Tactile Proprioceptive Input in Robotic Rehabilitation After Stroke

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***Abstract*— Stroke can lead to loss or impairment of somatosensory sensation (i.e. proprioception), that reduces functional control of limb movements. Here we examine the possibility of providing artificial feedback to make up for lost sensory information following stroke. However, it is not clear whether this kind of sensory substitution is even possible due to stroke-related loss of central processing pathways that subserve somatosensation. In this paper we address this issue in a small cohort of stroke survivors using a tracking task that emulates many activities of daily living. Artificial proprioceptive information was provided to the subjects in the form of vibrotactile cues. The goal was to assist participants in guiding their arm towards a moving target on the screen. Our experiment indicates reliable tracking accuracy under the effect of vibrotactile proprioceptive feedback, even in subjects with impaired natural proprioception. This result is promising and can create new directions in rehabilitation robotics with augmented somatosensory feedback.**

I. INTRODUCTION

A. Motivation and Background

Each year nearly 800,000 new or recurrent stroke incidents occur in the United States [1]. Approximately 50% of stroke survivors experience tactile and proprioceptive impairments that negatively impact functional movements and rehabilitation outcomes [2]. Proprioception is the ability to sense the position and orientation of our limbs and body in space; proprioceptive feedback is essential for planning and controlling limb postures and movements needed for successful accomplishment of most common motor tasks ([3], [4]), from tying one's shoes to carrying a spoonful of soup to the mouth. Lack of effective proprioception is seen as one of the main factors limiting recovery of the motor skills most important to independent daily living. Nevertheless, the primary emphasis of most current research and clinical efforts on rehabilitation robotics is directed toward motor retraining ([5], [6], [7]) with only limited focus on manipulating sensory feedback for enhancing motor performance.

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The idea of promoting recovery of motor skill by combining robotics and sensory substitution ([8], [9]), thus mitigating sensory loss, may be a viable alternative to conventional rehabilitation approaches. Auditory, haptic and vibrotactile interfaces have been proposed as potential supplements to visual feedback. While motor learning however is highly driven by error making ([10]), it is not clear whether haptic interventions that constrain responses to predefined references ([11]) lead to actual learning or adaptation to the workspace of the experiment ([12], [13]). Additionally, several comparison studies have shown that neurologically-intact people provided with tactile feedback can perform better than those acting on similar forms of auditory feedback; there are also cases in which tactile feedback is at least equally effective as vision, if not more so ([14], [15]). Other studies exploring the use of tactile feedback to promote motor learning in healthy participants include balancing tasks [16], simple motion replication [17] and wearable suits [18]. The conclusion to be drawn from that previous work is that tactile feedback can indeed be effective in promoting desired motor behaviors. However it is not clear whether sensory substitution using tactile feedback is even possible in stroke survivors due to stroke-related loss of the central processing pathways that normally subserve somatosensation.

B. Objective

The purpose of this pilot study was to assess the utility of tactile proprioceptive feedback in a small cohort of hemiparetic, unilateral middle cerebral artery stroke survivors (MSS) having impaired or absent somatosensation in their moving, hemiparetic arm, but intact proprioception in their non-moving, ipsilesional arm. For this kind of sensory substitution, tactile feedback was preferred over visual feedback due to its closer resemblance to natural proprioception; for instance, healthy individuals know how their limbs are positioned in space without having to look at them. To examine the efficiency of tactile-driven limb guidance we selected a tracking task since it should be immediately obvious whether or not the synthetic feedback provides any benefit to the user. In contrast to other limb guidance approaches that constrain motion (e.g. haptic interfaces), participants were entirely free to decide how to utilize the feedback that was provided to them. The Robot Operating System (ROS) was used to handle the integration of the hardware and software parts of the experiment.

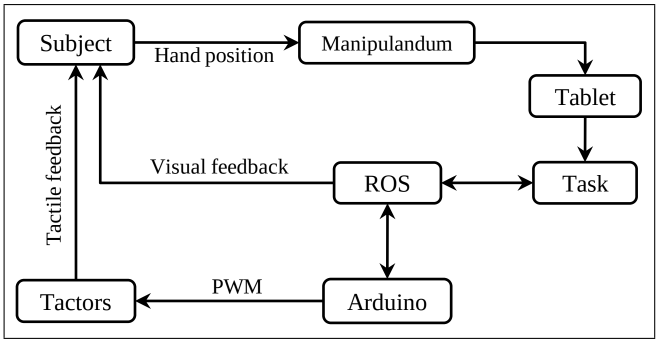

Fig. 1. System overview. Arrows indicate flow of information.

