DidRen VR: An Evolutive Virtual Reality Application Satisfying Fitt's Law to Assess and Train Cervical Mobility

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Abstract

Clinical tests are of paramount importance for clinical practice in physiotherapy to assess patients' functional abilities, evaluate their progress, or even train them. They mostly consist in fixed standardized motor tasks. However, assessing one patient's evolution along time may demand modular tests in which the difficulty of a given task can be tuned to offer a relevant challenge to patients at any moment of their rehabilitation. The use of virtual reality (VR) in this context allows the development of clinical tests and exercises in a 3D virtual environment. Through programming, the environment can be made modular in much simpler way than with real clinical tests. In this paper, we introduce the DidRen VR test, a VR version of the DidRen laser test which aims to assess the mobility of the cervical spine using a targeting system triggered by a laser beam moved by rotating the neck. The DidRen VR test is designed to run on low-cost VR headsets, affordable for clinicians. Since the Fitts' law is satisfied with the DidRen VR test among a population of 50 participants it can be therefore be seen as a relevant alternative to the real-world DidRen laser test for cervical mobility assessment.

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I. INTRODUCTION

Neck pain has a 22% to 70% lifetime prevalence, with about 44% of patients developing chronic symptoms [1]. It is related to an unpleasant sensory and emotional experience that may be associated with actual or potential tissue damage in the cervical region. Real-world tests have been used to assess the sensorimotor performance of the head-neck complex, providing a better understanding of the pathophysiological mechanisms associated with neck pain, such as the "joint position error" [2] and "The Fly" [3], both of which use a commercially available three-dimensional (3D) electromagnetic motion tracking system. Real-world tests are generally straightforward to implement and affordable to clinicians, both regarding time and budget. The use of sensors, even low-cost ones, to these tests adds complexity but also relevant clinical indicators, see e.g. [4].

A test of peculiar importance for the present study is the DidRen laser test (Figure 1), with a setup similar to the well-known work of Revel [5, 6], though different in its purpose and complexity. The participants sit on a chair and wears a helmet with a laser pointer. They must perform rapid and precise axial rotations of the head from right to left and back (30^o from the neutral position, which corresponds to the cervical movements most used during activities of daily living [7]. The laser beam must hit three red visual targets (Figure 2). Green LEDs directly above the red targets validate each hit in addition to producing a sound [8–12]. The DidRen laser test consists of a simple, standardized, and repetitive sensorimotor task performed in the real world, involving axial head rotations from "target to target" in the same 5-cycles sequence (center, left, center, right). In clinical practice, it is particularly useful because it focuses simultaneously on the sensory and motor control systems of the head-neck complex and has many direct neurophysiological connections between the proprioceptive, visual, and vestibular systems [13]. To date, the DidRen laser test has been successfully used to: (1) assess rotatory sensorimotor control of the head at a specific time point [10, 14]; (2) track immediate changes in rotatory sensorimotor control after cervical manual therapy treatment [11]. This test can also be used as a standardized rehabilitation training system, although it may be difficult to maintain patient's adherence with such a repetitive task.

In addition to real-world tests, virtual reality (VR) may provide an interesting framework to implement clinical tests assessing sensorimotor performance of the head-neck complex

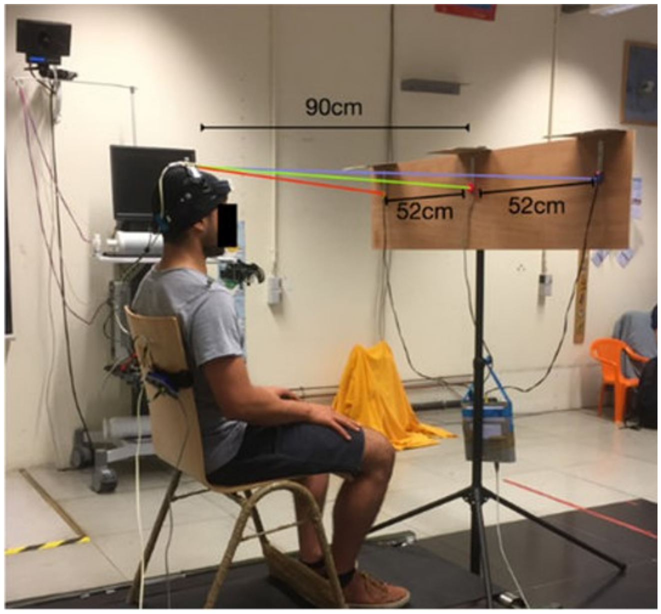

FIG. 1. Participant performing the DidRen laser test in real world.

