BIOMEDICAL ENGINEERING | RESEARCH ARTICLE

Construction of a haptic-based virtual reality evaluation of discrimination of stiffness and texture

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Abstract: Sensory impairments have a negative impact on performance. We designed and validated a haptic-based Virtual Reality (VR) system for the evaluation of discrimination of stiffness/texture and tested its agreement with current conventional tactile sensitivity evaluations. Forty-four individuals (age 25.2 ± 4.1) performed three tactile tests: the newly constructed haptic-based VR system, the Shape/Texture Identification Test (STI), and the Moberg Pick-Up Test. Bland-Altman plots tested for agreement between the haptic-based VR system and the standard tests. We found very good agreements (>95% of the data points lie within ±2SD of the mean difference) between the haptic-based VR scores and the scores of the conventional tests, except in the cases of the STI trial, when performed with the non-dominant hand, and the Moberg Pick-Up Test when performed with the dominant hand with open eyes. The advantages of the haptic-based VR evaluation of discrimination of stiffness and texture and its agreement with standard tests of sensory loss might suggest that the system can be used in the clinical settings.

Subjects: Biomechanics; Chronic Diseases; Medical Technology & Engineering

Keywords: neuropathy; occupational therapy; clinical evaluation

1. Introduction

Somatosensory loss has a negative impact on occupational performance and activities of daily living. For example, one or more sensory impairments of touch, pressure, vibration, temperature, and/or pain appear in 53–64% post-stroke patients (Connell et al., 2008). Other populations that are also affected by somatosensory loss are individuals with carpal tunnel syndrome (Heywood & Morley, 1992; Mia et al., 2019), chronic pain (Mailis-Gagnon & Nicholson, 2010), cerebral palsy (Brun et al., 2021), as well as somatosensory timing deficits in individuals with schizophrenia (Teale et al., 2013). Somatosensory discrimination training has been shown to improve sensory capacity (Leeanne et al., 2011). The evaluation of these deficits is therefore of great importance in order for the therapists to devise a patient-specific treatment plan. For example, atypical neuropathy requires electro-diagnostic testing as a first step for categorizing its subtype (Callaghan et al., 2015).

While several noninvasive tools are used to assess the level of neuropathy, e.g., Semmes Weinstein Monofilaments (Suda et al., 2021), graduated tuning fork for perception of vibration (Cheng et al., 1999), and the Moving and sustained Touch-Pressure evaluation (Dannenbaum et al., 2002), their results may be dependent on the examiner skill for stimulus control and judgment of performance (Williams et al., 2006). Also, the resolution of the examination is fixed, so that the accuracy level is limited. For example, the Semmes Weinstein Monofilaments test comprises
a finite number of monofilaments so that if the sensory threshold of the patients falls between the values of the two filaments, this cannot be recorded. Finally, current evaluation kits might be compromised by visual information acquired by the subjects, regarding the properties of the objects used during the evaluation. The neurometer (Înceu & Andrei Veresiu, 2015), a transcutaneous electrical stimulator seems to surpass these disadvantages by measuring current perception thresholds at different frequencies. However, conflicting information and methodological problems exist regarding its usefulness for evaluation of specific conditions.

With the advancement of technologies, Virtual Reality (VR) has provided a safe and enjoyable means for patient rehabilitation. Adding haptic feedback to a VR system further enhances the user’s experience by the participation of the added tactile input. This combination of haptic-based VR has been used to test the user’s ability to detect and differentiate small forces (Wu et al., 2015), evaluating toepthesia (Rinderknecht et al., 2015), and demonstrating the decline of tactile and haptic performance with age (Kalisch et al., 2012). Due to the aforementioned advantages of haptic-based VR system, and the described limitations of current sensory discrimination evaluations, the implementation of a simple haptic-based VR evaluation of discrimination of stiffness and texture has a great potential for clinical practice. We therefore aimed to design a haptic-based VR system for the evaluation of discrimination of stiffness and texture, and to test its agreement with current conventional evaluation of tactile sensibility.

