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Vibrotactile Pattern Perception as a Method for the Assessment of Brain Dysfunction

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***Abstract*— An immediate need exists for a portable diagnostic device for the assessment of cortical function, and diagnosis of mTBI. This paper presents initial results using a vibrotactile acuity test for the objective and quantitative diagnosis of acute mTBI suspects. mTBI is hypothesized to involve derangement or damage to the underlying cortical network. In particular, fundamental building blocks of the cortex are changed in such a way as to limit the functional connectivity within and between cortical columns. Our approach is based on sensory illusions that are configured as a test of neural connectivity. Pilot clinical test data showed differences between a small healthy normal group and a concussion group using a sports concussion model.**

I. Introduction

Traumatic brain injury (TBI) and mild traumatic brain injury (mTBI) are some of the many risks faced by military personnel in combat. mTBI is particularly difficult to diagnose and quantify as the injury may involve derangement or damage to the underlying cortical network that is not detectable using conventional CT and MRI imaging [1]. This paper presents a new portable assessment approach that is based on the presentation of various real and phantom vibrotactile stimuli, and configured as a test of a subject's tactile, spatial and temporal perception limits compared to normative data.

It is known that the somatosensory system may provide a measure of neural and intra-cortical connectivity [2,3]. In fact, the traditional two-point tactile discrimination test (TPD) remains widely used as a neurological test in spite of it being criticized as an imprecise measure of spatial acuity. The TPD threshold is extremely dependent on the criterion that subjects adopt for responding that they perceive two points [4] and the perceived tactile location is affected by the interaction between the actuation sites and stimuli [5].

Phantoms or somatosensory illusions [6] are a number of related effects that can be observed from the interaction of two or more stimuli. One such phantom sensation occurs when several precisely timed pulses are delivered in rapid succession, first to one stimulator site, then to a second located a short distance away from the first. The resultant sensations are felt at discrete and evenly spaced locations between the two activated stimulators. This is known as the "saltation" or "cutaneous rabbit" phantom illusion [7] (see Figure 1).

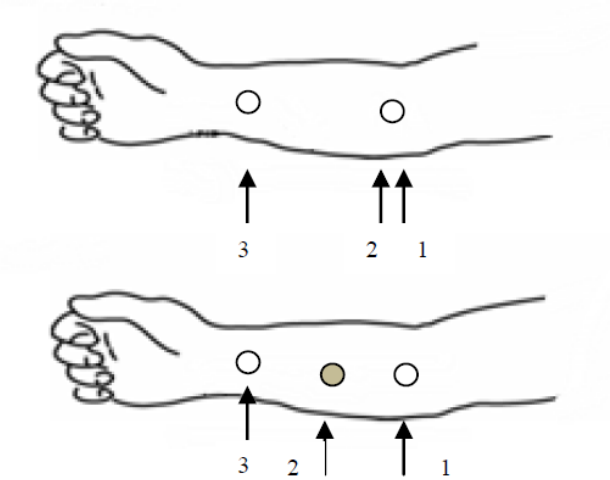

Fig. 1. An example of a tactile sensory illusion – the "cutaneous rabbit" or saltation. Two stimulation sites are shown in this example. Three vibrotactile pulses (numbered arrows) are sequentially applied (top) to the stimulation sites. The resultant perceived sensation (lower) is a "row" of spatially separated events (numbered arrows) at sites that depend on temporal timing. This particular example is known as the "reduced" rabbit illusion (only two stimulation sites). However, the illusion can also be created using additional adjacent stimulation sites in an "extended" rabbit [8].

Functional magnetic resonance imaging (fMRI) studies [9] have shown that the saltatory effect is neuroprocessed in the primary somatosensory area (SI), corresponding somatotopically to the illusory stimulus location. Thus illusions are processed in an almost identical manner to their veridical equivalents.

In another series of experiments [10], actuators were located on different sides of the body and although these studies showed that the rabbit failed to jump across arms, a stimulus presented on one body-half can be attracted by a subsequent stimulus presented on the other body-half and thus produce the illusion of saltation. This result suggests that saltation may be generated in higher order somatosensory areas. Although saltation is still observable across the midline, the neurological basis for processing the illusion in this instance may, in fact, be different to the processing required for an illusion administered to a single side of the body.

