived workload imposed on the subject by the task should be assessed as well, in order to give an indication of the brain's effort during the task [7]. The combination of both can lead to an optimal trade-off between functionality and ease-of-use.

The ITR assessment strategy and the experimental design of the current study were inspired by Klemmer et al. [8], who also tried to assess and optimize the ITR in healthy subjects during a button pressing task. Their subjects had to respond to 5 visual stimuli in 5 different frequencies by pressing the correct button(s). The main differences in our study compared to [8] are the introduction of a 1-dimensional workload assessment [9] and that our subjects did not have extensive training. The present study aims at assessing the ITR, in order to set limits for the design of an active orthotic hand device for people with DMD, by simulating such a device. To do that, we developed and used our own portable setup. Our approach aims to support the idea that "less is more", where less is related to complexity and more is related to functionality. An evaluation of our method has been carried out with 8 healthy participants that serve as baseline and 1 with DMD. The results support our hypothesis. Both differences and similarities are observed between healthy and DMD finger function.

II. Methods

In this paper we present a portable setup for the assessment of the ITR during a mouse clicking task (Fig. 1). The subjects have to respond to 1 to 6 stimuli using their fingers at 4 different frequencies by pressing the correct button(s) with their fingers. This results in 24 different trials. After every trial the perceived workload of the subjects was assessed via a questionnaire [9]. An evaluation of the setup and assessment of the ITR of the human hand was carried out with 8 healthy subjects. Additionally a case study was also performed with a 21-year old adult with DMD, in order to validate if our setup can be used to quantify their finger control.

A. Participants

The main experiment was carried out with 8 healthy (4 male and 4 female), right handed participants, without any hand related impairment. The mean age of the subjects was 21 ± 1 year. Subjects had no prior experience with the setup. A single-case pilot study was also carried out with one 21-year old person with DMD with good finger function (Brooke scale 2). All subjects were informed via a letter and signed a consent form at least one week prior to the experiment. The Medical Ethics Committee of Twente approved the study design, the experimental protocol and the procedures.

TABLE I
PERFORMANCE METRICS

Metric	Short Description
ITR (bits/sec)	The amount of mutual information between stimuli and responses [6].
Pattern Accuracy (%)	Percentage of correct reproduction of a pattern of stimuli by the subject.
Perceived Workload	Workload imposed by the task on the subject. It is assessed using a uni-dimensional assessment technique [9]

B. Materials and Data Acquisition

The setup (Fig. 1) used for this experiment was developed by us. It consists of a regular suitcase that contains all the components ensuring portability.

Based on previous studies of finger independence [10] and finger involvement in functional grasps [11] plus on our own grasp analysis questionnaires for people with DMD, we chose to include the thumb, index and middle finger of both hands. This was also done in an effort of resembling the control of a hand orthosis, with independent finger motion. Two vertical mice one right and one left handed, were used as a clicking interface.

A real-time computer (myRio, National instruments Inc.) was used for the data acquisition, digitizing the mice signals at a sampling frequency of 48 Hz. The same computer controlled the visual stimuli to the subjects. Six LEDs were connected to the computer in order to act as visual stimuli. The LEDs were placed in a wooden board in front of the subject in a comfortable position (Fig. 1). All the data of the trials were logged by the real-time computer.

All the electrical components were secured on the hollow part of the suitcase and protected by a wooden board (Fig. 1). The LEDs and the mice have custom made connectors, allowing for a quick set-up of the device and enhance it's overall portability.

C. Experimental Procedure

The experimental setup is illustrated in Fig. 1. The subjects were placed in a chair in front of the setup. The protocol was explained to the subjects and they were allowed to get familiar with the device until they felt comfortable to start the experiment. This included 24 trials since it was a combination of 4 different stimuli frequencies (1-4 Hz) with 6 different stimuli numbers (1-6 stimuli/LEDs). The order of the 24 trials was randomized to account for any learning and fatigue related effects. The researcher chose the trial number using a tablet made sure that the subject knew which trial started next. After every trial the subject was asked to fill a simple questionnaire about the perceived workload [9]. This specific workload assessment technique was chosen because it is very simple to perform and reportedly as sensitive as multi-dimensional workload assessment techniques such as NASA-TLX [12]. Fatigue effects are very strong for people with DMD. Hence, for the DMD pilot an extra questionnaire (1-10) was used to monitor perceived fatigue, in order to makes sure it did not affect the results. If there was a recorded score of above 2, the subject took a short break (10 min).

