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Original Research

Subclinical Neck Pain Leads to Differential Changes in Early Somatosensory Evoked Potentials in Response to a Novel Force Matching Tracking Task

Ushani Ambalavanar[1], Paul Yielder[1], Heather S. McCracken[1], Hailey Tabbert[1], Bernadette Murphy[1,*]

[1]Faculty of Health Sciences, University of Ontario Institute of Technology (Ontario Tech University), Oshawa, ON L1G 0C5, Canada
*Correspondence: bernadette.murphy@ontariotechu.ca (Bernadette Murphy)
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Abstract

Background: Neural adaptions in response to sensorimotor tasks are impaired in those with untreated, recurrent mild-to-moderate neck pain (subclinical neck pain (SCNP)), due to disordered central processing of afferent information (e.g., proprioception). Neural adaption to force modulation, a sensorimotor skill reliant on accurate proprioception, is likely to be impaired in those with SCNP. This study examined changes in somatosensory evoked potential (SEP) peak amplitudes following the acquisition of a novel force matching tracking task (FMTT) in those with SCNP compared to non-SCNP. **Methods**: 40 (20 female (F) & 20 male (M); average age (standard deviation, SD): 21.6 (3.01)) right-handed participants received controlled electrical stimulation at 2.47 Hz and 4.98 Hz (averaged 1000 sweeps/frequency) over the right-median nerve, to elicit SEPs before and after FMTT acquisition. Participants used their right thumb to match a series of force profiles that were calibrated to their right thumb (abductor pollicis brevis muscle) strength. To determine if motor learning was impacted, retention was assessed 24 to 48 hours later. Outliers were removed before running independent *t*-tests on normalized SEP peak amplitudes, and repeated measures analysis of variance (ANOVA) with planned contrasts on absolute and normalized motor performance accuracy. Benjamini-hochberg test was used to correct for multiple independent SEP comparisons. **Results**: SEP peaks: N18 ($t_{(29.058)} = 2.031$, $p = 0.026$), N20 ($t_{(35)} = -5.460$, $p < 0.001$), and P25 ($t_{(33)} = -2.857$, $p = 0.004$) had group differences. Motor performance: Absolute error (n = 38) had a main effect of time, and significant pre-and post-acquisition contrast for time (both $p < 0.001$). **Conclusions**: Group differences in the olivary-cerebellar pathway (N18), and cortical processing at the somatosensory cortex (N20 and P25), suggests that SCNP alters cortical and cerebellar processing compared to non-SCNP in response to FMTT acquisition. The sensory-motor integration differences in the SCNP group suggests that those with SCNP may rely more on feedback loops for discrete sensorimotor tasks dependent on proprioception. Early SEP changes may be used as a marker for altered neuroplasticity in the context of motor skill acquisition of a novel discrete FMTT in those with SCNP.

Keywords: neck dysfunction; cerebellar processing; cortical processing; sensorimotor integration; motor performance; somatosensory evoked potentials

1. Introduction

There are various occupational tasks and daily tasks of living that rely on accurate force production and matching ability, which are likely to be impacted as a result of postural stress on the spine, such as: hand-held tool use, typing on keyboard without smashing keys and/or keyboard, overhead work, performance of surgical procedures, etc. As the reliance on computer/laptop use increases there is an associated increase in the prevalence of neck pain in adolescents [1], and university-aged students [2,3]. There is literature indicating that six months of repetitive low-load work with the neck in flexion (placing stress on the cervical spine) induces sensorimotor disturbances of the neck and shoulder, seen as impairments in motor performance [4]. The execution of a movement is dependent on the central nervous system's ability to adapt to ongoing changes via the intergration of sensory inputs, a process known as sensorimotor integration (SMI) [5]. SMI is dependent on feedforward and feedback processing for the execution of smooth skilled movements in response to motor learning and sensorimotor adaptation [5]. Feedforward processing relies on incoming somatosensory information from the periphery to continually update the central nervous system through body schema (also known as the internal body map which is developed using accurate awareness of body position [6,7]), to create a planned motor command [5,6]. Feedback processing allows for online corrections through the motor output by comparing the planned motor command to the actual motor response, which is dependent on the internal feedback tracts of the cerebellum as well as the basal ganglia [5,8–10]. The cortico-cerebellar networks are active during the early stages of acquiring a motor skill [11–13] and are needed for tasks reliant on proprioceptive acuity [14,15], changing signals in response to somatosensory feedback for feedforward control. It is postulated that the alterations in somatosensory processing in response to a neck dysfunc-

tion induces changes in cortical organization [16,17] and structure [18], possibly the result of maladaptive plasticity due to an altered afferent input from a musculoskeletal dysfunction.

A change in neck sensory input from head position [19,20], vibration of neck musculature [21] and/or fatigue [22] disrupts the central processing of somatosensory input, and in turn, development of an accurate body schema leading to altered motor behavior [23]. Disordered SMI from a change in the neck sensory input also translates to neuroplastic changes in response to motor learning, seen as altered processing in the olivary-cerebellar pathway (N18) in response to experimentally induced acute pain [24,25], as well as increased activity of the cerebellar-somatosensory processing pathways (N24) following cervical extensor muscle fatigue [26] compared to healthy controls, examined using somatosensory evoked potentials (SEPs). SEPs are complex waveforms that are generated following the controlled stimulation of a peripheral nerve, with sensory information ascending along the dorsal column medial lemniscus pathway [27]. SEPs allows for the examination of the neuroplastic changes along the somatosensory pathway, following sensory adaptation to a sensorimotor task. These neurophysiological changes in response to transient alterations in neck sensory input indicate that alterations in SMI are the result of differences in cerebellar processing, since it is involved in integration and modification of the sensory feedback loop.