II. Materials and Methods

A. Experimental Setup

Fig. 1 shows a block diagram of the experimental setup. Our goal was to examine whether tactile-driven limb guidance can be successfully achieved in cases of impaired proprioception. Subjects were provided with synthetic feedback (in the tactile case it was applied to the non-moving hand via vibrotactile stimulators) and performed a target tracking task using a single-degree-of-freedom manipulandum. The goal of the task was to move the handle of the manipulandum so that the position of a red, on-screen cursor overlaid a moving, black, screen target. A pen tablet system was used to map the position of the hand/handle onto the position of the red cursor on the display screen. Cursor and target motion were constrained to move in the horizontal direction on the screen. The major components of the testing platform include:

1) Robot Operating System: ROS [19] is a distributed framework of processes (called nodes) that communicate via message passing. It offers all the standard services of a typical operating system and handles the integration of all hardware and software parts of the experiment.

2) Tactors/Arduino: The tactile stimulus was provided by Eccentric Rotating Mass (ERM) vibrating motors ("tactors") typical of those found in cellphones. Their compact size (5mm radius), low weight (1.2g) and high output to power ratio are ideal for our setup. The tactors were controlled by an Arduino microcontroller board (through ROS) using PWM signals (0 to 100%). Depending on the operating pulse width, the range of the vibration frequency and amplitude were $0-200$Hz and $0-0.8G$ respectively ($G \approx 9.8m/s^2$).

3) Manipulandum/Tablet: The position of the on-screen controllable block was determined by a one-degree-of-freedom, passive manipulandum and a tablet/pen setup (Intuos4 Extra Large Professional Pen Tablet by Wacom). The pen was attached at the tip of the manipulandum, which was in turn placed on top of the tablet. Changes in the x-coordinate of the tip/pen were translated into horizontal-axis motions of the block. The range of motion, and thus block positions, was approximately $0-30$ cm along the x-axis.

B. Clinical Evaluations

In order to quantify somatosensory and motor deficits, all MSS participants taking part in this experiment also participated in a clinical evaluation session. The assessments relevant to this pilot study include:

1) Upper extremity motor portion of the Fugl-Meyer Assessment (FMA) of Physical Performance: This portion of the FMA evaluates motor impairment of the arm. A maximal score of 66 indicates that the subject retains normal reflexes, can move outside of motor synergies, and has a variety of intact grasps.

2) Upper extremity sensation portion of the FMA: This evaluation played a key role in our objective, since in order to test the efficacy of artificial proprioceptive information, participants with both impaired and intact proprioception were necessary. Two things are assessed here; the first one is the sensitivity of the arm and hand to light touch, with a maximal score of 4 indicating intact light touch sensation and a score of 0 indicating its absence.

The second and most relevant assessment involves proprioception at the shoulder, elbow, wrist and thumb. This procedure is a version of the "up/down" test [20]; the tested joint is passively moved back and forth in a plane of movement and when the movement stops, the subject is asked to indicate segment orientation, i.e. up or down. Six repetitions are performed at each joint. If all responses are correct, that joint is given a numerical score of 2 and proprioception is rated "intact"; if one response is wrong, proprioception is rated as "impaired" and the joint is given a score of 1; finally if there are two or more wrong responses, proprioception is rated "absent" and the joint is given a score of 0, implying that the subject cannot reliably determine the joint orientation. A maximal score for intact proprioception at all joints tested is 8.

3) Montreal Cognitive Assessment (MoCA): This test is used to evaluate cognitive condition in terms of conceptual thinking, mental calculations, attention and concentration, memory, language, orientation etc. A score of 26 or greater out of a maximal score of 30 on the MoCA indicates normal cognitive function.