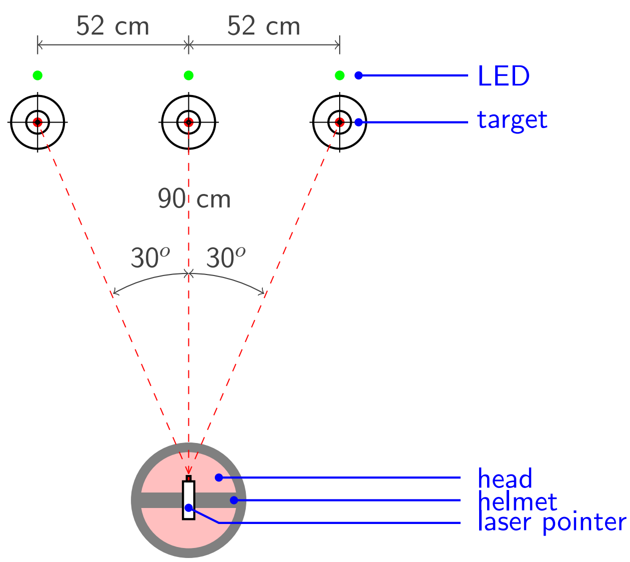

FIG. 2. Schematic representation of the DidRen laser test; view from above.

since: (1) VR headsets are nowadays affordable for all clinicians and contain motion sensors accurately tracking the head motion; (2) VR environments are more modular – more easily customisable – than real-world ones. This may have a positive impact in rehabilitation since the difficulty of the test may be more easily adapted to a given patient and their evolution. An example of such a framework is the “Virtual Reality Test”, developed to assess the functional range of motion of the cervical spine in patients with neck pain [15, 16]. Although this test has a higher sensitivity than the conventional assessment and can also be used to improve the range of motion of the cervical spine [15]. Its major drawbacks relies on the attachment of sensors on the head and the cost for on-site clinical practice.

Similarly, assessing or training a patient with the DidRen laser test in clinical practice is not easy and is very time-consuming, as multiple adjustments must be made to ensure good standardization of the test. Using a VR headset with an environment simulating the DidRen laser test is a promising approach since it allows motion analysis thanks to integrated sensors and the implementation of tests in different spatial directions with vertical (flexion-extension) or even oblique (flexion-extension combined with lateral flexion) movements of the head. Other parameters are in principle easy to modifiy in a VR environment: The distance between the targets, the number of targets, the validation time, the number of cycles, etc. The VR version of the DidRen laser test, called DidRen VR, has been developed by our team and is presented below.

In view of sensorimotor assessment, the VR environment should not induce different motor strategies than in real-world. Regarding targetting movements, Fitts' Law is a widely accepted model of human locomotor behaviour [17, 18] relying on Shannon's information theory [19, 20]. In his original investigation, Fitts [17] defined the index of motor performance (IP) as

$$IP = \frac{ID}{MT}, \tag{1}$$

with ID the motor index of difficulty and MT movement time (MT). Note that IP, expressed in bits/s, is frequently called throughput in more recent literature. Fitts' law has been formulated in [18] and states that, in a targetting task, the following link, generalizing (1), holds:

$$MT = A + B\, ID, \tag{2}$$

with A and B empirical positive constants. Moreover, ID should depend on the distance between two adjacent target centers (D) and on the width (W) of the targets through

$$ID = \log_2 \left(\frac{D}{W} + 1 \right). \tag{3}$$

The latter expression for ID is not the one originally proposed by Fitts. It is a modified proposal [21, 22] that avoids a negative ID for values of $D/W \ < 1$. Equation (3) directly mimics Shannon's original theorem #17 [22].

Although Fitts' Law was originally validated for the upper extremities [17, 18], other studies have found that it also describes movements of the lower extremities [23, 24] and head [25, 26]. The mean IP, which ranged from 5 [25] to 7 bits/s [26], is much lower than values reported for the extremities, which ranged from 10 [17] to 18 [23] or 22 bits/s [18]. These studies show that the locomotor system is less efficient in executing pointing movements of the head than that of the extremities for identical values of ID. Therefore, the study of information capacity during the execution of pointing movements of the head, as performed in the DidRen laser test, is of great importance to determine expected values of sensorimotor capacity in healthy subjects or in patients with neck pain .

Turning back to VR applications in motion assessment, therapists must be able to ensure that there are no conflicts between the real and VR worlds, or that these conflicts are intentional, especially with respect to the position, velocity, and acceleration of different body parts during pointing movements. A simple way to quantify the relevance of a newly developed VR environment and its validity is to calculate Fitts' Law and see if the model is verified. The question we address here is therefore the following: "Does Fitts' Law holds during the DidRen VR test performed in healthy subjects?". To answer this question, the DidRen VR application developed by our team and described in section II.1 was designed to allow specific settings for different target widths (challenging the participant's accuracy) and different inter-target amplitudes (challenging head movement range and velocity), resulting by multiple levels of ID according to Fitts' Law. Our hypothesis is that Fitts' Law will hold during the DidRen VR test.