To examine the chronic alterations in sensory-motor pathways that are influenced by pain, without pain itself impacting movement patterns on the day(s) of testing, subclinical neck pain (SCNP) populations are often investigated [28,29]. SCNP refers to untreated recurrent neck pain with individuals experiencing asymptomatic states (e.g., minimal pain or pain-free days) on which neurophysiological measures can be tested [28]. Individuals with SCNP have impaired upper limb proprioception [29,30] and control [23], reflective of disordered SMI. Maladaptive neuroplasticity associated with SCNP affects the excitability and/or upregulation of synaptic connectivity between the cortex and the cerebellum, impairing the ability to learn visuomotor tasks (e.g., novel motor typing or tracing task) using the abductor pollicis brevis (APB) muscle of the right-hand [31, 32]. Andrew *et al*. [33] demonstrated a greater increase in the inhibitory activity along the olivary-cerebellar pathway (N18) and reduced activity of the cerebellar-somatosensory processing pathways (N24) in the SCNP as compared to a control group following acquisition of a pursuit tracing task, suggestive of altered cerebellar processing and greater reliance on cerebellum for thumb movement coordination. Based on this literature, there are deficits pertaining to the central processing of somatosensory input, likely the result of altered afferent feedback from the neck musculature.

It is plausible that the ability to produce and modulate forces could also be impaired. The acquisition of a visuomotor tracking task reliant on proprioceptive input induces changes in synaptic connectivity within the cortico-cerebellar network [34], increased excitability in the descending cortico-motor networks [35,36], as well as hemispheric and lateralized changes in brain areas involved in proprioception and movement planning [37] in healthy participants. In response to the acquisition of a novel force-matching tracking task using the right thumb, there are changes in the olivary-cerebellar pathway (N18), cortical somatosensory processing pathways (N20 and P25), and motor circuit of the cortico-basal ganglia-thalamo-cortical loop (SMI; N30) [38] in healthy participants. There appears to be decreased activity along the olivary-cerebellar pathway (N18) and increased activity along the cerebellar-somatosensory processing pathway (N24) following the acquisition of a novel force-matching tracking task in individuals who receive vibration to the neck muscles (right sternocleidomastoid and left cervical extensor muscles) [39] compared to healthy controls. This altered cerebellar processing suggests that altered somatosensory feedback from the neck musculature alters processing of somatosensory input. Despite the changes in cerebellar input and processing in response to acquisition of a force-matching tracking task, improvements in motor performance did not carry over into retention for the neck muscle vibration group. Bleton *et al*. [40] revealed that individuals with altered SMI from a neuromechanical disruption at the level of the hand also had an impaired ability to control grip-force during a visuomotor force-matching tracking task, seen as increased error and greater variability in force measures compared to healthy controls. These studies suggest that altered sensory input from the neck or hand impairs the ability to produce and match muscle forces, as well as altering neural correlates pertaining to cerebellar processing pathways; however, it is unknown whether chronic alterations in neck sensory input from SCNP also impairs force production and modulation.

The primary objective of this study was to determine whether there are differential changes in the amplitude of short and middle latency SEPs in response to a force matching tracking task in individuals with and without SCNP. It was hypothesized that SEP peaks associated with cerebellar pathways/networks (N18, and N24 SEP peaks) would decrease in the SCNP group following the acquisition of the force-matching tracking task. A secondary objective was to determine if there are differences in motor performance following motor acquisition and after memory consolidation (at retention), when compared to healthy controls. It was hypothesized that individuals with SCNP would have minimal continual improvement following memory consolidation when compared to non-SCNP participants.

2. Materials and Methods

2.1 Participants

Fourty participants (21.3 $\pm$ 2.33 years of age) who attended Ontario Tech University (Oshawa, ON, Canada) between the ages of 18 and 30 were eligible to participate

in this quasi-experimental (pre/post) study. Twenty SCNP participants and 20 non-SCNP participants performing a novel force matching tracking task (FMTT) with changes in brain plasticity measured before and after task performance using SEPs. All participants were right-hand dominant confirmed using The Edinburgh Handedness Inventory (EHI), scored >+40. Non-SCNP participants were to have a grade of 0 (pain-free) and SCNP participants were to have a grade of I (low disability-low intensity), II (low disability-high intensity) or III (high disability-moderately limiting) on the Von Korff Chronic Pain Grade Scale, as this has been used to discriminate pain severity, and evaluate pain intensity and degree of pain-related disability over the span of 6 months [41]. None of the participants had any neurological conditions that could have led to cognitive deficits or alterations in central processing, nor did they report having tension headaches or co-morbidities (e.g., fibromyalgia). Written and oral informed consent was obtained on the day of the collection. The Ontario Tech University's Research Ethics Board approved this study (File #: 14686), and the study was conducted in accordance with their guidelines.

2.1.1 Clinical Assessments of Neck Pain or Disability On Day of Testing

The Neck Disability Index (NDI) and Pain Visual Analog Scale (VAS) were administered on the day of testing. Both of these clinical tools were used together to determine whether SCNP participants were asymptomatic as a great degree of pain can impact mobility/movement patterns [42], which is reflective of altered central processing [43]. Non-SCNP participants were to have an NDI score between 0 and 4 (no disability) [44] and a pain VAS score <1 cm (no pain), on the day of testing. SCNP participants were to score less than 15 (acceptable asymptomatic state) on the NDI [44,45] and <3 cm (acceptable asymptomatic state) on the pain VAS, on the day of collection [46].

2.1.1.1 NDI.

The NDI consists of 10-items that sought to identify whether neck pain impacts their ability to perform various tasks of daily living [44]. A score out of 5 is provided for each item, and it is the summation of the item scores that equates to the total score (/50) [44].

2.1.1.2 Pain VAS.

The pain VAS required individuals to denote the intensity of neck pain they were experiencing at that moment on a 10 cm long horizontal scale with a descriptor on either side of the scale, no pain (0 cm) and extreme pain (10 cm) [47,48]. The distance between no pain and the participant's denotation (mark or vertical line) was measured in centimeters [48].