2. Methods

2.1. Population
We recruited 44 healthy individuals (40 females, mean age and standard deviation 25.2 ± 4.1). Ethics approval was granted by the occupational therapy department’s ethics committee in Tel Aviv University (approval #0004–2019-SM). All of the subjects read and signed an informed consent form pretrial.

2.2. Study tools
The haptic-based VR evaluation system: A VR system (Devinesense, Järfälla, Sweden) and 6 degrees of freedom haptic pen-like device (TouchTM haptic device, 3D systems, Rock Hill, South Carolina) were used (Figure 1). A set of 3D Vision 2 wireless glasses (NVIDIA, Santa Clara, California) was used to view the 3D virtual environment. Python-based programing of the virtual
environment and the haptic feedback was performed in H3D API (SenseGraphics AB, Kista, Sweden).

The evaluation was divided into a texture-module and a stiffness-module. In both modules, two visually identical surfaces are presented side by side. The two surfaces differ in either their friction coefficient or their stiffness, depending on the chosen module. In the texture-module, the subject is requested to slowly trace a circular path, presented on each of the two surfaces, in order to sense the textures of the two virtual materials. The subject is then asked to determine which of the materials, marked by “1” and “2”, is smoother. In the stiffness-module, the subject is requested to press on a location on each surface, marked by an X (placed in the middle of both surfaces). The subject is then asked to determine which of the materials, “1” or “2”, is stiffer. There is no time limit, and the subject can go back and forth from one surface to the other until he or she is certain of their answer. After the subject has chosen “1” or “2”, a new screen is presented, where the difference in the friction coefficient or stiffness properties between the two surfaces is reduced. The task is repeated until he or she cannot discriminate between the textures or stiffness of the two materials, thereby a discrimination threshold is found. In total, we created 20 different screens for each of the two evaluations. In each evaluation, there are two example screens, where the mechanical property differences between the two surfaces are very large. The purpose of these screens is to allow the user to become acquainted with the virtual environment and the activation of the haptic device. Then, we created six screens (labeled 1.0 to 6.0) for each evaluation, where the difference between the mechanical properties of the two surfaces gets harder to notice, as it is reduced in constant steps. Also, the mechanical property assignment for the stiffer or smoother is randomly assigned to either surface “1” or surface “2”. If the subject’s answer was correct, then the evaluator jumps to the next screen (from 1.0 to 6.0). Once the subject provided a wrong answer or reported that he or she cannot detect a difference in the texture or stiffness of the two surfaces, i.e., when the subject’s response has changed, the evaluator goes back to the previous screen (as accustomed in the staircase method), and activates a new screen that has a smaller difference in the mechanical properties compared to previous screen (that was successfully detected by the subject) but larger difference compared to the screen where the subject failed to detect. The adaptation of the step size that reduces the level of stimulus level difference is meant to focus more accurately on the ability of the subject to discriminate between the mechanical properties of the two surfaces.

For each screen, there are two more “sub-screens” like this. So, for example, after the subject experiences with the two examples, the evaluation begins. If the subject answered correctly in screen 1.0, the evaluator opens screen 2.0. If the subject answered correctly in screen 2.0, the evaluator opens screen 3.0. If the subject cannot discern which of the surfaces is smoother, the evaluator opens screen 2.1. If the subject cannot discern which of the surfaces is smoother, then the subject’s ability of texture discrimination is set at level 2.0. But if the subject answered correctly in screen 2.1, then the evaluator opens screen 2.2. Finally, if the subject cannot discern which of the surfaces is smoother, then the subject’s ability of texture discrimination is set at level 2.1 and if he answered correctly, then the subject’s ability of texture discrimination is set at level 2.2. The two levels of difference sizes were chosen in order to shorten the evaluation time so that a person with a high discrimination ability can quickly get to screen 6, without having to delay on all sub-screens. The final score of each examination is the final level achieved by the subject, separately for stiffness and texture. A sum score for both examinations can be totaled.