C. Subjects

Three hemiparetic survivors of unilateral, middle cerebral artery stroke gave written, informed consent to participate in this study in compliance with policies established by the Marquette University Institutional Review Board. All MSS were in the chronic stage of recovery (>6 months post-stroke). The individual details of the MSS participants are shown in Table I. In addition, four, right-handed, neurologically intact (NI) subjects, all of them graduate students, served as the control group after providing written consent which was approved by Northwestern University's Institutional Review Board. NI control subjects participated in a session that lasted approximately 20-25 minutes. The corresponding session for MSS subjects was about 3 hours long, mostly a result of frequent breaks.

The rationale for including a NI control group, as well as trials with multiple combinations of sensory feedback was to establish performance relationships between the different sensory conditions tested. Our goal was to test whether the

TABLE I
ASSESSMENT SCORES FOR MSS PARTICIPANTS

ID	Age	Gender	Affected Arm	Time Since Stroke	FMA_M	$FMA_{prop.}$	FMA_{LT}	MoCA
1	61	Male	Right	>15 years	27	1_S, 1_E, 0_W, 0_T	2	10*
2	65	Female	Left	>15 years	30	2_S, 2_E, 2_W, 2_T	4	26
3	64	Female	Right	>15 years	45	2_S, 1_E, 1_W, 0_T	1	14*

Abbreviations. ID: Subject identifier; FMA_M: upper extremity motor portion of the Fugl-Meyer Assessment of Physical Performance; $FMA_{prop.}$: "up or down?" test from the upper extremity sensory portion of the FMA; S, E, W, T: Shoulder, Elbow, Wrist, Thumb; FMA_{LT}: light touch test from upper extremity sensory portion of the FMA; MoCA: Montreal Cognitive Assessment Test.
* Subjects with expressive aphasia.

same relationships hold for the MSS group, which would imply that tactile stimuli are integrated similarly in both groups, and also to compare the results of the two groups in each condition separately. Finally, from Table I, we can see that all three members of the MSS have relatively good motor function (FMA_M). Nevertheless, unlike subject 2, subjects 1 and 3 have impaired proprioception and also suffer from expressive aphasia ($FMA_{prop.}$ and MoCA respectively). Hence, within-group comparisons should provide some insight on whether or not artificial proprioception can confer any benefit to performance.

D. Protocol

The experimental setup is shown in Fig. 2. In a typical session, subjects sat in a high-backed chair and grasped the handle of a horizontal planar manipulandum using their dominant hand (NI group) or their involved hand (MSS group). The position of the hand/handle along the horizontal axis was mapped to a red block/cursor on the screen, and the goal of the task was to match the red block to a moving black block. The position of the black block was sampled using a uniform distribution from the allowable range of motion ($0-30$ cm along the horizontal axis), and it changed every 5 seconds. The arm performing the task was minimally supported during the sessions, so efficient tracking required a collaborative effort of the shoulder, elbow and wrist.

We tested three different sensory feedback conditions, i.e. visual feedback only, tactile feedback only, and combined visual plus tactile feedback, in a counterbalanced fashion. In the last two cases, participants received tactile feedback by two small tactors (Fig. 2) attached to the thumb and fifth finger of the non-tracking hand. The tactile stimulus provided non-collocated cues about the position of the black block by encoding two types of information; direction (whether the black block was to the left or right of the target determined which tactor was activated) and error (the magnitude of positioning error determined the strength of vibration). Stronger vibration indicated larger error. To acquire experience with the artificial feedback, i.e. what the amplitude of vibration means and how they should use it, participants practiced the corresponding parts of the experiment for 5 to 10 minutes before the data collection.

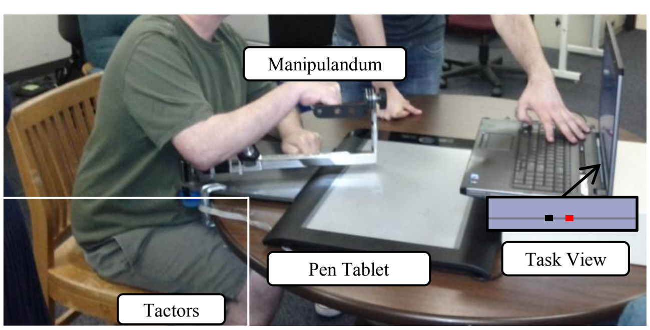

Fig. 2. Experimental setup with a participant seated in front of the computer. The subject holds a cylindrical handle mounted at the end of the manipulandum.