II. MATERIALS AND METHODS

II.1. Choice of VR headset and development of the DidRen VR application

Three VR headsets have been a priori considered to develop the DidRen VR application. A comparison of their characteristics is available in Table I. The major drawback of Samsung Gear VR is that it is smartphone-dependent and does not allow body positioning, which jeopardizes potential interactions with objects in the VR environment. A single controller is available with Samsung Gear VR but without creating the position of the hands in space.

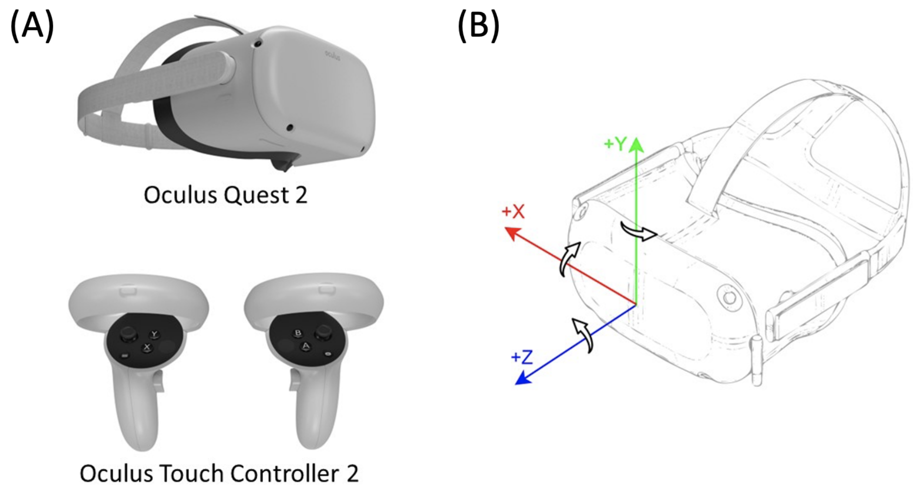

FIG. 3. (A) Presentation of the Oculus Quest 2. The VR headset and the touch controllers are shown. (B) The three axes (X,Y,Z) of the frame used by the motion sensor for kinematic variables recording.

The two touch controllers of the Oculus system solve this problem (Figure 3). A prototype version of the DidRen VR application has been developed for a Oculus Quest 1 (2019–2020). In 2021, the application was upgraded to run on Occulus Quest 2: This VR headset is an autonomous system with price, resolution and movement tracking possibilities well adapted for clinicians.

We now give a summarized presentation of the DidRen VR application. The main menu – Figure 4 (A) – allows for managing the application, selecting the desired test, and setting the parameters. A total of 9 tests are currently available (Figure 5): horizontal (standard DidRen laser test), vertical, diagonal 1, diagonal 2, triangle up, triangle down, triangle left, triangle right, and random. The accuracy needed to reach a target may be tuned as illustrated in Figure 6. The laser beam of the DidRen laser test is replaced by a blue circle in the DidRen VR application. To validate a target, the user has to move the beam by head rotation and stabilize the beam in the validation zone during a particular duration that can be configured. We refer the reader to a video demo, downloadable at `https://osf.io/t8zwj/`, for a better visualization of the VR environment.

In addition to these 9 tests, different parameters can be set directly in the application menu – Figure 4 C: the validation time (from 0.1 to 1.5 s by steps of 0.1 s), the number of

TABLE I. Characteristics of the three VR headsets tested during the developement of the DidRen VR application.

Characteristics	**Oculus Quest 1**	**Oculus Quest 2**	**Samsung Gear VR**
Introductory price (Euro)	450-550	350-450	100 +650-750 (phone)
Release date [dd/mm/yyyy]	21/05/2019	13/10/2020	27/11/2015
Discontinued [mm/yyyy]	30/09/2020	–	30/09/2020
Storage (Gb)	64/128	64/256	32-256
Controller (n)	2	2	1
Degrees of freedom (n)	6	6	3
Display	OLED	LCD	OLED
Resolution (per eye)	1440x1600	1832x1920	1280x1440
Frequency (Hz)	72	60/72/90	60
Field of view (°)	110	110	101
Pupillary distance (mm)	58-68	58/63/68	62
Dimension [w x h x d] (mm)	193x105x222	191.5x102.0x142.5	207.1x82.8x120.7
Mass (g)	571	503	345 (empty) +130-180 (phone)
Autonomy (yes,no)	yes	yes	yes
Battery life (h)	2-3	2-3	2-2.5

cycles (from 1 to 10), the size of the validation area or accuracy (from 1 to 4), the starting side (left, right, random), the position of the targets (distance target-floor, distance target-user) and the desired angle (distance between targets). All these parameters are saved and loaded at the next session related to a given participant, so the settings do not have to be changed every time. The positions of the targets can be set in a dedicated menu, and all possible target positions are displayed directly.