2.2 SEPs Stimulating Parameters

Bipolar surface electromyography (EMG) electrodes (Kendall™ Medi-Trace® , Mansfield, MA, USA) were placed on the skin overlying the median nerve, to administer an electrical stimulation at 2.47 Hz and 4.98 Hz. The anode EMG electrode was placed close to the distal crease of the right wrist while the cathode EMG electrode was placed adjacent to the anode electrode [27,49]. Two different stimulating frequencies were used as 2.47 Hz results in clear visualization of the N30 SEP peak amplitude (without attenuating the signal), while a 4.98 Hz results in the identification of the N24 SEP peak (with attenuation of the N30 SEP peak) [50]. A stimulation intensity that consistently induced a twitch of the right thumb (~1 cm deviation from anatomical position) was administered [49].

2.3 SEPs Recording Parameters

Bipolar surface EMG electrodes were placed on non-cephalic sites, according to the International Federation of Clinical Neurophysiologists (IFCN) guidelines [49], in order to record the N9, N11 and N13 (peripheral SEP peaks). The N9 SEP peak was recorded over the ipsilateral Erb's point, and referenced to the ipsilateral ear lobe [27,49,51]. The spinal SEP peaks (N11 and N13) were recorded over the spinous process of the fifth cervical vertebrae, with the reference being the anterior tracheal cartilage of the neck [27,49]. These electrodes were referenced to the left clavicular bone, common ground electrode. Impendences of these electrodes were kept below 5 kΩ. Central SEP peaks (N18, N20, P25, N24, N30 and N60) were recorded using a Waveguard™ 64-electrode encephalography (EEG) cap (ANT Neuro, Hengelo, Netherlands), which was placed according to the 10–20 international system as per IFCN guidelines [49,52]. The common average of the electrical signal was used for all electrodes on the EEG cap. The electrical impendences were kept below 10 kΩ for the 64-channel EEG cap.

Throughout the SEPs collection, participants maintained an upright seated posture, backs supported by the chair, their feet on the floor, and their right arm rested in a supinated position on an adjustable-height table. To reduce the impact of movement artifacts on EEG recordings, participants were asked to minimize excessive movements or blinking.

The SEP signal acquired from non-cephalic electrodes was amplified by a gain 10,000× during preprocessing using Signal® software (Cambridge Electronic Design, Cambridge, UK). The SEP signal acquired from the cephalic electrodes was amplified by a gain of 40,000× amplification during the post-processing in Advanced Source Analysis (ASA) Software (ASA™; Hengelo, Netherlands). Artifacts (e.g., eye blinks, ocular movement, and muscular activity) were removed from the EEG data to extract the cortical SEPs by averaging epochs that were time locked to the median nerve stimulation. An average of 1000 right median nerve stimulus responses elicited SEPs, as per IFCN guidelines [49]. The SEP signal was filtered using a 0.2 Hz to 1000 Hz band-pass filter as it has been found to lead to reproducible SEP waveforms [33].

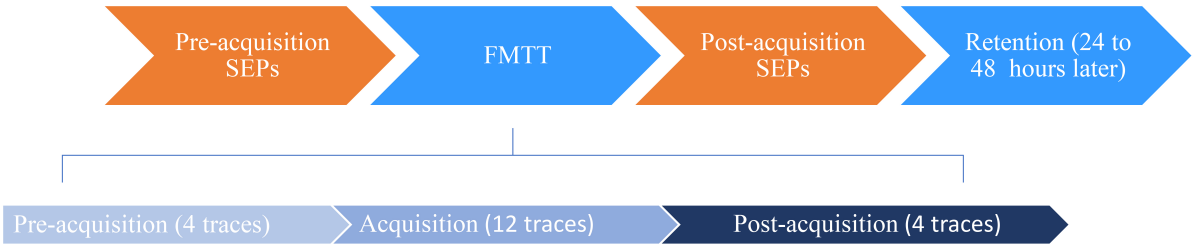

Fig. 1. Experimental flow. SEP, somatosensory evoked potential; FMTT, Force Matching Tracking Task.

2.4 Experimental Sequence

Participants attended two data collection sessions. Dual SEPs (2.47 Hz and 4.98 Hz) were collected prior and after acquiring the FMTT for each participant, during the first data collection session. It took 15 minutes to undergo each dual SEP measure, ~10 minutes for 2.47 Hz and ~5 minutes for 4.98 Hz. Retention of the performed task was measured 24 to 48 hours later, considered second session. The experimental sequence of this study can be seen in Fig. 1.

Motor Task: Force Matching Tracking Task (FMTT)

A series of force traces that were calibrated to the individual's right thenar muscles (based on average of three maximum voluntary contractions (MVCs)) were presented on a screen. Participants were to push or flex and abduct their right thumb against a 50 kg load cell force transducer (Unbranded, Shenzhen, Guangdong, China) to match the force traces, see Fig. 2 for participant setup of FMTT. As described in our recent publication, red bars were positioned 0.05% above and below the white-dotted force traces, used as cues for participants to replicate the trace.These traces were presented on a monitor as one trial comprising of two 10-second-long force traces. The tracking performance and presentation of traces were managed via a custom-made LABVIEW software program (National Instruments, Austin, TX, USA). Throughout the task, participants received augmented feedback in the form of a yellow line that depicted their force exertion against the transducer while the target trace remained stationary [38].

To acquaint participants with the task prior to initiating pre-acquisition and subsequent phases, they completed two practice trials using their right thumb. Participants were to match four blocks of force traces, where there was a variation in force amplitude (2% to 12% of averaged MVC), and isometric hold durations (1 to 2.75 seconds). Force amplitude, hold duration, and traces were randomized within each block, and between the four blocks. A rest interval with a work-to-rest ratio of 0.50 was embedded within each trial, to prevent and reduce likelihood of developing muscle fatigue [53]. For the acquisition phase, each block of force traces was performed three times, and post-acquisition measures consisted of the same four blocks, which took 20 minutes to complete. The same four traces were completed at retention, measured 24 to 48 hours later.