Finally, inability to sense the position and orientation of the arm can be naturally mitigated by simply looking directly at the arm; in this experiment, this translates into simultaneously incorporating visual cues from the screen and visual feedback of the arm while disregarding tactile cues from the tactors. To avoid this scenario, during the two critical sessions which involved impaired proprioception (MSS subjects 1 and 3) we used an adjustable opaque screen to block view of the hand and arm. As a result, we ensured that those participants would only rely on tactile and visual cues (the latter presented on the video display) to complete the task. Each participant in the NI group performed a single one-minute trial in each of the three feedback conditions whereas each of the MSS subjects participated in three one-minute trials in each condition. As mentioned above, the sessions of the NI and the MSS group lasted about 20-25 minutes and no more than 3 hours respectively.

E. Metrics and Data Analysis

We evaluated performance based on the goodness of fit, i.e. how good was the fit between the actual hand trajectory -determined by the position of the red block - and the target trajectory - determined by the position of the black block. For this reason we selected both an absolute metric, i.e. the Mean Absolute Deviation (MAD), and a relative metric, i.e. the coefficient of correlation, r, between the target and the actual hand trajectory. We selected two performance metrics because, absolute metrics like MAD are sensitive to the time horizon and also, in this case, to the total distance traveled by the hand. This is due to the discrete nature of the task and the fact that the location of the black block was randomly sampled from a uniform distribution. One way to deal with the sensitivity in the trajectory itself would

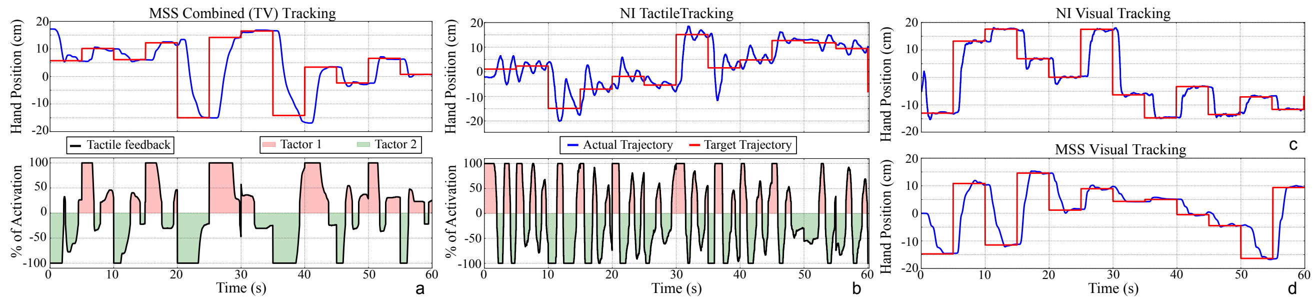

Fig. 3. Sample responses for the three tested feedback conditions. a) MSS combined tracking, b) NI tactile tracking, c) NI visual tracking, d) MSS visual tracking. There are two interesting observations here: 1) the underdamped hand response in the tactile tracking case which is shown in b top (and is also present with lower frequency in the MSS trial in Fig. 4) and 2) the slower responses observed by the MSS group (e.g. c vs d or b vs Fig. 4-bottom).

be to generate the same sequence of block positions every time. This could have an impact on the performance though, through memorizing/predicting the position pattern. As an alternative, in addition to all trials being one-minute long, the actual and the target hand trajectory in each trial were scaled such that the total distance traveled by the black target was the same in all trials (approximately 160 cm). Thus,