The stiffness and texture levels were found empirically and set as follows: the difference in stiffness between the two surfaces in the first screen (screen 1.0) was 0.988 N/cm (0.006 N/cm and 0.994 N/cm) and in the last screen (screen 6.2) 0.274 N/cm (0.370 N/cm and 0.644 N/cm). The difference in friction coefficient between the two surfaces in the first screen (screen 1.0) was 0.984 (0.008 and 0.992) and in the last screen (screen 6.2) 0.260 (0.380 and 0.640).
The Moberg Pick-Up Test (Ng et al., 1999): A test that assesses for hand dexterity and functional sensibility in individuals with peripheral nerve injury and other pathologies. It is a timed test performed once with opened eyes and once with closed eyes, separately in each hand. During the test, the subject is asked to pick up 12 objects from a table one by one (screws, paper clips, diameter ring, safety pin, small nuts, coins, and key) and place them in an 11 × 15 cm plastic box as quickly as possible, without sliding them. The Moberg test is done in two phases: first with eyes open and then with eyes closed. For each phase of the test, the dominant hand is tested first. For young adults, the average time for completion of the test is 11.6 s for the dominant hand and 12.4 s for the non-dominant hand (Nasim Amirjani et al., 2007). The test has a good to excellent test-retest and inter-rater reliability with a coefficient alpha for test-retest reliability of 0.985 (N Amirjani et al., 2011).

The Shape/Texture Identification Test (STI) (B. Rosén & Lundborg, 1998): A test that assesses the peripheral nerve injury and peripheral nerve diseases (B. Rosén & Lundborg, 1998; Brigitta Rosén & Jerosch-Herold, 2016; Svensson & Häger-Ross, 2006; Rosén, 2016). The grade range from “0” (did not detect any of the shapes and textures) to “6” (detected all of the shapes and textures). A grade below “6” denotes tactile dysfunction.

2.3. Protocol
The subjects completed three evaluations: the described haptic-based VR evaluation, the Moberg Pick-Up Test, and the STI. They were asked to wear rubber gloves, to reduce tactile sensation and mimic neuropathy (Dianat et al., 2012) during the three examinations. We chose to use simple rubber gloves (for dishwashing) and refrained from using gloves with latex since some individuals show sensitivity or may experience an allergic response to it. Since it was shown that using gloves of various thicknesses had no effect on dexterity and tactility (Nelson & Mital, 1995), we used a constant type of gloves of different sizes, to ensure fit according to the anatomy of each subject.

2.4. Post analysis
Bland-Altman were drawn, i.e., the x-axis is the mean between the total score in the VR trial and each of the three other tests separately (the STI score and the score in the Moberg Pick-Up Test, once with closed eyes and once with open eyes). The y-axis is the difference between the two scores. The plots were drawn separately for the dominant hand trials and the non-dominant hand trials. In each plot, the mean difference as well as mean ± 1.96SD lines are drawn. It is recommended that agreement between the two quantitative measurements is shown when 95% of the data points lie within ±2SD of the mean difference (Giavarino, 2015). For this study, 5% of the data are two data points. We used SPSS software (version 27, IBM) for statistical analyses. Intra-subject comparisons between the performance with the dominant and non-dominant hands were performed separately for each evaluation using the Wilcoxon signed-rank test. Statistical significance was set to p < 0.05.

3. Results
The results of the tests are detailed in Table 1. In the haptic-VR texture test, 14 participants (31.8%) and 22 participants (50%) reached a ceiling effect in their dominant and non-dominant hands, respectively. In the haptic-VR stiffness test, 12 participants (27.3%) and 14 participants (31.8%) reached a ceiling effect in their dominant and non-dominant hands, respectively.

We found very good agreements between the VR scores and the scores of the STI and Moberg (with closed and opened eyes), for both hands (Figure 2), but for the STI trial with the non-dominant hand, in which four data points (9% of the data points) were outside the mean ± 2SD lines (Figure 2f) and the Moberg trial with the dominant hand performed with open eyes (Figure 2a), in which three data points (6.8% of the data points) were outside the mean ± 2SD lines. The Bland-Altman plots of the four Moberg trials (Figures 2a-d) show proportional bias, so
Table 1. Median and interquartile scores (N = 44) of the virtual Reality (VR) evaluation, the Moberg Pick-Up Test, and the Shape/Texture Identification Test (STI). Statistical differences between the results of the dominant and non-dominant hand were found using the Wilcoxon signed rank test