During each test, the DidRen VR application records data and creates files that can be used later by the operator. These files contain, on the one hand, the general data, and on

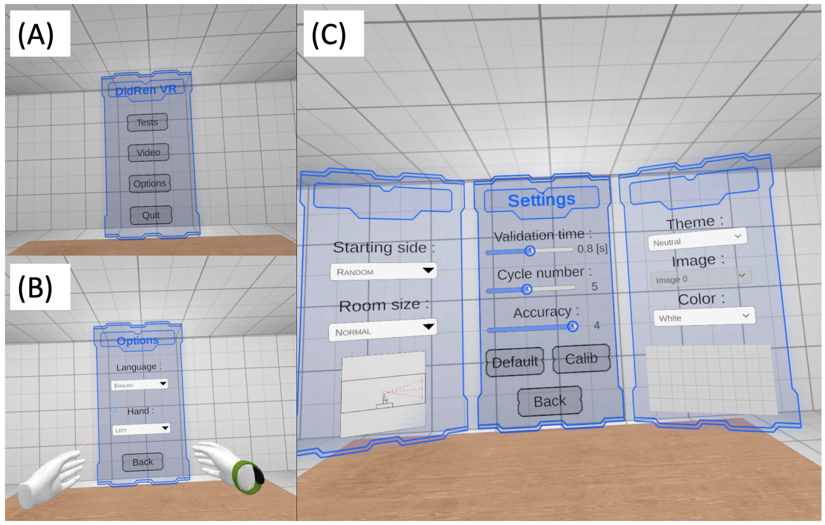

FIG. 4. (A) DidRen VR main menu: "Tests" leads to the various environments, "Video" leads to a tutorial, "Options" leads to the choice of language and dominant hand. (B) "Options" menu, allowing to chose language (English, French and Dutch available) and dominant hand. (C) "Tests" main menu allowing to customize the environment. Validation time is the time during which the beam must stay in the validation zone of the target for the target to be considered as reached. Cycle number is the number of cyclic patterns to be performed during the test, e.g. center-right-center-left-center with three horizontal targets. Accuracy is the size of the validation zone of the targets, ranging from 1 (whole target) to 4 (central disk).

the other hand, the 3D kinematic data of the head (movements around the X, Y, and Z axes) recorded at a sampling frequency of 100 Hz. The general data file includes the identification of the test, the date and the start and end times of the test, the test performed, the room, the total time of the test, the starting rotation side, the target positions, and a link to the corresponding kinematic data file. The latter includes time-series of the following variables: acceleration, velocity, position, angular acceleration, angular velocity (GyrX, GyrY, GyrZ) and angular position. It is therefore possible to carry out detailed analyses of the movements performed during the test. The application creates the folders, files, and the backup hierarchy itself and checks if the required folders are present before saving/uploading. A schematic view is displayed in Fig. 7.

The application can be freely downloaded at `https://sidequestvr.com/app/9647/didrenvr_demo`, where a video presentation can also be found.

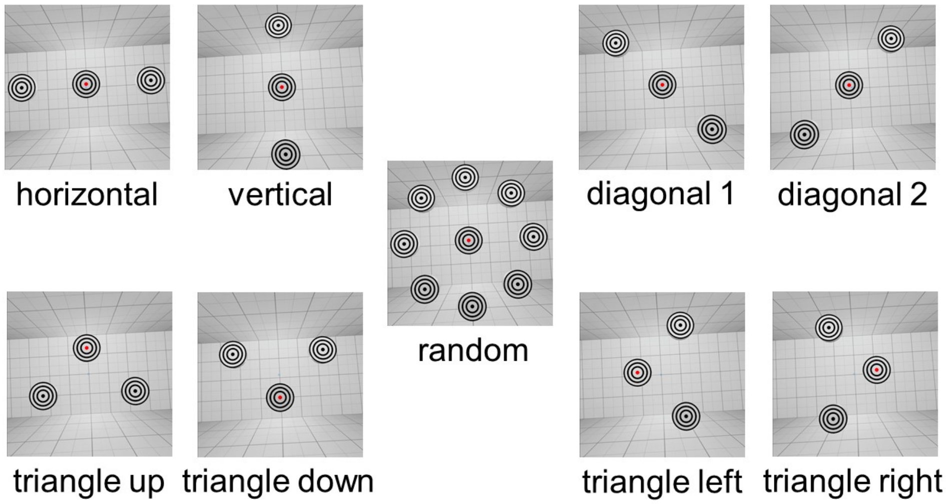

FIG. 5. Position of the targets for the 9 developed tests. The horizontal test corresponds to the standard DidRen laser test. In these illustrations, accuracy is set to 1: The validation zone is the central disk, displayed in red for the target to be reached. Larger accuracy values include the larger concentric circles in the validation zone.