Each trial had the duration of 30s. For each trial a certain number of LEDs was used. For each stimulus in a trial, each LED involved, was on or off with equal probability. Setting N_L as the number of LEDs, this resulted to 2^{N_L} possible different stimuli. The subjects were instructed to click the button(s) based on the visual stimuli and try to avoid random clicks. The order of finger recruitment is right and left index finger, right and left middle finger and right and left thumb.

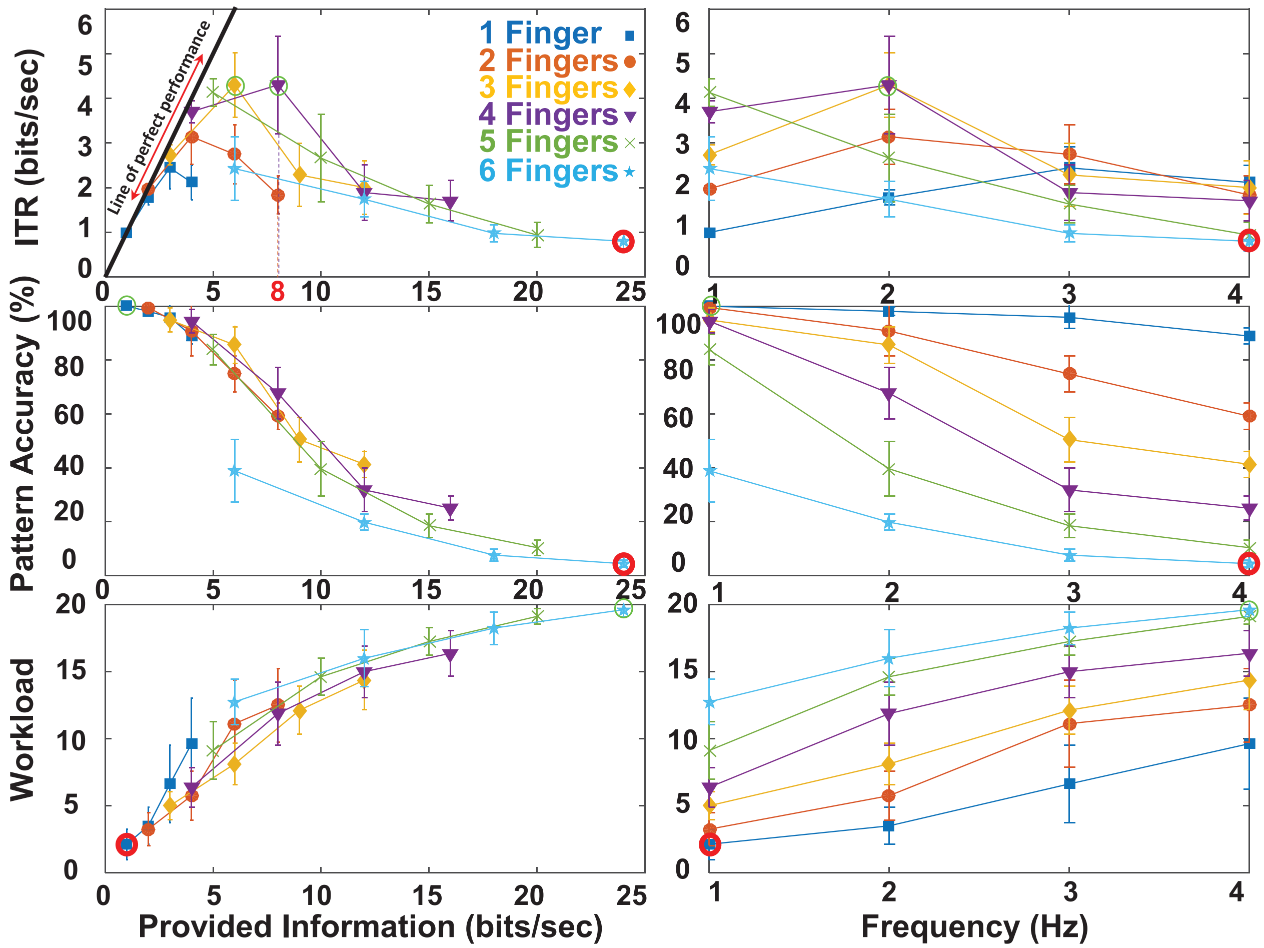

Fig. 2. The results for the healthy participants. For each data point, mean and standard deviation are plotted. Provided information can depict more than one trial at the same point. For example (top left plot) 8 bits/sec can represent the second purple data point (4 fingers · 2Hz) or the fourth orange data point (2 fingers · 4Hz). The diagonal line represents perfect performance (provided information=ITR). The green (thin) circles indicate the highest values for each metric and the red (thick) the lowest as reported in the results section. The plots on the right row of the figure are expressing the same information as in the left, but in the frequency domain. It is necessary in order to observe the effect of different frequencies.

D. Data Analysis

First the data were pre-processed in order to determine which response corresponds to a certain stimulus, by applying a window. The position of the window was obtained by analysing all the correct responses during two seconds after each stimulus for every subject and every trial. From these response times the offset for a time window was found by positioning it in a way that it contains the maximum number of correct responses. The length of a time window is equal to the inverted pattern frequency, and the windows are placed next to each other without overlap. Correct responses were considered those contained in the time window applied, corresponding to the current stimulus.