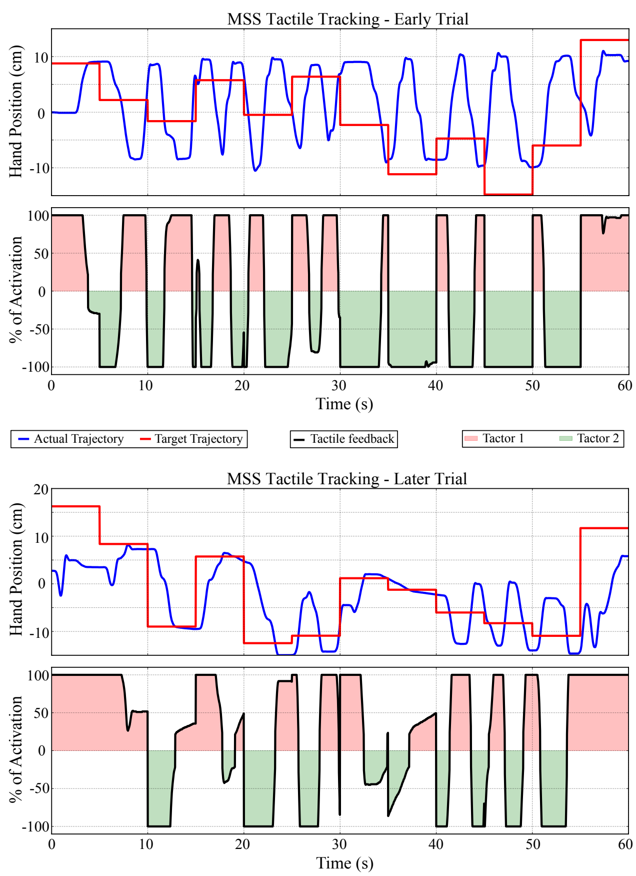

Fig. 4. MSS tactile tacking at an early stage (top) and a later stage (bottom). The responses suggest that this participant successfully integrated the artificial proprioceptive feedback into her course of action, despite post-stroke impairment of natural proprioception. Similar learning effect was observed in the other two MSS participants as well; this is promising preliminary evidence that supports our initial hypothesis, i.e. that tactile feedback can successfully substitute natural proprioception.

comparisons between different trials were possible.

Moreover, before calculating the MAD and r in each trial, we used the cross-correlation of the target and cursor positions, to calculate the optimal lag between the two, i.e. the time when the correlation takes its maximum value. Then we calculated the MAD and r using the shifted curves. Without this step, the values of r would be very low, leading to the misleading idea of inadequate performance. Also, since this is a simple linear regression case, the time lag is of no importance here; we are only concerned with accuracy.

III. Results

A. Sample Responses

Fig. 3 and Fig. 4 show a number of sample responses from the two groups in the three tested feedback conditions. These plots allow for some important observations. Specifically, looking at Fig. 3b and Fig. 4 bottom, it is clear that the MSS responses are slower than the NI ones. The same is true for Fig. 3c and Fig. 3d. This lag is most likely a consequence of post-stroke motor and sensory deficits. As explained above, in our analysis we were only concerned with accuracy of tracking, so we used the cross-correlation and the corresponding optimal lag to account for this discrepancy.

A second point that becomes apparent by looking at Fig. 3b and Fig. 4 is the underdamped hand response in the pure tactile tracking cases. Naturally, due to lack of complete and fine control of the arm, the frequency of any underdamped oscillatory behavior observed in the MSS responses is lower. It is possible that this behavior is the result of an incomplete mapping between the available tactile information and the corresponding actions. After all, the participants were asked to utilize their sense of touch in an entirely unconventional way. We would anticipate that with additional training, this behavior will gradually attenuate. Still, even with limited amount of exposure to this condition, tracking accuracy was satisfying.

Finally, Fig. 4 illustrates the response of subject 3 from the MSS group in the tactile tracking case. The top part shows one of the very first attempts to complete the task and the bottom part shows the improvement after mere minutes of training. Given that this participant has impaired natural proprioception (see Table I), *the amount of improvement* *shown is promising preliminary evidence that supports the proposed sensory substitution, i.e. that tactile feedback can successfully substitute natural proprioception.*

B. Statistical Results

We sought to determine whether the application of movement-related vibrotactile feedback to a non-moving limb can be an effective form of sensory substitution following stroke, even in subjects who have suffered stroke-related loss of central processing pathways subserving somatosensation. To do so, we first compared the MSS correlation values in the tactor-only condition against the average "spurious" correlations obtained by cross-correlating the tactor-condition cursor motions against the target motions from the other two feedback conditions (vision-only and combined). This test was used to demonstrate that the MSS correlations in the tactor-only condition were significantly greater than zero, and is presented in section III-B.1. We then performed a pair of two-way (2×3) mixed-design ANOVAs, one for each of the two dependent variables (r and MAD) to compare the effects of feedback condition on accuracy of tracking. The independent variables were the group (between-subjects variable with two levels, i.e. NI or MSS), and the feedback condition (within-subjects variable with three levels: visual, tactile and combined tracking). These tests are provided in sections III-B.2 and III-B.3. Finally, we compared the performance (r and MAD) of the three MSS participants in the two cases involving tactile feedback, i.e. tactile and combined tracking (see section III-B.4). As mentioned before, one of the MSS had intact proprioception, whereas the other two did not. A finding of similar performances in all three MSS participants would strengthen our initial hypothesis, i.e. that the provided tactile information can actually be used for limb guidance, even in cases of impaired proprioception.