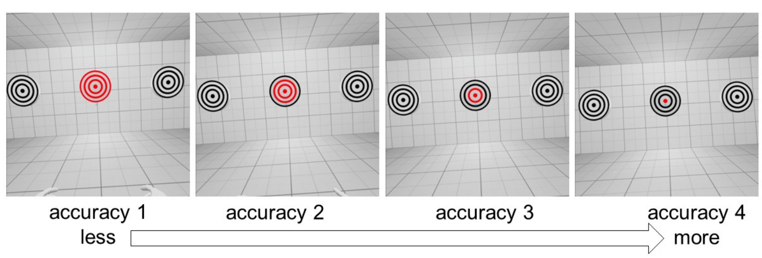

FIG. 6. Illustration of the accuracy parameter, ranging from 1 (low accuracy, the whole target is the validation zone) to 4 (high accuracy, the central disk is the validation zone).

II.2. Fitts' law validation

All the participants were informed about the details of the study through the reading and approval of an informed consent. The study was approved by the ethics Committee of

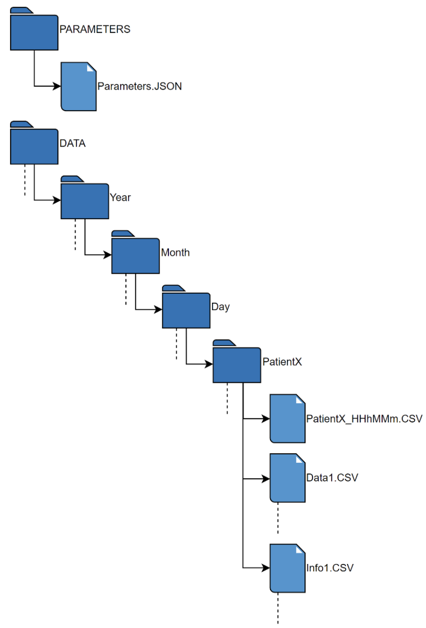

FIG. 7. Schematic view of the folders and file created by the DidRen VR application.

the University of Reims Champagne Ardenne with the approbation number 2022008.

The inclusion criteria were: a Neck Disability Index [27] lower than 4%, a response to a numeric pain rating scale assessing neck pain equal to 0 – no pain, no neck pain in the last 6 months, no vestibular disorders (vertigo, nausea, motion sickness, etc.), no surgery or trauma related to the cervical spine in the last 6 months, no history of laser eye surgery, no medication that alters perception and no history of epileptic episode(s) or loss of consciousness. Before the test phase, every subject completed the French version of the Bournemouth questionnaire [28] in order to evaluate patients with neck pain.

Participants were sat on a chair with a backrest but no armrests and equipped by the experimenter with an Oculus Quest 2 connected to a computer. Participants were placed in the standard DidRen setup with 3 horizontal targets separated by 30°. Instructions were then given by the experimenter: "When a target becomes red you must reach it with the beam as quickly as possible". One of the four levels of accuracy was set randomly before the test by the experimenter and the validation time was set equal to 0.8 s, *i.e.* the validation time of the original DidRen test [14]. ID was therefore randomly chosen between a minimal possible value of 0.269 bit for an accuracy level of 1 and an angle of 15°, and a maximum possible value of 3.170 bits for an accuracy level of 4 and an angle of 55°.

The sequence of head rotations was predefined and similar for all (centre-right-centre-left-centre, corresponding to one of the five cycles to be performed per angle). In order to become familiar with the task, a practice test was first carried out before measurements. Participants were then asked to perform the task at 9 different target distances, 15º–20º–25º–30º–35º–45º–50º–55º, in random order. Kinematic data were measured during these 9 tests. After the experimentation, a last questionnaire was submitted to the participant to obtain an overall feedback on the virtual reality as well as on the experience lived during the study. The questionnaire has been inspired by [29]. We assessed in particular the following items under the binary form yes/no: (1) Skills, identified with " the attitude of a user toward a computer technology, the degree with which he feels comfortable with a computer"; (2) Engagement, which is a component defined as "energy in action, between a person and its activity consisting of a behavioural, emotional and cognitive form"; (3) Usability, a component defined as "the ease of learning (learnability and memorizing) and the ease of using (efficiency, effectiveness and satisfaction) the virtual environment" [29]. These three aspects should be satisfied in the current, prototype, DidRen VR application. The percentage of positive answers was recorded.

At each different angular separation and choice of accuracy, the motor index of difficulty (3) can be computed by equating D to the diameter of the validation zone and L to the distance between two targets. The movement time, MT, is defined by the mean reach time, i.e. the time needed to reach a target that becomes red starting from an other target. This time is computed for each pair of targets and averaged for each pair during the 5 cycles. A linear fit of MT versus ID is then performed and the co efficients A and B appearing in Eq. (2) are computed, as well as Pearson's correlation coefficients, r.