Every subjects' performance was evaluated in terms of ITR, pattern accuracy and perceived workload. A brief explanation of the metrics is given in Table I. For each metric its mean value over subjects was calculated together with the median and standard deviation.

ITR is defined as the mutual information [13] between stimulus and response [6], [8]. We estimated the ITR per finger by counting the number of occurrences of each stimulus (on/off) – response (click/no click) pair. These numbers provide the maximum likelihood estimate of the probability of these pairs occurring in a trial and provide an estimate of $\mathrm{ITR}_{\mathrm{finger}}$, the ITR per finger per stimulus, as

$$\mathrm{ITR}_{\mathrm{finger}} = \sum_{i\in\{\mathrm{on,off}\}} \sum_{j\in\{\mathrm{noclick,click}\}} \frac{n_{ij}}{N} \log_2\left(\frac{n_{ij}N}{n_i n_j}\right), \quad (1)$$

where n_{ij} is the number of times event (i,j) occurs, $n_i = \sum_{j\in\{\mathrm{noclick,click}\}} n_{ij}$, $n_j = \sum_{i\in\{\mathrm{on,off}\}} n_{ij}$ and N is the total number of stimuli provided in the trial. To illustrate, in a trial at 2 Hz, $N = 30 \cdot 2 = 60$. The $\mathrm{ITR}_{\mathrm{finger}}$ was summed over all fingers and multiplied with the frequency to obtain the total ITR in a trial.

Another way to quantify the performance is to determine the fraction of patterns, i.e. stimuli in the same time interval, that are replicated correctly. This information is estimated by