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Saltation occurs within relatively narrow temporal and spatial parameters. Deviation from these leads to a complete breakdown in the illusion – a relatively "bright line" threshold. The inducing stimuli are either localized at the generating sites, or appear to be distributed between the sites. This effect is a function of both the physical separation between the two sites, as well as the temporal separations among the events. Consequently, we have proposed that manipulating both spatial and temporal parameters might reveal subtle differences between normal and mTBI participants with a relatively simple task.

We chose the forehead as our site of stimulation for several reasons. First, Granacher [11] discusses data from Yadav & Khosla [12] showing that trigeminal nerve (cranial nerve V) lesions occur in some 3.6% of head injured patients (pg 127). This is typically owing to facial fractures (and less often basilar skull fractures) that injure some or all branches of the trigeminal nerve. Second, the forehead, innervated by the trigeminal, provides a study area that allows us to study both lateralized as well as stimuli that cross the body midline, potentially useful for exploring unilateral as well as bilateral damage in mTBI. Finally, Geldard [7] has shown that the tactile illusion that we intend to study shows interesting dissociations when presented to the forehead, requiring that a tactor be placed on the midline or else only other illusory tactile motion phenomena (i.e., phi motion) would be observed.

Once the spatial conditions for phantoms / sensory illusions have been established, their perceived locations can be primarily controlled by varying the timing between stimuli – i.e. the illusions are presented on a fixed linear array of vibrotactile actuators and the effect can be controlled using only temporal variables. This eliminates the need for physically moving any actuators during an acuity test, simplifying the test conditions and avoiding confounding variables. Our approach implements a multi-point tactile discrimination test using a fixed array of vibrotactile actuators. Complex tactile stimuli, including somatosensory illusions, are presented and compared by subjects.

II. METHODS

A. Subjects/apparatus/experimental setup

A linear vibrotactile array, comprising 7 EAI C-3 tactors [13] with a 22 mm center to center spacing was mounted on the forehead of subjects with an adjustable strap. The 4th tactor in the array was aligned with the subject's mid-line as shown in Fig. 2. Tactors were driven under software control with a series of tone-bursts (10-20 ms in duration) of 250 Hz sinusoidal vibration. Headphones together with a masking track (≈ 85 dBA pink noise and time random samples of tactor auditory signals) were presented to the subject to mask audio cues during test trials.

Nineteen control and 8 newly concussed individuals, male and female, were recruited from 1) athletic teams of Florida Institute of Technology; 2) Florida Tech students who presented to the Holzer Health Center of Florida Tech with mTBI; and 3) individuals newly presenting with mTBI to community physicians who have allowed recruiting of their patients. Participant ages ranged from 18-33. Newly concussed participants were tested with the same protocol as the control subjects within 72 hours of their injury (average ≈ 48 hours after injury).

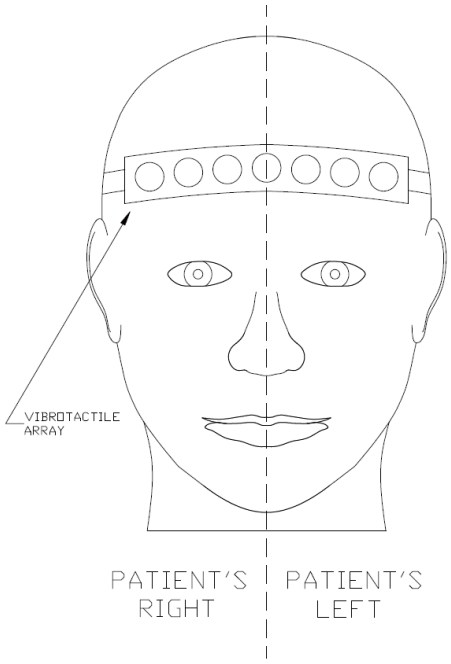

Fig. 2. Forehead mounted, seven vibrotactile array showing mounting, left and right orientations and the location of the 4th tactor in the array positioned on the body mid-line.