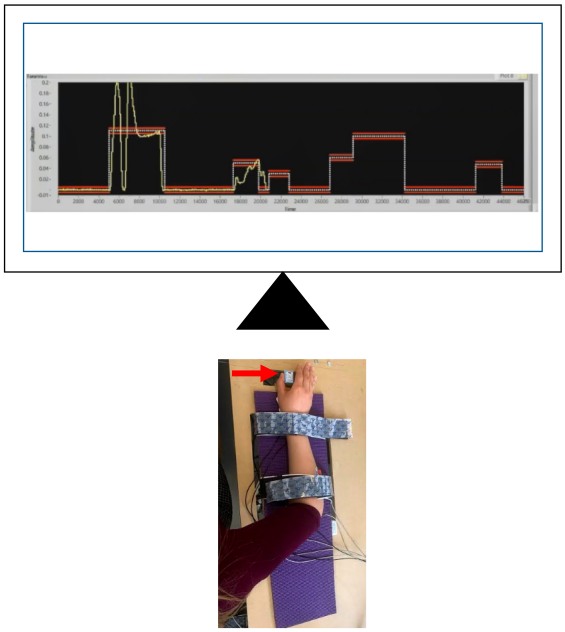

Fig. 2. Experimental set-up for the completion of the FMTT. Red arrow shows that the direction in which the thumb is pushing against the transducer. FMTT, force matching tracking task.

2.5 Data Analysis

2.5.1 Data Analysis of SEPs

As per IFCN guidelines, amplitudes of each SEP peak were measured from the peak of interest to the preceding or succeeding peak [49]. All SEP peaks were normalized to pre-acqusition, expressed as proportional change of the pre-acquistion SEP peak amplitude. Datasets that had a $\pm$ 20% proportional change in the N9 (afferent volley arriving at the Erb's point/brachial plexus) SEP peak in either the 2.47 Hz or 4.98 Hz stimulation frequencies, were excluded from statistical analysis [49].

Non-cephalic electrodes recorded the following SEP peaks: N9 (P9 – N9 Complex), N11 (P9 – N11 complex), N13 (P9 – N13 complex). The Frontal-Central1 (FC1) channel of the 64- channel EEG cap recorded the N24 (P22 – N24 complex), N30 (P22 – N30 complex) and N60 (P40 – N60 complex) SEP peaks. The Frontal-Central2 (FC2) channel (ipsilateral to the right median nerve stimulation) recorded the N18 (P14 – N18 complex) SEP peak, due to minimal contamination from cortical components compared to the FC1 [54]. The Central-Parietal3 (CP3) channel recorded the N20 (P14 – N20 complex) and P25 (N20 – P25 complex) SEP peaks.

None of the participants from either group (n = 40; 20 per a group) were excluded as they met the N9 criteria of a change within $\pm$ 20% [49].

2.5.2 Data Analysis of FMTT

Absolute percent error for each block within the pre-acquisition, post-acquisition and retention phase was calculated by examining the difference between the participant's filtered force trace against the target force trace [38] . The filtering (0.5 second moving average window) and calculation of percent error was done through a customized data analysis program with filtering parameters embedded created using LabVIEW. It is the average of the four blocks within each of the phases that was used to assess for changes in motor performance. Normalized motor performance accuracy was expressed as a proportion of the pre-acquisition phase, to allow for comparison between groups.

2.6 Statistical Analysis

All statistical tests were performed using SPSS version 26 (IBM Corp., Armonk, NY, USA) [55] and statistical significance was set at $p \leq 0.05$. SPSS uses Tukey's method to identify outliers and extreme outliers [55]. Outliers are determined on whether or not the value is outside of 1st or 3rd quartile of a boxplot, with a $\pm$ 1.5 * interquartile range for outliers and $\pm$ 3 * interquartile range for extreme outliers [55]. Percent of data rejected due to outliers of the SEPs data were: 10% for N11 (4 SCNP), 5% for N13 (2 SCNP) and N24 (1 SCNP and 1 non-SCNP), 7.5% for N20 (3 SCNP) and N30 (2 non-SCNP and 1 SCNP), and 12.5% for P25 (3 non-SCNP and 2 SCNP). 5% of the absolute motor performance data had to be removed (2 non-SCNP) and 10% for the relative motor performance data (2 SCNP and 2 non-SCNP). The distribution of the datasets was assessed using the Shapiro Wilk test following the removal of outliers.

2.6.1 SEP Peak Amplitude

All of the SEP peaks except for the N18 were normally distributed, where a $\log_{10}$ transformation was applied to normalize the N18 dataset. Homogeneity of variance was assessed using Levene's Test for Equality of Variance, which the N18 violated, thus results for "the equal variance not assumed" was reported for the N18. Separate one-tailed independent *t*-tests were run on the proportional change in amplitude for each SEP peak. In order to correct for multiple comparisons of SEP peaks that are independent of each other, the Benjamini-Hochberg test was used [56]. The test adjusts the *p*-value to control for false discoveries when multiple comparisons are made. The false discovery rate (proportionate of type I error) for the Benjamini-Hochberg test was set at $\leq$0.15 [56,57]. The unadjusted *p*-values are reported in the results sections, but this correction determined whether the SEP peak was statistically significant or not [58]. Cohen's *d* was reported for estimates of effect sizes, where 0.2 was considered small, 0.5 was considered medium, and 0.8 was considered large [59,60].

2.6.2 Motor Performance

None of the datasets were non-normally distributed. Sphericity was assessed using Mauchly's test, where a violation resulted in the reporting of Greenhouse-Geisser corrections. A 2 $\times$ 3 mixed repeated measures analysis of variance (ANOVA) with a repeated contrast was run with group as the between subject factor and percent error at the three time points (pre-acquisition, post-acquisition and retention) as the within subject factor, to compare mean differences in absolute motor performance accuracy between groups. Pre-planned repeated contrast were used as this permits for the comparison of adjacent measures [55,61], e.g., pre-acqusition versus post-acquisition, and post-acquisiton versus retention. A 2 (group) $\times$ 2 (time: proportional change at post-acqusition and retention) repeated measures ANOVA with a repeated measures contrast was run for relative percent error, to examine rate of learning and group differences in normalized motor performance accuracy. Partial eta-squared (η_p^2) was reported for estimates of effect sizes, where 0.01 was considered small, 0.06 considered medium, and 0.14 considered large [62].