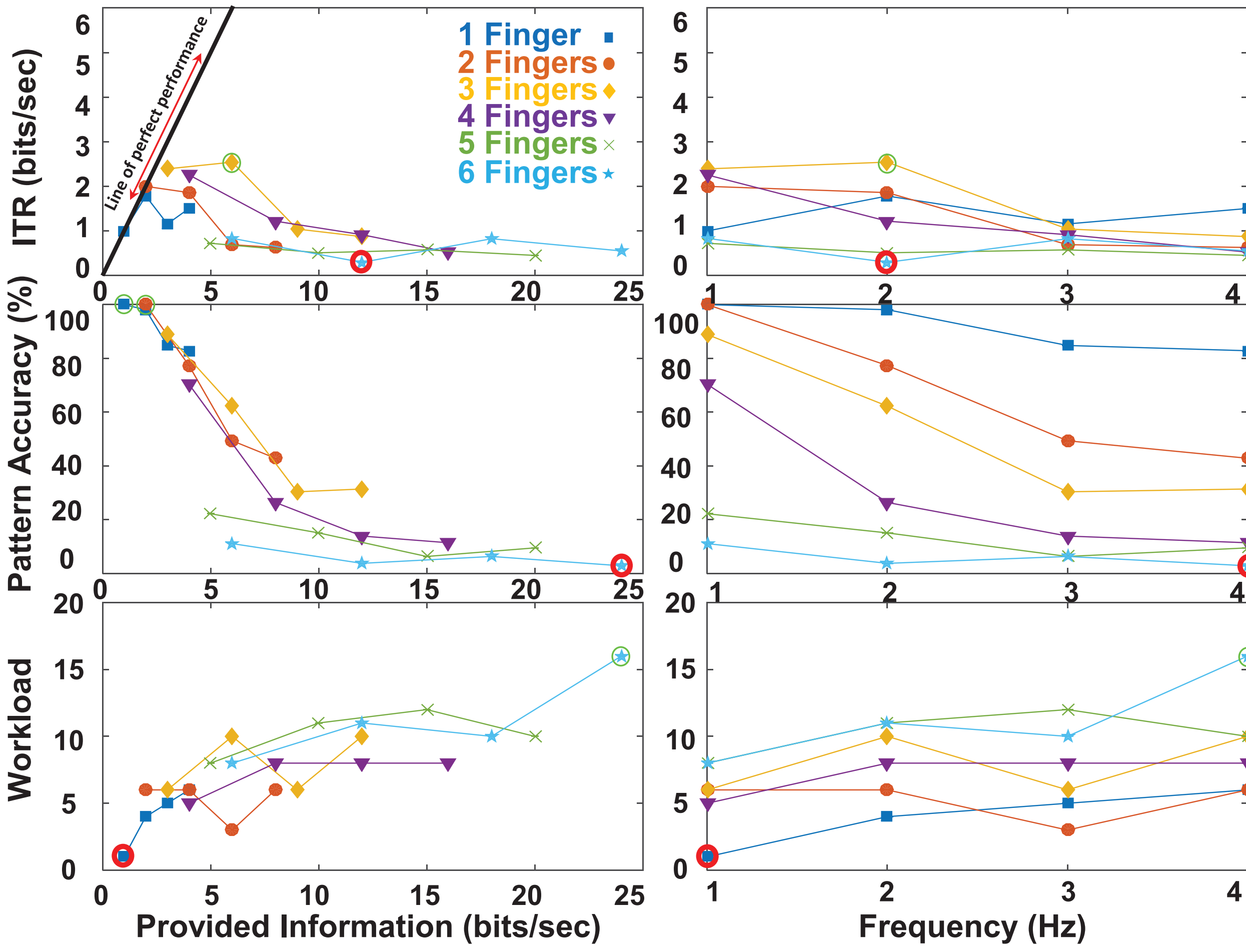

Fig. 3. The results for the participant with DMD.

using:

$$\mathrm{PA} = \frac{P_c}{P_t} \cdot 100\% \qquad (2)$$

Where PA is the pattern accuracy estimate, P_c is the number of patterns that are replicated correctly, and P_t is the total number of patterns.

A comparison between different frequencies and number of fingers was performed. The main results are illustrated in Figures 2 and 3.

Since our interest is in both ITR and perceived workload we have depicted the ITR versus the perceived workload for all trials in Figure 4. We compare the different trials w.r.t. the number of fingers used and the frequency of the stimuli. The trials in which the ITR cannot be improved without increasing the workload are called Pareto optimal [14] and these have been depicted in Figure 4 with filled markers. The figure illustrates that in many cases it is possible to simultaneously reduce the workload and improve the ITR, i.e. many configurations are not Pareto optimal.

III. Results

A. Healthy Participants

The results for the healthy participants are illustrated in Fig. 2. Each point shown is the mean over the eight healthy participants plotted with the standard deviation.