1) Non-collocalized tactor feedback can drive somatosensory control of the hemiparetic arm post-stroke - r from the MSS group was significantly greater than zero: Importantly, a one-sample t-test found that the mean value of r from the MSS group in tactile tracking (*mean* = 0.744, *SD* = 0.06) was significantly greater than the spurious correlations (*mean* = 0.05, *SD* = 0.04), and thus significantly greater than "zero" ($t(8) = 34.77$, $p < 0.0005$). This preliminary finding strongly suggests that stroke survivors were able to use the synthetic proprioceptive feedback applied to the non-moving ipsilesional arm to regain somatosensory control of their hemiparetic arm.

2) ANOVA results for r - Significant differences between all factor levels: Brief training with the synthetic proprioceptive feedback did not yield tactor-only performances on par with visual feedback in either group of participants. Analysis of the correlation coefficients across groups and feedback conditions showed that r is significantly affected by both feedback condition ($F(2, 10) = 203.81$, $p < 0.0005$) and the group factor ($F(1, 5) = 18888.58$, $p < 0.0005$). There was also a significant interaction between the group and the feedback condition, ($F(2, 10) = 74.78$, $p < 0.0005$). Due to the interaction effect we chose to analyze the simple main effects of the two independent variables.

Feedback simple main effects on r - Relationship between T, V and TV tracking was similar in both groups: First we examined the feedback simple main effects, i.e. the performance differences between the three feedback conditions for each of the two groups separately. To control for Type I error across the two simple main effects, we set the alpha level for each at 0.025 (0.05/2). For the NI group, feedback condition had a significant effect on r, $F(2, 6) = 53.79$, $p < 0.0005$. Post hoc pairwise comparisons using the Bonferroni correction revealed significant differences between tactile tracking (*mean* = 0.938, *SD* = 0.01), $p < 0.025$, and visual tracking (*mean* = 0.982, *SD* = 0.004) and also between tactile and combined tracking (*mean* = 0.986, *SD* = 0.005), $p < 0.025$. However, there was no significant difference between visual tracking and combined tracking, $p = 1$. The same procedure determined that feedback type had a significant effect on r for the MSS group as well ($F(2, 4) = 116.06$, $p < 0.0005$). The performance patterns observed above for the NI group were confirmed in the MSS group. More specifically, from pairwise comparisons we found that the correlation coefficient in tactile tracking (*mean* = 0.744, *SD* = 0.05) was lower than visual tracking (*mean* = 0.934, *SD* = 0.02, $p < 0.005$) and combined tracking (*mean* = 0.928, *SD* = 0.01, $p < 0.005$). Also, as analyzed above, r was statistically the same for the last two, $p = 0.759$. Thus, additional research is needed to optimize the form of vibrotactile feedback in order to bring its efficacy up to the level of visual feedback.

Group simple main effects on r - NI group performs better (naturally), but tracking is accurate in both groups: We next examined the group simple main effects, i.e. the performance differences between the NI and the MSS group for each one of the three feedback conditions we tested. To control for Type I error across the two simple main effects, we set the alpha level for each at 0.0125 (0.05/3). As one would expect, due to subject-specific deficits of motor and sensory function, the MSS group performed worse than the NI group and the p-values were found significant at the 0.0125 level for all three comparisons, i.e. tactile, visual an combined tracking. Even so, the correlation coefficients were reasonably high in all cases, implying a good relative fit between the model trajectory and the actual one.

3) ANOVA results for MAD - Significant differences between all factor levels: We repeated the sequence of tests for the MAD. Ideally we would expect those results to match the patterns reported above. The two-way ANOVA indicated a significant effect of both the group factor ($F(1, 5) = 285.17$, $p < 0.0005$) and the feedback condition ($F(1.032, 10) = 112.98$, $p < 0.0005$) on the MAD. There was also a significant interaction between the two factors ($F(1.032, 10) = 12.23$, $p = 0.016$). For this reason we proceeded with analyzing the corresponding simple main affects.