3. Results

All descriptive data or statistics are reported as mean $\pm$ standard deviation (SD).

3.1 Demographic and Clinical Characteristics

Twenty SCNP participants (10 female (F) and 10 male (M); 21.4 $\pm$ 2.36 years of age) and 20 non-SCNP participants (10 F and 10 M; 21.2 $\pm$ 2.21 years of age) participated in this quasi-experimental pre/post study.

According to the Von Korff Chronic Pain Grade Scale, fifteen SCNP participants were classified as Grade I, four were classified as Grade II and the remaining one was classified as grade III. All 20 non-SCNP participants were classified as Grade 0. The NDI score on the day of collection was 7.25 $\pm$ 4.10 and 1.00 $\pm$ 1.52 for the SCNP and non-SCNP group, respectively. The pain VAS score on the day of collection was 1.15 $\pm$ 0.85 and 0.035 $\pm$ 0.11 for the SCNP and non-SCNP group, respectively.

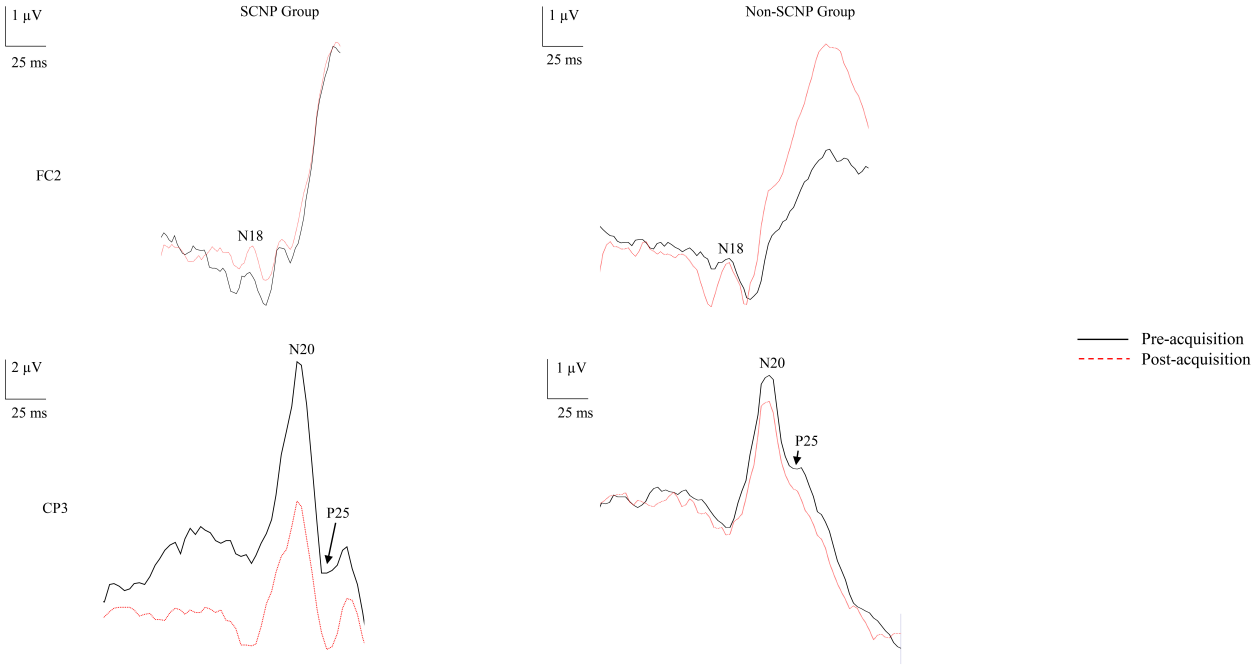

Fig. 3. Representative dataset of cortical SEP peaks (N18, N20, and P25) with group differences from an individual in the SCNP and non-SCNP group, recorded at 2.47 Hz. Black solid represents pre-acquisition, and red dotted line represents post-acquisition. SCNP, subclinical neck pain; SEP, somatosensory evoked potential.

3.2 SEP Peak Amplitude

The peripheral N9 SEP peak was not significantly different between groups, where the SCNP (0.99 ± 0.11) and non-SCNP group (1.02 ± 0.88) had similar amplitudes ($t_{(38)} = 0.947$, $p = 0.175$, $d = 0.30$), meaning changes in central SEP peaks in both groups were the result of changes in neural activity rather than an altered afferent volley.

N18 SEP Peak: There was a statistically significant difference between groups ($t_{(29.058)} = 2.031$, $p = 0.026$, $d = 0.64$), where the SEP peak amplitude increased by 3.06 ± 0.45% in the SCNP group (n = 20) and by 102.08 ± 1.55% in the non-SCNP group (n = 20). *N20 SEP Peak:* There was a statistically significant difference between groups ($t_{(35)} = -5.460$, $p < 0.001$, $d = 1.80$), with a 14.06 ± 0.12% increase in SCNP (n = 17) and a 6.27 ± 0.11% decrease in non-SCNP (n = 20) participants. *P25 SEP Peak:* There was a statistically significant difference between groups ($t_{(33)} = -2.857$, $p = 0.004$, $d = 0.97$), with a 10.86 ± 0.89% increase in the SCNP group (n = 18) and a 2.65 ± 0.81% increase in the non-SCNP group (n = 17). See Fig. 3 for a representative dataset from an individual in each group for the aforementioned cortical SEP peaks. See Fig. 4 for mean proportional change of the SEP peaks that demonstrated statistical significance.