ITR follows the line of perfect performance (maximum ITR) for the low complexity trials (low frequency and small number of fingers), then peaks for the provided information of 6 bit/s and 8 bits/s (green circles in Fig. 2), with a highest mean ITR at 4.3 bit/s (3 fingers at 2 Hz and 4 fingers at 2 Hz). The lowest mean ITR value is 0.80 bits/s (6 fingers at 4 Hz). The highest individual ITR value observed was 7.6 bits/s for subject 8 (4 fingers at 2 Hz).

The pattern accuracy decreases rapidly with the increase of provided information. The highest pattern accuracy of 100% was observed at the simplest trial (1 finger at 1 Hz) and the lowest of 4.4% at the most complicated (6 fingers at 4 Hz).

The last row of Fig. 2 illustrates the perceived workload by the subjects. It increases when either the frequency or the number of fingers increases. There is a point around a provided information of 8 bits/sec when the perceived

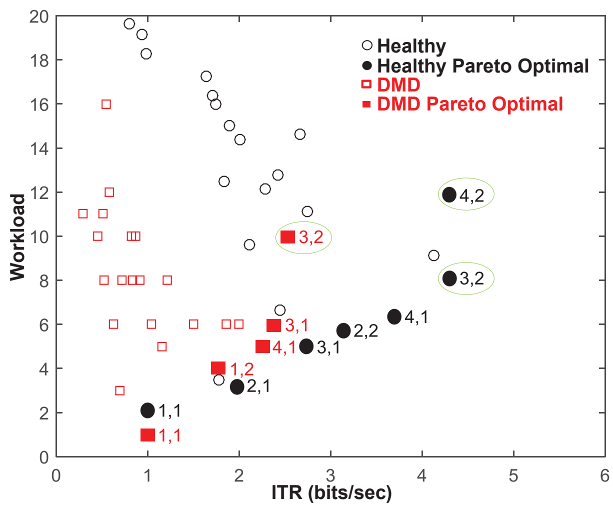

Fig. 4. The results of the pareto optimization. The trials for healthy and DMD are illustrated both here. The filled coloured trials are the optimal trials based on the perceived workload they impose on the subject.The trials with the highest ITR are indicated by the green ellipsoid. Optimal trials are those where the ITR cannot go any higher without raising the workload. The first number refers to the number of fingers and the second number to the frequency.

workload starts having a less steep increase. Inversely from pattern accuracy, the perceived workload has its lowest value for the simplest trial at 2.12 and it peaks for the most complicated trial at 19.62.

B. Adult with DMD

The proposed method was tested additionally with an adult with DMD. The results for this participant are illustrated in Fig. 3.

ITR follows the line of perfect performance (maximum ITR) for a few low complexity trials (low frequency and small number of fingers), then peaks for the provided information of 6 bit/s (green circle in Fig. 3), with a highest ITR at 2.5 bit/s (3 fingers at 2 Hz). The lowest ITR value is 0.29 bits/s (6 fingers 2 Hz).

The pattern accuracy decreases rapidly with the increase of provided information also for the DMD participant. The highest pattern accuracy of 100% was observed at the trials of 1 finger at 1 Hz and 2 fingers at 1 Hz. The lowest of 2.8% was observed at the most complicated (6 fingers at 4 Hz).

The perceived workload increases when either the frequency or the number of fingers increases. It shows it's lowest value for the simplest trial at 1 and it peaks for the most complicated trial at 16.

IV. Discussion

A. Data Analysis and Protocol

The use of ITR started more than 60 years ago and it became a popular way of assessing the performance of haptic communication systems [6] and Brain-Computer Interfaces [15]. Those studies tried to show that maximizing ITR can make the control of such systems more intuitive and accurate [6]. We used ITR as a performance indicator and in order to quantify finger control, without trying to maximize it as the majority of previous studies did [6].

Our approach did not include any extensive training with the setup. It is very probable that more training would improve the ITR, while lowering the perceived workload to a point. Nevertheless, our current method gives an indication of the need for simplicity and points out the differences between healthy and DMD participants.