B. Test Protocol

Our test protocol comprised of three test blocks that were administered consecutively (see Table 1). Each test block contains trials that used a "same" / "different" forced-choice comparison between two vibrotactile presentations. The order of the trial presentations was randomized in each test block. Each presentation was paired together with itself and all of the other possible presentations, and the number of trials in a block were arranged such that 50% of the trials were perceptually the "same" and 50% "different".

Patterns were separated by a short delay between presentations (1200 ms). Subjects compared the two presentations and had to identify which pairs of presentations were perceptually the same and which were different. Subjects made their selections on a touch screen, and, when ready, chose the next presentation (or test block remaining).

The presentations could be veridical (V) – real, or saltatory (S) – phantom, and had various temporal and spatial parameters. It is known that a wide range of spatial and temporal variables can create the saltatory effect in healthy subjects. Therefore, by varying the temporal and spatial intervals, we were able to explore the robustness of the saltatory effect, and all presentations could be made on the same fixed linear array of vibrotactile actuators.

TABLE 1
PHASE I PROTOCOL TEST BLOCKS

Test Block	Description	Trials
1	Extended Rabbit over Midline	64
2	Reduced Rabbit LEFT	40
3	Reduced Rabbit RIGHT	40

Test Blocks 2 and 3 comprised the same number of trial presentations. These tests utilized the reduced rabbit (saltatory) presentation and were restricted to two tactors on only one side of the array for each particular block. Four inter-burst intervals (IBIs) were chosen for the first two test blocks; 40, 60, 80, 120 and 160 ms. For healthy subjects, this range of IBI is known to produce the saltatory effect. Trials contained only saltatory – saltatory (S-S) presentations. Each presentation was preceded by a pre-pulse 700 ms before the sequence. The pre-pulse has been used by others [14] as an attention focusing or "preparatory" cue for the reduced rabbit which occurs rather rapidly.

Test Block 1 utilized between three and five tactors in the complete vibrotactile array. Both veridical (V) and extended rabbit (S) presentations could be presented. Thus, trials were either saltatory - saltatory (S-S), saltatory – veridical (S-V) or veridical – veridical (V-V). The pulses were separated by an inter-burst interval (IBI); 20, 40, and 80 ms. Care was taken to make the presentations symmetrical with the tactor on the mid-line as the saltatory effect is known to only cross the mid-line if an "intermediate" actuator location is used.

III. Results

The percentage of trials with a correct response as well as time taken to complete the test were compared between the control and concussed subjects. Total percent correct and time to completion as well as percent correct across the three blocks and time taken to complete the blocks were analyzed and are summarized in Figures 3 and 4 respectively.

Independent samples *t*-tests were used to compare the total percent correct and completion times, while one-way MANOVAs were used to compare the percent correct and completion times of the three blocks of trials. Since Levene's test revealed that the variances of the two groups were not equally distributed, the more conservative *t* comparison was employed.

TABLE 2
t-TEST COMPARISONS OF TOTAL PERCENT CORRECT AND COMPLETION TIME.

Comparison	Group	Mean	df	*t*	*P*
Percent Correct	Normal	72.2	25	2.971	.01
	Concussion	59.9			
Completion Time	Normal	15.6	25	2.266	.05
	Concussion	18.4			

As shown in Table 2, both total percent correct as well as completion time differed significantly between groups. The concussion group made more errors and took longer to complete the full test.

For the comparison of normal and concussed subjects across the three blocks of trials, Box's Test of Equality of Covariance was not significant. This indicates that even with the unequal group sizes in the present study, there was no appreciable difference in the covariance of dependant measures across groups. This finding imparts greater confidence in the MANOVA outcomes. We used Pillai's Trace as the multivariate test of significance due to the small sample size. Alpha was set at .05.

TABLE 3
MANOVA INFORMATION FOR COMPARISON OF PERCENT CORRECT AND COMPLETION TIME FOR THE THREE BLOCKS OF TRIALS.

Variable	Pillai's Trace Value	*F*	df	*p*	Partial Eta Squared	Observed Power
Percent Correct	.361	4.333	3, 23	.015	.361	.802
Completion Time	.578	8.216	3, 18	.001	.578	.973

As shown in Table 3, both total percent correct and completion time for the three blocks of trials differed significantly between the normal and concussed groups. Univariate analyses showed that percent correct and completion times differed between groups for Blocks 1 and 2, but not for Block 3. Block 2 and 3 standard deviation was higher than for Block1.