The N11 did not have significant group differences ($t_{(34)} = 0.368$, $p = 0.357$, $d = 0.123$), with a 1.46 ± 0.30% decrease in the SCNP group (n = 18) and a 3.14 ± 0.44% increase in the non-SCNP group (n = 18). The N13 did not have significant group differences ($t_{(36)} = 0.117$, $p = 0.454$, $d = 0.038$), with a 0.34 ± 0.22% decrease in the SCNP group (n = 20) and a 0.81 ± 0.36% increase in the non-SCNP group (n = 18). The N24 did not have significant group differences ($t_{(36)} = -4.95$, $p = 0.312$, $d = 0.161$), with a 4.31 ± 0.25% increase in the SCNP group (n = 19) and a 0.87 ± 0.17% increase in the non-SCNP group (n = 19). The N30 did not have significant group differences ($t_{(35)} = -1.439$, $p = 0.079$, $d = 0.47$), with a 10.26 ± 0.15% increase in the SCNP group (n = 19) and a 2.03 ± 0.20% increase in the non-SCNP group (n = 18). The N60 did not have significant group differences ($t_{(38)} = -0.726$, $p = 0.236$, $d = 0.230$), with a 11.96 ± 0.32% increase in the SCNP group (n = 20) and a 5.15 ± 0.27% increase in the non-SCNP group (n = 20).

3.3 Motor Performance

3.3.1 Absolute Percent Error

The absolute motor performance error had an overall main effect of time ($F_{(1.320,47.517)} = 103.425$, $p < 0.001$, $n_p^2 = 0.742$) but no time by group interaction ($F_{(1.320,47.517)} = 3.227$, $p = 0.068$, $n_p^2 = 0.082$). The pre-acquisition to post-acquisition contrast had a significant effect of time ($F_{(1,36)} = 102.025$, $p < 0.001$, $n_p^2 = 0.739$) but no time by group interaction ($F_{(1,36)} = 3.435$, $p = 0.072$, $n_p^2 = 0.087$), with a 20.51 ± 0.60% and 15.75 ± 0.45% reduction in the SCNP and non-SCNP group, respectively. The post-acquisition to retention contrast was not a significant for time ($F_{(1,36)} = 1.058$, $p = 0.311$, $n_p^2 = 0.029$) or time

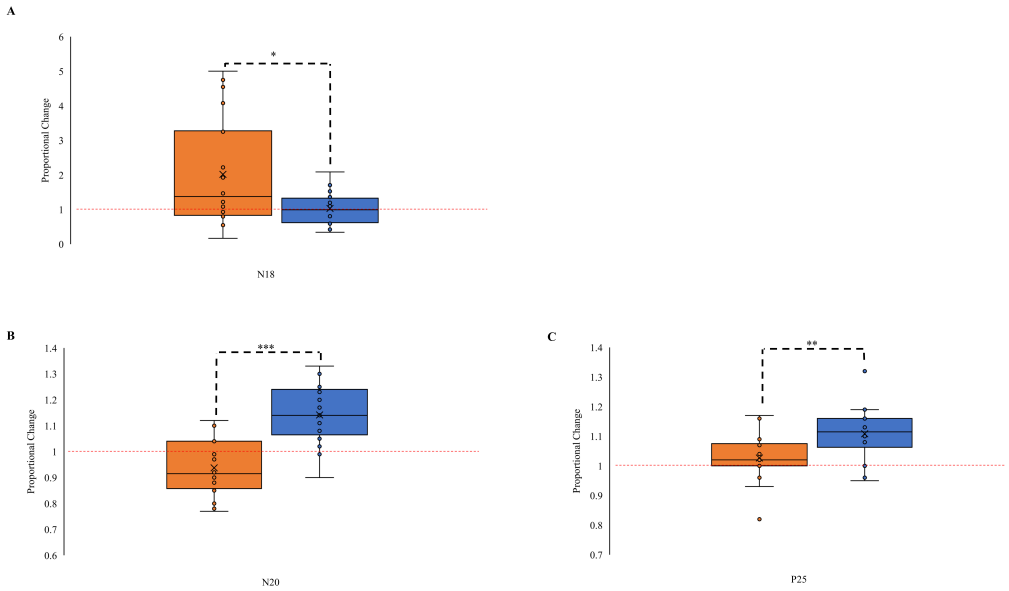

Fig. 4. Box and whisker plot of mean proportional change (relative to baseline) in (A) N18 (n = 40), (B) N20 (n = 37), (C) P25 (n = 35) SEP peak amplitude following acquisition of FMTT. Red dotted line represents baseline. Orange represents non-SCNP group and blue represents SCNP group. The whiskers reflect minimum and maximum values. The boxes reflect the quartiles, and x symbol represents median. Dashed bars and asterisk(s) denote significant group differences. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

by group ($F_{(1,36)} = 0.015$, $p = 0.902$, $n_p^2 = 0.000$), with a 0.87 $\pm$ 0.016% and 1.17 $\pm$ 0.13% reduction in the SCNP and non-SCNP group, respectively (see Fig. 5).

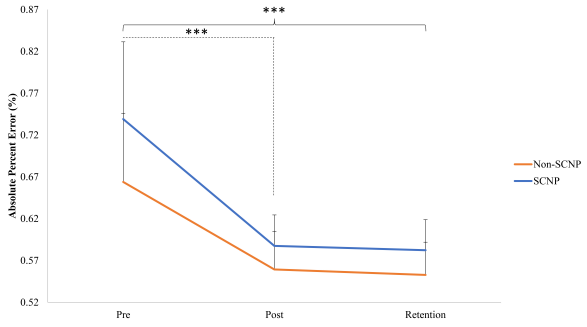

Fig. 5. Mean absolute percent error over time. Orange represents the non-SCNP group (n = 18) and blue represents the SCNP group (n = 20). The error bar represents SD. Asterisks alone indicates a significant main effect of time. Dashed bars and asterisk(s) denote a significant contrast. ***$p < 0.001$. SD, standard deviation.

3.3.2 Relative Percent Error

Relative motor performance error had no main effect of time ($F_{(1,34)} = 1.284$, $p = 0.265$, $n_p^2 = 0.036$) or time by group interaction ($F_{(1,34)} = 0.917$, $p = 0.345$, $n_p^2 = 0.026$), see Table 1.