III. RESULTS

III.1. Population

137 individuals were recruited and 126 accepted to participate in the study after having been informed. 71 participants did not meet the inclusion criteria and 5 were excluded for not performing the test correctly. The data of a final number of 50 participants were

recorded and analyzed.

TABLE II. Description of participants. Data are written under the form median [Q1–Q3] with Q1 and Q3 the first and third quartiles respectively. BQ=neck Bornemouth Questionnaire, NDI=Neck Disability Index, T=DidRen VR time at 30°, $GyrY_{max}$ =maximal norm of the head rotation speed during DidRen test VR at 30°. The last line shows the distribution of the randomly chosen ID.

Parameter	**median [Q1–Q3]**
Gender (M/F)	28/22
Age (years)	39 [23−51]
BQ (/70)	1.5 [0−5]
NDI (%)	0 [0−2]
T (s)	28.9 [27.1−31.1]
$GyrY_{max}$ (°/s)	18.0 [11.5−23.7]
Skills (%)	97.5
Engagement (%)	98.1
Usability (%)	97.5
ID (bit)	0.820 [0.528−1.146]

III.2. Fitts' law in the VR environment

Typical plots are shown in Figure 8 for the reader to appraise the quality of the linear fits between MT and ID, i.e. Fitts' law. The worst and best linear correlations are shown, as well as the median one. In all cases it is observed that MT vs ID follows a clear linear trend. As shown in Table III, the linear trend is clearly followed by the data since the median r has the high value of 0.938.

IV. DISCUSSION

Our results showed that we have positively answered our research question: Fitts' law held true during the DidRen VR test, with Pearson correlation coefficients equal to 0.938 [0.883−−0.968] confirming the linear link between MT and ID. Therefore, by extending

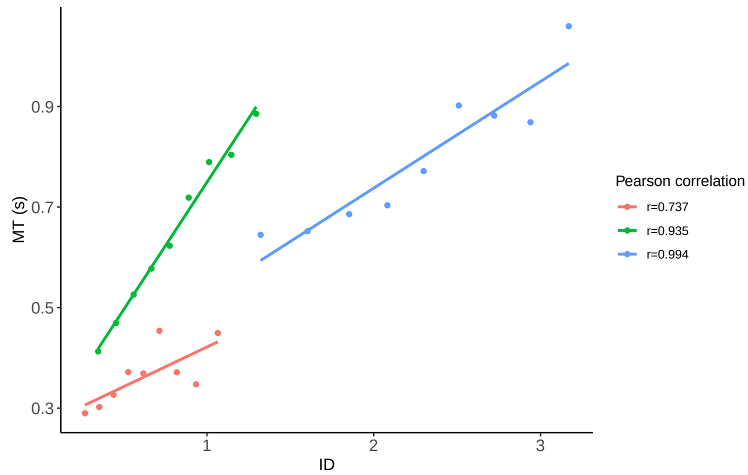

FIG. 8. MT (s) versus ID for three participants. Measured data are plotted (points) and the linear regression corresponding to Fitt's law has been added (lines). Selected participants are such that their Pearson correlation coefficient is minimal (red), maximal (blue) or median (green). Recall that the accuracy level was randomly chosen for each participant, leading to different ranges for ID.

TABLE III. Values of Fitt's law parameters (A and B) and Pearson correlation coefficient (r) . Data are written under the form median [Q1–Q3] with Q1 and Q3 the first and third quartiles respectively.

Parameter	**median [Q1–Q3]**
A (s)	0.309 [0.214–0.365]
B (s)	0.295 [0.247–0.353]
r	0.938 [0.883–0.968]

the knowledge on the neuromuscular control of the cervical spine evaluated according to a protocol assessing Fitt's law with the DidRen VR, we can conclude that DidRen VR offers an environment in which movements are "natural", i.e. follow the same basic law as in real-life movements. A subjective evaluation of the environment by the participants also leads to the conclusion that participants feel at ease in the environment and find it usable. Note that, in the real-word DidRen laser test, ID is fixed, making impossible a comparison with the present results.

The relationship between movement time and difficulty index during the DidRen VR used in this study is an other illustration of the linear speed-accuracy trade-off previously described and observed in previous work on the Fitts' law [17, 30, 31]. Our results were calculated with the variable "time" which is in line with the previous study [32] showing similar results. As a limitation of the current protocol we mention that the influence of age on the parameters of Fitts' law was not studied. It is known from other studies that, although Fitts' law is satisfied at any age, the latter has an impact on the the coefficients appearing in the regression [31, 33]. The fact that Fitts' law is maintained with age is consistent with age-related deterioration in central processing, planning, or perceptual mechanisms [34]. Using the real laser DidRen test, the elderly have been shown to exhibit altered sensorimotor behaviour, manifested by decreased total time [11]. An obvious outlook of the present study is the assessment of age's impact on Fitts' law in the DidRen VR test.