B. Healthy Participants

Considering previous research by Klemmer et al. [8] our results show a lower mean maximum ITR of 4.3 bits/s compared to 10.4 bits/s shown there. This may be attributed to the differences between our methods and the fact that our subjects did not have as much training. For a low amount of provided information (1-3 bits/s), the subject's seem able to replicate patterns. The decline after that is very rapid. indicating that replication of patterns is very hard in higher frequencies or number of fingers.

C. Adult with DMD

The subject with DMD achieved lower maximum ITR (2.5 bits/s), although at the same trial (3 fingers 2 Hz) as the healthy population. The pattern accuracy also has pretty similar results. This is an indication that the lower performance is probably to be attributed to the physical limitations of the subject, rather than his finger control. Another interesting finding is that the subject with DMD seems to underestimate the workload. In all cases he reported lower workload values than the healthy subjects. This is probably due to the subjective nature of such workload assessment techniques [7]. It also might be because he is more frequently challenged in his finger control than the healthy participants.

D. Optimization

ITR can be increased by increasing the stimuli frequency or number or both. Which approach is the best, depends on the application. One interesting finding of our study, is that certain trials with equal provided information (like 2 fingers at 4 Hz and 4 fingers at 2 Hz, where the provided information equals 8 bits/s) do not have the same perceived workload (Fig. 2, lower right corner). In Fig. 4, we are trying to identify the optimal combination of fingers and frequencies based on the perceived workload.

Trials with low number of frequencies and fingers provide higher ITR with relatively lower perceived workload. The maximum frequency for pareto optimal values for both groups is 2 Hz, while the number of fingers goes up to 3 for DMD and 4 for healthy (Fig. 4). The main difference is that the absolute ITR values are lower for DMD. This shows that a potential orthosis for people with DMD should focus more on assisting more fingers, than utilizing speed.

E. General Implications and Limitations

One limitation of this study, lies in the estimation of ITR. Due to the low number of samples per trial, ITR estimation can be misleading. We plan to test our method with artificial data in order to improve our estimator.

In this paper we present data from one DMD subject due to the low DMD population density and the difficulty to recruit them. Nevertheless, people with DMD have different finger function (depending on age, healthcare and training), hence allowing us to treat their results as separate case studies.

In Fig. 4, trial 4,1 of DMD, has lower workload than 3,1. This is probably a measurement error, representative of the subjectiveness of the perceived workload measurement.

Unlike similar studies [8], we did not train our subjects. Training can have a strong effect on the pareto results (shift more trials towards the optimal side). Thus our results have a suggestive nature rather than conclusive.

We believe that our portable setup and ITR estimation methods can be applied for various other purposes. DMD hand function decreases with time. Our tool can be used as a technique to quantify this hand function deterioration complimentary to Brooke scale [16]. Similarly the same could apply for stroke patients in order to assess their recovery similar to [17] and or help them train their fingers.

The modularity of our portable setup allows for different response interfaces. In our case we use vertical mice. But depending on the application or special needs of any target group, different interfaces could be used, such as keyboards or custom made buttons. Different frequencies can be imposed with smaller steps between frequencies, while engaging a greater or lower number of fingers/stimuli.

V. Conclusions And Future Work

This paper presents a portable setup for assessing ITR in healthy subjects and one person with DMD. This assessment is performed via a series of mouse clicking tasks, related to visual stimuli. Furthermore, the workload imposed from each trial is derived via a questionnaire. We believe that our setup provides a reliable way of assessing the ITR related to finger control. Results on healthy people and one adult with Duchenne, show that low frequencies and number of fingers/stimuli, achieve higher ITR, with lower perceived workload. Thus our hypothesis that ”less is more”, seems to be asserted. Future work will include improvement of the ITR estimator and investigating the training effects of our task on healthy subjects. We also plan to perform a thorough evaluation of our method with a larger group of people with DMD in order to assess their hand function compared to healthy people. Our findings will support and motivate the design and control of the active hand orthosis for people with DMD, currently developed in the Flextension Symbionics project [3].

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