Feedback simple main effects on MAD - Similar to the r case, relationship between T, V and TV tracking was similar in both groups: As before, we first examined the feedback simple main effects at the 0.025 alpha level. For the NI group, feedback condition had a significant effect on the MAD, $F(2,6) = 20.38$, $p = 0.002$. Post hoc pairwise comparisons using the Bonferroni correction revealed significant differences between tactile tracking (*mean* = 2.96, *SD* = 0.9), $p < 0.025$, and visual tracking (*mean* = 0.95, *SD* = 0.06) and also between tactile and combined tracking (*mean* = 0.99, *SD* = 0.2), $p < 0.025$. However, there was no significant difference between visual tracking and combined tracking, $p = 1$. Feedback type also had a significant effect on the MAD for the MSS group ($F(1,2) = 277.57$, $p < 0.005$). Corresponding pairwise comparisons suggest that in tactile tracking (*mean* = 5.99, *SD* = 0.6), the MAD was higher than in visual tracking (*mean* = 1.97, *SD* = 0.42, $p < 0.025$) and in combined tracking (*mean* = 2.19, *SD* = 0.43, $p < 0.025$). Also, similar to the NI group, the MAD was statistically the same for the last two, $p = 0.12$.

Group simple main effects on MAD - Similar to the r case, NI group performs better (naturally), but tracking is accurate in both groups: For the group simple main effects, the alpha level was set at 0.0125. The comparison between the two groups resulted in $p < 0.005$ for all three feedback conditions, indicating that the NI group, naturally, performed better. Still, the MADs were reasonably low in all examined cases, suggesting a good absolute fit between the target and the actual responses.

4) Comparison between MSS participants only - Similar performance for both r and MAD: We compared r across the three MSS participants in the two conditions that required tactile feedback (tactile and combined tracking). A series of one-way ANOVAs showed no significant differences in r in tactile ($F(2,6) = 2.45$, $p = 0.167$) and combined tracking ($F(2,6) = 0.63$, $p = 0.564$). The final step was a similar comparison for the MAD. Again, a series of one-way ANOVAs indicated no significant differences in the MAD of tactile ($F(2,6) = 0.291$, $p = 0.757$) and combined tracking ($F(2,6) = 1.947$, $p = 0.223$). Thus, despite the different levels of proprioception impairment, all three MSS participants had similar and reasonably good performance.

The results are summarized in Fig. 5. The bar graphs confirm that comparisons for both metrics converge to the same outcomes in terms of the goodness of fit and that the MSS correlations are significantly greater than zero.