The median $[Q1 - Q3]$ time of the Didren VR test at 30°, T, was 28.9 $[27.1-31.1]$ s compared to 49.6 $[45.6 - 55.6]$ s in a group of young adults previously studied with the real-world version of the DidRen laser test [9] or to 50.0 $[47.1-52.8]$ s for cervicalgic patients aged 46.2 ± 16.3 years [11]. The DidRen VR test has therefore a higher IP than the real-world one: MT is lower at fixed ID. It can be hypothesized that a target is more easily validated in the VR environment because there is no loss of accuracy due to laser beam dispersion, dust on the light sensors etc. This may also be the result of an increase in the participants' engagement due to the VR environment.

Although there is evidence of the efficacy of VR for chronic neck pain [35–37], the extension of Fitts's law in VR environments with low-cost technology to assess and train neck mobility is not present in the literature. Our results show for the first time that this law is applicable to the DidRen VR. Therefore, modelling the DidRen in a VR environment does not appear to cause major perceptual conflicts. To avoid these, the targets were placed in a frontal plane (2D) at a perceived distance of 90 cm, as in the real version of the DidRen, although the environment is 3D and the targets can be placed at different distances from the participant. This distance is necessary to control and limit the range of motion of the cervical spine, within a range compatible with use in patients with neck pain. However, using targets at different distances in the DidRen VR would also be a strategy to increase or decrease ID. In this more complex case, the effect of target depth on cervical mobility performance could be evaluated. A previous study [38] investigated the applicability of

Fitts's law models in 3D environments using the same VR headset as in the present study and showed that target depth affects movement performance. These results suggest that our application should be developed in this direction. The impact of a modification of every parameter has also to be further investigated. For example, the validation time is not adjustable in the real version, so the participant cannot be prompted to reach the next target faster. One strategy that could be used, for example, when assessing patients with neck pain after a training session, is to shorten or lengthen the validation time to avoid training and assessment being similar.

It is worth recalling that VR has shown encouraging results in the treatment of neck pain and disability in a virtual context [39, 40]. These studies have shown that patients who used virtual reality improved more than those who did not. However, not all studies show conclusive results [41], so it is important to continue research in this area. Most patients with neck pain do not receive high-intensity, task-oriented training as part of a typical rehabilitation plan. With the DidRen VR, high-intensity repetitive training of neck movements using real and/or misleading ranges of motion, depending on the onset of pain, can now be easily performed in the clinic or at home. In addition, the use of misleading ranges of motion appears to us to be a real option in the treatment of kinesiophobia due to neck pain. This option is currently under development in the DidRen VR application and needs to be tested on neck pain patients in the near future.

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Data are available here: `https://osf.io/t8zwj/`. Files are described in the README.txt file . A demo video can be downloaded at `https://osf.io/t8zwj/files/osfstorage/6414602a28e5c50dfb9379db`.

The authors declare no conflict of interest.

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[1] P. R. Blanpied, A. R. Gross, J. M. Elliott, L. L. Devaney, D. Clewley, D. M. Walton, C. Sparks, and E. K. Robertson, Journal of Orthopaedic & Sports Physical Therapy **47**, A1 (2017), pMID: 28666405, https://doi.org/10.2519/jospt.2017.0302, URL `https://doi.org/10.2519/jospt.2017.0302`.

[2] X. Chen and J. Treleaven, Manual Therapy **18**, 562 (2013).

[3] E. Kristjansson, L. Hardardottir, M. Asmundardottir, and K. Gudmundsson, Archives of Physical Medicine and Rehabilitation **85**, 490 (2004).

[4] R. Hage, F. Buisseret, M. Houry, and F. Dierick, Sensors **22** (2022), ISSN 1424-8220, URL `https://www.mdpi.com/1424-8220/22/7/2805`.

[5] M. Revel, C. Andre-Deshays, and M. Minguet, Archives of Physical Medicine and Rehabilitation **72**, 288 (1991).

[6] M. Revel, M. Minguet, P. Gergoy, J. Vaillant, and J. L. Manuel, Archives of Physical Medicine and Rehabilitation **75**, 895 (1994).

[7] C. M. P. W. JE Bible, D Biswas and J. Grauer, J Spinal Disord Tech pp. 15–21 (2020).

[8] R. Hage, F. Dierick, N. Roussel, L. Pitance, and C. Detrembleur, PeerJ **7**, e7095 (2019).

[9] R. Hage, F. Buisseret, L. Pitance, J.-M. Brismée, C. Detrembleur, and F. Dierick, PLOS ONE **14**, e0219515 (2019).