4. Discussion

This study demonstrated that acquisition of a discrete novel FMTT led to differential changes in short-latency SEP peaks associated with cerebellar input (N18), somatosensory input (N20) and somatosensory processing (P25) in those with SCNP, when compared to non-SCNP participants. Both groups demonstrated similar increases in the N30 SEP peak (reflective of SMI), with no (near statistical significance) group differences. These early SEP changes suggest that the novel FMTT can capture maladaptive neuroplasticity in a population with altered central processing, as a result of a neck dysfunction. Absolute motor performance accuracy appears to be worse at all timepoints for those in the SCNP group compared to the non-SCNP group, with no differences in changes of motor performance in response to training in both, absolute and relative motor performance. The study findings indicate that disordered SMI from SCNP results in cortical differences in response to a discrete sensorimotor task, but this does not translate to motor performance differences using such a task.

4.1 SEP Peak Amplitude

It is speculated that reorganization of the various series and parallel circuits of synchronized flow of information from the medulla, subcortical and cortical levels of the central nervous system is impacted during SMI in those with altered cortical and/or cerebellar processing due to a musculoskeletal dysfunction [5,17,63]. It is the neural substrates that contribute to somatosensory adaptations of a repetitive task and the feedforward and feedback loops

Table 1. Mean ± standard deviation (SD) of the normalized motor performance error for each group, at each time point.

	Pre-acqusition	Post-acquisition	Retention
SCNP group	1.00 ± 0.00	0.80 ± 0.06	0.80 ± 0.07
Non-SCNP group	1.00 ± 0.00	0.83 ± 0.09	0.82 ± 0.08

during SMI that are of interest, specifically the cerebellum. The modulation and coordination of movement via the cerebellum enables sensorimotor learning and/or adaptation [11,12,64,65]. The execution of the motor response via the motor loop of the cerebral cortex is dependent on the sensory information received by the primary somatosensory cortex [66]. These processes have been demonstrated to be impacted in those with SCNP [31–33], and they also appear to be impacted following the acquisition of the novel FMTT.

The neural correlates recorded over the N18 SEP peak reflect the inhibitory activity of the region between the lower medullar and mid-brain-pontine region [50,67]. It is postulated that the dorsal column nuclei, collaterals from the dorsal column nuclei which contribute to the cuneocerebellar tract, the cerebellum, and the accessory inferior olives are the neural generators of this SEP peak [50,68–70]. It could also reflect cerebellar SMI, as the inferior olive transmits proprioceptive input to the cerebellar cortex and deep cerebellar nuclei via the inferior cerebellar peduncle, where information is filtered prior to cortical processing for feedforward or feedback control [71]. The large increase in the N18 in the non-SCNP group was also observed in other studies that have employed the same task [38,39,72]. This could suggest that the non-SCNP participants have greater inhibitory activity along the olivary-cerebellar pathway, to accommodate for the need to accurately produce and modulate forces via the right thumb during acquisition. The minimal increase in the SCNP group does not correspond with past work that has assessed neuroplastic changes in response to the FMTT in those with attention-deficit/hyperactivity disorder [72] or healthy participants who had their neck vibrated for 10 minutes at 60 Hz [39], where they demonstrated a decrease in the N18 [39,72]. This could suggest that this group is less able to accurately process proprioceptive input or rely more on vision (via augmented feedback provided during the task), due to the chronic altered neck sensory feedback impacting feedforward control. The group differences could suggest that there are differences in cerebellar SMI as past studies have also demonstrated that those with SCNP exhibit altered cerebellar processing following the acquisition of a motor task [31–33].

The N20 and P25 SEP peaks reflect the arrival of somatosensory input from the periphery at Brodmann's area 3b [73,74] and the processing of that somatosensory input in the primary somatosensory cortex, S1 [74,75], respectively. The changes observed in the N20 SEP peak in the non-SCNP group have been observed in past work [38,72], possibly suggesting that there is sensory gating of somatosensory/proprioceptive input. The slight increase in the P25 SEP peak in the non-SCNP group corresponds with the control group in a past study of individuals who did not have their neck musculature vibrated for 10 minutes at 60 Hz [39], which could suggest that accurate sensory feedback is needed to perform this task. The increases in the N20 and P25 SEP peaks are in line with work that employed the same task in those with attention-deficit/hyperactivity disorder [72], and individuals who had their neck muscle vibrated for 10 minutes at 60 Hz [39], suggesting that altered sensory input influences force production and modulation, whether it be neurodevelopmental, transient or chronic. The N20 and P25 SEP peaks are similar in the SCNP group, and the corresponding spinal SEP peaks (N11 and N13) are also similar, suggesting that there may not be any gating of somatosensory information at a spinal level and greater reliance on feedback processing of proprioceptive input to perform this motor skill, which is in line with the minimal increase in the N18 SEP peak. It is also possible that these cortical somatosensory processing changes are the result of greater reliance on visual feedback that was provided during the task (seen in visuomotor control), as opposed to proprioception alone. This could suggest that vision may have played a role in motor control of the right thumb while matching a series of static force traces. It is possible that the impaired feedforward control in response to altered chronic neck sensory input leads to alterations in the arrival of somatosensory input and somatosensory processing in the SCNP group when learning to produce and modulate forces, reflected by the group differences and subsequent increased reliance on feedback processing.

The cortico-basal ganglia-thalamo-cortical loop and the motor circuit (supplementary motor area, primary motor cortex and the somatosensory cortex) within the prefrontal cortex have been identified as the neural source of the N30 SEP peak [76–80]. This peak reflects the neural basis of SMI (feedforward and feedback processing), which is reliant on the synchronized flow of somatosensory information from various levels of the central nervous system [76,78,79,81]. The increase in the non-SCNP group corresponds with other studies that have utilized the same motor task [38,39,72], and the same goes for the increase in the SCNP group with altered central processing, such as attention-deficit/hyperactivity disorder [72] or neck muscle vibration [39]. The lack of group differences in N30 could be the fact the visuomotor tracking task was static in nature, with minimal force modulation perturbations and greater reliance on augmented feedback, barely impacting the motor

circuits greatly, which are needed for motor output that relies on going changes in somatosensory information. Despite there not being a group difference, the visibly greater increase (10%) in the SCNP group compared to the non-SCNP group (2%) alongside the minimal increase in the N18 SEP peak could suggest that there is greater reliance on feedback loops to make rapid changes during motor training in response to acquisition of the FMTT.