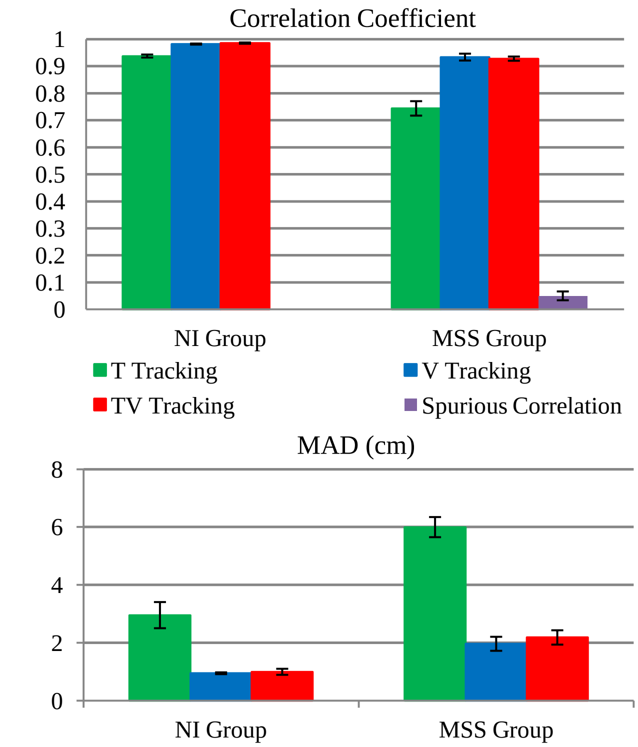

Fig. 5. Summary of results; error bars indicate standard error. T:tactile; V:visual; TV: combined tactile and visual. The NI group performs better as expected. The purpose of multiple sensory feedback conditions was to ensure that NI and MSS followed the same performance patterns, as illustrated above. Visual tracking was better than tactile tracking, possibly due to higher channel bandwidth. Unlike touch however, vision is not a "natural" substitute of compromised proprioception, since natural proprioception does not require visual attention. Nevertheless, tactile tracking was reasonably good, with low MAD and significantly greater r than the spurious correlation. Also, tactile feedback did not appear to degrade visual tracking in the combined tracking condition. Similarity of visual and combined tracking could be due to a minimum energy approach employed by the brain.

IV. Discussion

In this study we used a vibrotactile feedback system to test the utility of synthetic proprioceptive feedback to facilitate post-stroke limb guidance in a tracking task that emulates many activities of daily living. In summary, our preliminary results suggest that *brief training with synthetic proprioceptive feedback applied to the non-moving ipsilesional arm was effective in restoring some level of somatosensory control of the hemiparetic arm in stroke survivors with compromised proprioceptive and tactile sensation.*

The stroke survivors were diverse in their sensory and motor impairments (Table I). Importantly, the absence of proprioception and light touch did not preclude the use of tactile feedback to drive tracking behavior when that feedback was applied to the non-moving arm. Because the two subjects with impaired proprioception, impaired light touch and poor MOCA scores were able to use the tactile feedback to perform the tracking task without visual feedback, the utility of synthesized proprioceptive feedback does not seem to be limited to individuals with intact central pathways serving proprioception, or to individuals who have no more than minimal cognitive deficits.

While these preliminary findings are very encouraging, the level of performance we observed with the vibrotactile feedback in both subject groups did not rise to the level observed when subjects had ongoing visual feedback of the task. Additional training and exposure to synthetic feedback may be one way to encourage better tactor-guided performance both for the MSS and for the NI groups; other ways to optimize performance of this technology are likely possible. It must be noted that while visual tracking was better, vision is *not* a "natural" substitute of compromised proprioception, due to the fact that natural proprioception does not require visual attention. Moreover, the performance of the two MSS participants with impaired proprioception was similar to the third MSS participant, even when the tracking arm was occluded from view. Good group means in pure tactile tracking (r = 0.744, MAD = 5.99cm), implied a good relative fit between the target and arm trajectories. On top of that, Fig. 4 clearly implies the rapid integration of externally provided tactile information into ongoing motor commands for controlling the hemiparetic arm.

While beyond the scope of this paper, when comparing visual and combined tracking, one can notice that the addition of tactile feedback does not seem to have any effect on performance. It is possible that performance with vision alone may have already reached a plateau and as a result there is little or no room for improvement. This phenomenon could be explained by earlier studies reporting an interesting progression of information capacities of $10^2 : 10^4 : 10^6$ b/s for the fingertip, ear and eye respectively [21]. Thus, since both tactile and visual cues in this study essentially represent position error, the brain may be exploiting this information redundancy, ignoring the slower, less detailed tactile cues to produce the minimum energy response.

V. Conclusions and Future Work

The primary emphasis of current research and clinical efforts on rehabilitation robotics is directed toward motor retraining with only limited focus on manipulating sensory feedback for enhancing motor performance. The idea of promoting recovery of motor skill by combining robotics and sensory substitution may be a viable alternative to conventional rehabilitation techniques.

In this preliminary study, we showed that a vibrotactile sensory substitution approach can be effectively applied even in cases where limb proprioception is compromised. Tactile feedback was preferred over visual feedback due to its closer resemblance to natural proprioception, i.e. healthy individuals know how their limbs are positioned in space at any time *without using their eyes*. While promising, our findings in both groups suggest that performance under vibrotactile feedback did not rise to the level observed when subjects had ongoing visual feedback of the task. Future studies should determine the frequency, duration, and optimal scheduling protocols for vibrotactile feedback training that seeks to promote optimization of task performance, its generalizability to other tasks of daily living, and the extent to which performance enhancements can be retained over time. Potential applications outside the neurorehabilitation field include cases of visual impairment, performance optimization in sports, skill optimization in the teleoperation of surgical tools.

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