|                     | Dominant hand | Non-dominant hand | p   |
|---------------------|---------------|-------------------|-----|
| VR texture          | 5.2 (3.0–6.2) | 6.2 (3.7–6.2)     | .002|
| VR stiffness        | 6.0 (3.2–6.2) | 6.0 (4.2–6.2)     | .175|
| VR (total score)    | 9.3 (8.2–11.4)| 11.2 (9.2–12.3)   | .001|
| Moberg with closed eyes | 67.5 (53.8–95.9)| 83.3 (66.4–101.5) | .011|
| Moberg with opened eyes | 32.1 (23.7–56.1) | 40.4 (22.8–55.1)  | .823|
| STI                 | 3.0 (2.0–4.0) | 3.0 (1.3–4.0)     | .314|

Figure 2. Bland-Altman plots of the VR score and the Moberg test with open eyes for the (a) dominant and (b) non-dominant hands, then VR score and the Moberg test with closed eyes for the (c) dominant and (d) non-dominant hands, and VR score and the STI test for the (e) dominant and (f) non-dominant hands. The diamond shaped marker on the plots, indicates the median values of the entire group (median for the mean and difference of all subjects.)
alqthough there is an agreement between the two methods, the characteristics of the agreement is not equal across the range of measurements. We performed Spearman correlation tests between the results of the haptic-based VR evaluation scores and the scores of the STI and Moberg and found no statistically significant correlations (Table 2).

4. Discussion
We found good agreement between our haptic-based VR evaluation system and standard tests (Moberg and STI), suggesting that our system might be used for early detection of sensory loss. Its advantages are in its high-resolution capabilities, allowing to adjust the levels of examination according to the capabilities of the patient, i.e., control the difference between the mechanical properties of the surfaces. In the SPI and Moberg, physical objects are used so that there is no option to change their properties. Also, the ability to present the subject with visually identical surfaces, which differ in frictional and stiffness mechanical properties, is unique. Another possible use of our system is exercises to enhance sensory stimulation, as exercise has been shown to improve symptoms and function in individuals with diabetic peripheral neuropathy (Balducci et al., 2006).

Our method for detecting the sensory threshold of individuals is similar to a previously shown shape discrimination evaluation, which was found to be valid, reliable, and clinically practicable in individuals with peripheral neuropathy (Holst-Wolf et al., 2019). The shape discrimination method, called The Minnesota Haptic Function Test, is an actual physical examination without VR, during which the subject is asked to manually explore the surface of two curved blocks presented consecutively. There were 28 blocks with varying center-point-heights. Consequently, the resolution of the result is limited. Also, in this aforementioned test, as well as in the STI and the Moberg, used herein to test for agreement with the haptic-VR method, the subjects are blindfolded for a partial duration or the entire duration of the test. Blindfolding is administered since the physical properties of the items presented to the subjects can be accurately predicted by the subject before touching them, e.g., the smoothness and stiffness of a toothpick or a screw and bolt. Therefore, when the subject is not blindfolded, he can use previous knowledge to assist him or her in performing the task. This might cause some discomfort for the subject. By creating visually identical surfaces in our virtual environment, which differ only by their mechanical properties, we eliminate the ability of the subject to predict the properties of each surface. Therefore, the subjects can perform the test with opened eyes, minimizing their discomfort.

The results of the Moberg scores with eyes closed were lower (i.e., longer durations to complete the Moberg) when performing the test with the non-dominant hand compared to the scores when performing it with the dominant hand. There were no such between-hand differences when performing the Moberg test with the eyes opened and when performing the STI. In the VR scores, the between-hand differences originated from the VR texture trial and not from the stiffness trial. This might imply that the reduced sensitivity in the non-dominant hand, produced by the rubber glove, was more pronounced when trying to discriminate between textures. This is also reflected