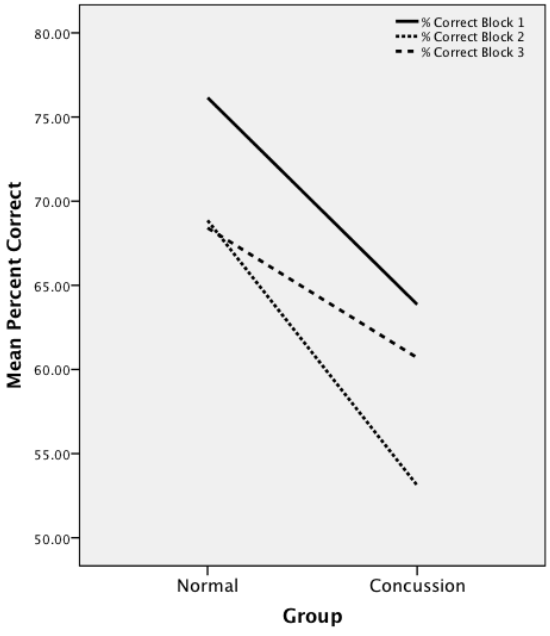

Fig. 3. Percent correct discriminations in each of the three blocks of trials.

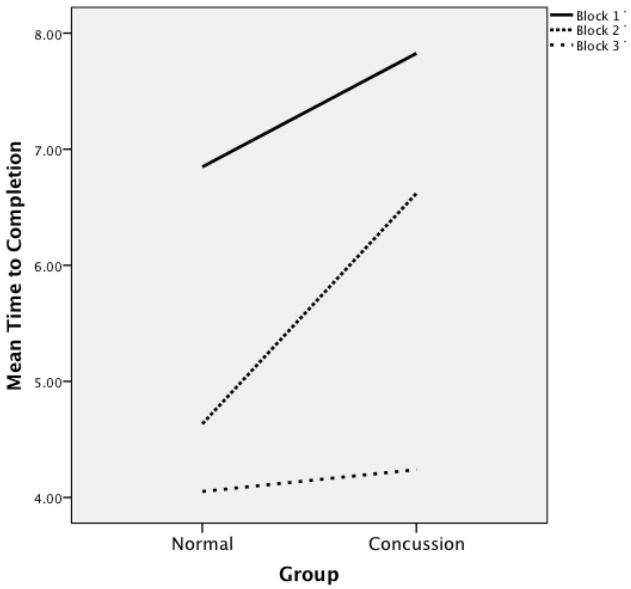

Fig. 4. Average completion times for each of the three blocks of trials.

IV. DISCUSSION

Because this area of the face is primarily innervated by the trigeminal nerve (CN V), at one level our testing should provide a quantitative metric of the functional state of the nerve and its projections. However, the same / different testing paradigm and the perception of saltatory illusions involve more distributed neuroprocessing when undertaking the task. Therefore our approach appears to reflect a rather broad assessment of functional neural processing.

Pilot clinical results show that our test was able to find significant differences between the healthy and concussed groups. Results showed that for healthy subjects, the data was consistent across each side (left/right) tested, age and sex. Concussed subjects typically took longer to complete the tests than the healthy normal group. There were significant differences between the test blocks, with Block 1 (extended rabbit) appearing to be a more sensitive measure for concussion.

The Normal group differed in total percent correct from the Concussion group. The effect sizes for the comparisons were small to moderate, as approximated by the partial eta squared statistic and the observed power, a measure that allows confidence in the conclusion about the comparisons was adequate.

Further examination of the subject responses to the various presentations revealed that the trial difficulty is correlated with the time duration difference between trial presentations i.e. the closer two pattern presentations are spatially and temporally (ISI) the more difficult the trial.

V. CONCLUSION

Objective and early screening of mTBI subjects would be of significant benefit for the military and civilian (particularly athletic) populations. We have presented initial data demonstrating the effectiveness of a vibrotactile assessment protocol in discriminating between recently concussed and healthy normal groups that could be readily implemented into a portable, fieldable testing device with modifications of existing technology.

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