This work has shown that even in the early stages of pain development (presence of recurrent pain) there are neural changes in the processing of incoming sensory input following performance of an FMTT that is heavily reliant on proprioception, in those with SCNP. Individuals in both groups demonstrated SEP changes in response to the acquisition of the FMTT, with some group differences, in response to task acquisition, as well as small to large effect sizes even in non-significant SEP peaks. The altered SMI in those with recurrent neck pain, who were tested on a pain-free day, is likely to be the result of altered neck sensory input resulting in altered central processing of somatosensory input [28–30]. This altered neck sensory input likely arises due to a change in muscle spindle firing or tendon organs, or muscle afferents (group III and IV), which has been observed in fatigue of the neck musculature [82]. The processing of altered proprioceptive input arriving via the dorsal column medial lemniscus pathway and anterior spinocerebellar pathways would result in a misrepresentation of the internal body map which is dependent on feedforward processing, leading to a mismatch between the internal and egocentric or allocentric frame of reference, seen as impaired sensorimotor function due to the correction of an inaccurate reference frame using feedback processing between the motor circuits of the cortex [28–30,83]. The SEP changes observed are reflective of the processing of altered sensory feedback at the cortical level on feedforward control, specifically the region between the lower medullar and mid-brain-pontine region, as well as the cortical somatosensory processing pathway.

4.2 Motor Performance

The SCNP group has visibly worse performance at all time points, however, there were no group differences in their rate of learning, suggesting that the central nervous system of those with SCNP was able to compensate for the altered processing. Learning a sensorimotor skill refers to improvements in performance accuracy (either rapid improvement within a single motor training session or continual improvement across multiple motor training sessions), and efficiency of a movement following memory consolidation [84,85]. This study appears to demonstrate rapid improvements within the single motor training session within each group, seen as improvements at post-acquisition and at retention, relative to pre-acquisition. These improvements in relation to baseline suggest that both groups learned the novel FMTT. The visible difference between the SCNP and non-SCNP group at each time point in absolute error, suggests that the SCNP participants exhibit a decreased ability to perform the FMTT. Both groups showed minimal continued improvement at retention in following post-acquisition improvements, which coincides with past studies that have employed the same motor task [38,39,72]. In contrast, a task reliant on visuomotor information demonstrated that SCNP participants had deficits in acquiring a pursuit movement task compared to healthy controls, who continued to improve following memory consolidation [33]. The lack of time by group interactions relative to retention could be due to the use of a discrete FMTT (e.g., lack of ballistic thumb movements to produce and modulate force of clearly defined plateaus) as there may have been insufficient contextual interference during the acquisition of the FMTT, since higher interference yields greater improvements at retention [86]. It may be attributed to the nature of the FMTT, greater reliance on visual feedback alongside lack of continuous force production and modulation perturbations in the task, which resulted in rapid improvement in visuomotor control in a single training session with no room for improvement thereafter [87] since it may rely more on memory recall once the pattern is recognized [88].

4.3 Neurophysiological and Motor Performance Observations

There are two cortical circuits with their own distinct subcortical and cortical interactions that change in response to motor skill learning, where the respective circuits change in accordance with the demands of the motor task and stage of skill acquisition [64,89]. The acquisition of a sequential motor skill is suggested to increase activity in the deep cerebellar nuclei and cerebellar cortex followed by an increased reliance on the striatal-cortical circuit (striatum, supplementary motor area, inferior parietal, precuneus and ventrolateral pre-frontal cortex) and diminished reliance of cerebellar-cortical circuits with improvements in task proficiency [12]. Both groups in this study demonstrated improvements in the FMTT following acquisition, which corresponded with differential changes in the olivary-cerebellar pathway and cerebellar SMI, and cortical somatosensory processing pathways. These changes correspond with the literature pertaining to increased reliance on cerebellar networks in the early stages of skill acquisition [10–12,89,90]; however, this does not translate to a transition to reliance on striatal networks for long-term retention, reflected by an increase in the N24 SEP peak (cerebellar-somatosensory cortex processing) in the SCNP group, but no group differences in the N24 SEP peak, and between post-acquisition and retention. These cortical changes with a lack of drastic changes with respect to motor performance between groups correspond with literature regarding experimentally induced cutaneous pain on motor learning [25,91,92]. Early SEP changes can be used as a marker for altered neuroplasticity in the context of motor skill acquisition of a novel discrete FMTT in those with SCNP.

4.4 Limitations

This study comprises a study population who have SCNP, which may not be reflective of the general public, nor are the results presented applicable for those outside of the ranges of 18 and 30 years of age. The version of the FMTT that we used may not have been sensitive enough to show the effects of altered proprioceptive input as the force traces were stationary and not as dynamic (e.g., they hit a plateau of 0% instead of constantly fluctuating between 2% and 12%). The participants may also have "learned" the task too easily, leaving minimal room for additional improvement in retention. Future work should employ a more difficult, unpredictable and/or dynamic force-matching task, to address these limitations.

5. Conclusions

This study demonstrates that there are neurophysiological differences in cerebellar and somatosensory processing pathways in those with SCNP following the acquisition of a discrete sensorimotor task reliant on proprioceptive information. This suggests that there is greater initial reliance on feedback, possibly due to altered feedforward control in the SCNP group.

Availability of Data and Materials

The data can be made available upon request.

Author Contributions

UA, PY, and BM designed the research study. UA, HM, and HT performed the research. UA analyzed the data. UA wrote the manuscript. All authors contributed to editorial changes in the manuscript. All authors read and approved the final manuscript. All authors have participated sufficiently in the work and agreed to be accountable for all aspects of the work.

Ethics Approval and Consent to Participate

This research received approval from the Ontario Tech Research Ethics Board (REB #: 14686). Participants provided informed consent, verbally and in-writing, prior to starting the study. This research was performed in accordance with the principles set out by the Declaration of Helsinki for the use of humans in experimental research.

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Conflict of Interest

The authors declare no conflict of interest.

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