### Table 2. Correlation coefficient (r) and p value of the virtual Reality (VR) evaluation scores and the Moberg Pick-Up Test and the Shape/Texture Identification Test (STI) for the dominant and non-dominant hand

|            | Dominant hand | Non-dominant hand |
|------------|---------------|-------------------|
|            | VR texture    | VR stiffness      | VR texture | VR stiffness |
| Moberg with closed eyes | .036, .899   | -.212, .173       | -.019, .901 | -.033, .831  |
| Moberg with opened eyes | -.020, .899 | -.055, .727       | -.070, .653 | -.153, .320  |
| STI        | -.063, .683   | -.265, .086       | -.033, .831 | .259, .090   |
by the higher number of participants who reached a ceiling effect with their non-dominant versus their right dominant hands. The proposed explanation might rely on previous publications’ reports of asymmetric brain activity when applying vibrotactile cutaneous stimuli to the dominant and non-dominant index fingers (Jin et al., 2020). A similar asymmetry was also shown in the context of haptic discrimination (Cormier & Tremblay, 2013).

Although there was a very good agreement between the haptic-based VR evaluation scores and the scores of the STI and Moberg, there was no linear relationship between them. This is not surprising as the STI score scale is extremely limited with only three scores for texture and three scores for shape identification. As for the Moberg test, the score also depends on the hand speed of the subject and functional gripping ability. These abilities are often evaluated separately for individuals with neuropathy by means of standard tests, e.g., the Jebsen-Taylor Hand Function Test (Lima et al., 2017) or the Purdue pegboard test (Zhang et al., 2021). The presented haptic-based VR evaluation provides higher discrimination resolution compared to the STI and does not take motor dysfunction (hand speed or grip ability) as an affecting factor in the results.

The main limitations of our system lie in its high cost and stationary properties, so that it might not be affordable to all and it is confined to the laboratory/clinic settings. However, future modifications might include transferring the virtual environment to a VR headset that connects with the haptic device (Wang et al., 2019), so that the system will be portable. Also, in future versions of this evaluation, the screen numbers should be omitted as they might create a bias, and instead, the subject should be allowed to mark his or her choice and the software will automatically register the choice and move to the next screen. Another limitation is that we did not test the device with individuals with sensory impairment. While the gloves that the subjects wore were effective in decreasing tactile sensation, proven by the lack of ceiling effect in the Moberg and STI tests, the simulated state is not identical to that of individuals with actual sensory loss. Furthermore, several subjects reached a ceiling effect in the haptic-VR system, especially when using their non-dominant hand. Future studies should add new screens with more similar mechanical properties of the two surfaces. Also, most of our subjects were females. Although there were no differences in the VR scores between males and females, future studies should test for them. Our suggestion relies on results of a previous small sampled neuroimaging study showing that although there were no differences in tactile discrimination between males and females, there were differences in activation of the pre-motor cortex between the genders (Sadato et al., 2000). Finally, the geometry of the pen might not be suitable for testing partial sensory loss in the ulnar fingers, for example, so a 3D printed chassis that induces a different grasping of the haptic device is encouraged to fit the hardware to the patient.

In conclusion, the advantages of the haptic-based VR evaluation of discrimination of stiffness and texture and its agreement with standard tests of sensory loss might suggest that the system can be used in the clinical settings, pending clinical trials. Evaluation of the discrimination of stiffness and texture in other populations, e.g., individuals with Sensory Modulation Disorder (SMD), might propose further insight into the mechanism of the disorder. If necessary, adaptation of the system’s parameters to the patients’ range of perceptual abilities is not complex, so possible floor effects can be easily avoided. Additionally, since practice of discrimination between different tactile stimuli is a well-practiced treatment for individuals with sensory impairment, the haptic-based VR system proposed herein may be adjusted for treatment purposes as well. All aforementioned future endeavors would greatly benefit from evaluation of our setup by domain experts. Apart from its suggested role in the rehabilitation settings, the proposed tool can enrich our understanding regarding natural tactile perception. The effect of various restrictions, e.g., restricting finger pad deformation (Tao et al., 2021) on the ability to discriminate between stiffness and texture levels can be further researched. Also, testing novel devices, e.g., the feel-through tattoo for on-skin tactile output (Withana et al., 2018) or other epidermal devices based on flexural rigidity (Nittala et al., 2019) with the proposed tool can provide further insight into the human tactile mechanism.
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