[10] R. Hage, C. Detrembleur, F. Dierick, L. Pitance, L. Jojczyk, W. Estievenart, and F. Buisseret, Sensors **20**, 833 (2020).

[11] R. Hage, C. Detrembleur, F. Dierick, J.-M. Brismée, N. Roussel, and L. Pitance, BMC Musculoskeletal Disorders **22** (2021).

[12] R. Hage, F. Buisseret, M. Houry, and F. Dierick, Sensors **22**, 2805 (2022).

[13] E. Kristjansson and J. Treleaven, Journal of Orthopaedic & Sports Physical Therapy **39**, 364 (2009).

[14] R. Hage and E. Ancenay, Annals of Physical and Rehabilitation Medicine **52**, 653 (2009).

[15] H. Sarig-Bahat, P. L. T. Weiss, and Y. Laufer, Spine **35**, E105 (2010).

[16] H. Sarig-Bahat, P. L. Weiss, and Y. Laufer, Archives of Physical Medicine and Rehabilitation

91, 1884 (2010).

[17] P. M. Fitts, Journal of Experimental Psychology **47**, 381 (1954).

[18] P. M. Fitts and J. R. Peterson, Journal of Experimental Psychology **67**, 103 (1964).

[19] C. E. Shannon, Bell System Technical Journal **27**, 379 (1948).

[20] C. E. Shannon, Bell System Technical Journal **27**, 623 (1948).

[21] A. T. Welford, Ergonomics **3**, 189 (1960).

[22] I. S. MacKenzie, Human–Computer Interaction **7**, 91 (1992).

[23] C. G. Drury, Human Factors: The Journal of the Human Factors and Ergonomics Society **17**, 368 (1975).

[24] H. G. Williams and P. Werner, Perceptual and Motor Skills **60**, 403 (1985).

[25] R. J. Jagacinski and D. L. Monk, Journal of Motor Behavior **17**, 77 (1985).

[26] R. O. Andres and K. J. Hartung, Human Factors: The Journal of the Human Factors and Ergonomics Society **31**, 703 (1989).

[27] H. Vernon and S. Mior, Journal of Manipulative and Physiological Therapeutics **14**, 409 (1991).

[28] D. L. J Martel, C Dugas and M. Descarreaux, J Can Chiropr Assoc. **2**, 102110 (2009).

[29] K. Tcha-Tokey, O. Christmann, E. Loup-Escande, and S. Richir, International Journal of Virtual Reality **16**, 33 (2016), URL `https://ijvr.eu/article/view/2880`.

[30] M. Descarreaux, S. R. Passmore, and V. Cantin, Manual Therapy **15**, 445 (2010), ISSN 1356-689X, URL `https://www.sciencedirect.com/science/article/pii/S1356689X10000366`.

[31] J. B. SR Passmore and J. Lyons, Adapt Phys Activ Q pp. 352–363 (2007).

[32] C. G. J. L. SR Passmore, JR Burke and A. Dunn, Journal of Manipulative & Physiological Therapeutics pp. 189–192 (2010).

[33] P. L. B. R.-R. F. R. E. B. JJ Temprado, R Sleimen-Malkoun, Exp Brain Res **228**, 105 (2013).

[34] V. S. C. B. H. H. JW Youdas, TR Garrett and J. Carey, Phys Ther pp. 770–780 (1992).

[35] H. Sarig Bahat, H. Takasaki, X. Chen, Y. Bet-Or, and J. Treleaven, Manual Therapy **20**, 68 (2015), ISSN 1356-689X, URL `https://www.sciencedirect.com/science/article/pii/S1356689X1400126X`.

[36] C. C. A. H. E. S. J. T. H Sarig Bahat, K Croft, Eur Spine J. **27**, 1309 (2018).

[37] M. Gumaa and A. Rehan Youssef, Physical Therapy **99**, 1304 (2019), ISSN 0031-9023.

[38] L. D. Clark, A. B. Bhagat, and S. L. Riggs, International Journal of Human-Computer Studies **139**, 102413 (2020), ISSN 1071-5819, URL https://www.sciencedirect.com/science/article/pii/S1071581920300173.

[39] H. Cetin, N. Kose, and H. K. Oge, Musculoskeletal Science and Practice **62**, 102636 (2022), ISSN 2468-7812, URL https://www.sciencedirect.com/science/article/pii/S2468781222001369.

[40] I. Rezaei, M. Razeghi, S. Ebrahimi, S. Kayedi, and A. Rezaeian Zadeh, Journal of Biomedical Physics and Engineering **9**, 355 (2019), ISSN 2251-7200.

[41] N. Brady, J. G. McVeigh, K. McCreesh, E. Rio, T. Dekkers, and J. S. Lewis, Physical Therapy Reviews **26**, 262 (2021).