Use of Virtual Reality Feedback for Patients with Chronic Neck Pain and Kinesiophobia

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***Abstract*—This study examined how individuals with and without neck pain performed exercises under the influence of altered visual feedback in virtual reality. Chronic neck pain (n = 9) and asymptomatic (n = 10) individuals were recruited for this cross-sectional study. Participants performed head rotations while receiving programmatically manipulated visual feedback from a head-mounted virtual reality display. The main outcome measure was the control-display gain (ratio between actual head rotation angle and visual rotation angle displayed) recorded at the just-noticeable difference. Actual head rotation angles were measured for different gains. Detection of the manipulated visual feedback was affected by gain. The just-noticeable gain for asymptomatic individuals, below and above unity gain, was 0.903 and 1.159, respectively. Head rotation angle decreased or increased 5.45° for every 0.1 increase or decrease in gain, respectively. The just-noticeable gain for chronic pain individuals, below unity gain, was 0.950. The head rotation angle increased 4.29° for every 0.1 decrease in gain. On average, chronic pain individuals reported that neck rotation was feasible for 84% of the unity gain trials, 66% of the individual just-noticeable difference trials, and 50% of the "nudged" just-noticeable difference trials. This research demonstrated that virtual reality may be useful for promoting the desired outcome of increased range of motion in neck rehabilitation exercises by altering visual feedback.**

***Index Terms*—Gain, just-noticeable difference, patient rehabilitation, range of motion, virtual reality.**

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I. Introduction

NECK pain is a common problem and a major health concern [1]. In the United States, it was reported that 14.4% of adults over the age of 18 have experienced neck pain [2]. Neck pain, which is often musculoskeletal in nature, not only negatively impacts individuals' health but is also associated with the costs of lost workdays and productivity loss, medical treatment, rehabilitation, worker's compensation insurance, and human suffering [3]. Thus, it is important to identify interventions to effectively and affordably manage neck pain and minimize subsequent disability.

Neck pain rehabilitation exercises that involve stretching have been found effective. Although there existed numerous interventions for patients with chronic neck pain, ranging from rehabilitation, pharmaceutical and injection, and multimodal therapies [4]–[7], moderate evidence demonstrated that endurance and strength training of the scapulothoracic and upper extremity, and combined cervical and shoulder strengthening and stretching improve neck pain [8].

In addition to the discomfort and disability from musculoskeletal pain, patients with chronic pain can develop kinesiophobia, i.e., psychological pain-related fear associated with avoidance of movement and physical activity [9]. In these patients, true functional capacity is often masked due to pain-related fear [10]. People with high pain-related fear avoidance have reduced range of motion, decreased strength and are less active [11]. With neck flexion and extension, strength was less for those with greater fear of movement [12]. While chronic neck pain patients demonstrated improvements in neck muscle strength and neck disability over the course of an eight week exercise program, their fear avoidance belief did not decrease [13]. Challenges in existing therapies arise as pain symptoms and fear avoidance co-exist and recovery may be delayed due to fear of performing therapeutic exercises.

Virtual reality (VR) offers a simulated environment through computer generated stereoscopic graphics. Increasing attention has been directed toward using VR for stroke rehabilitation of the upper and lower extremities, and for improvements in activities of daily living [14]–[16]. Advancement in technologies permitted researchers to adapt commercial grade game consoles to conduct virtual rehabilitation-related activities [17]–[19] and have demonstrated positive outcomes including improvement in postural control, functional mobility, and balance. Virtual rehabilitation could possibly facilitate patients' motivation through the use of game-like experience in VR and help patients stay engaged during their exercises [20], [21]. It also can be used as a tool by clinicians to improve patient outcomes and possibly reduce cost and frequency of clinic visits [14], [22], [23].

Given the flexibility of a programmable environment, VR has been used as a desensitization tool in treating individuals with specific phobias [24], [25]. The graphical environment of VR has also been used to distract user attention from pain during wound care and experimentally controlled induced pain [26]–[29]. In a review, Keefe et al. [30] advocated that VR could potentially help individuals with persistent pain. Research to date provides support that visual feedback within a VR environment can mitigate fear of pain in patients, and may be useful in improving tolerance to movement and exercise for those with kinesiophobia and chronic neck pain.

For the current study, we manipulated the visual feedback provided to individuals performing physical exercise in VR. The manipulated visual feedback was designed to visually present a lesser degree of movement than the participant was actually moving, such that in the physical environment, they would be moving more than they actually saw. Burns and colleagues [31], [32] experimentally determined that healthy individuals were able to tolerate some visual discrepancies between the visual feedback in VR and their own proprioceptive feedback, and did not notice the discrepancies until they reached a certain threshold. As their study participants moved their hand and upper arm to aim at specific targets, the participants' physical hand was on average 20 cm away from the virtual hand before they noticed the discrepancies [31], [32]. Our approach to create the visual-proprioception mismatch was through the use of control-display (C-D) gain in VR [33]–[35]. The C-D gain is the ratio of the mapping between a patient's movement in VR and the corresponding visual feedback [36]. We hypothesize that there exists a C-D gain in VR at which the patients would not notice the visual feedback has been altered. This would be the C-D gain at the just-noticeable difference (JND). Providing patients with altered visual feedback at JND in VR may encourage them to perform certain therapeutic exercises or movements, without fear of pain interfering with activity or motion.

The purpose of this study was to examine how chronic neck pain and asymptomatic individuals perform neck exercises under the influence of altered visual feedback in VR. The first study determined the JND for individuals without neck pain. The second study similarly determined the JND for chronic neck pain patients, and then evaluated their performance in VR under manipulated visual feedback with C-D gain at the JND.

II. Methods

A. Participants

The asymptomatic study involved individuals free of musculoskeletal conditions, and the chronic neck pain study involved clinically diagnosed chronic neck pain individuals. The common inclusion criteria for both studies were that participants needed to be at least 18 years old and had normal or corrected-to-normal vision. The exclusion criteria for both studies were epileptic seizure or blackout, prone to motion sickness or nausea, Lasik eye surgery, taking perception-altering medication, and presence of neuro-motor impairments or injuries in the neck and shoulder regions. Individuals who had Lasik eye surgery were excluded because it has been shown to affect performance in VR [37]. All participants were screened to determine their eligibility prior to enrollment. Additional exclusion criteria for chronic neck pain individuals were neurological conditions (e.g., spinal cord injury, multiple sclerosis), progressive disorders (e.g., rheumatoid arthritis), cervical spine surgery, and major depressive and anxiety symptoms. Patients who were receiving treatment for clinically diagnosed depression were not referred. Both study protocols and informed consents were approved by the Institutional Review Boards of the University of Wisconsin-Madison.

B. Apparatus

The VR system comprised widely available, low-cost gaming equipment including an infrared-depth motion tracking camera, game controller for user input, and a 3D head-mounted display (HMD) with inertial sensors for visual feedback and head orientation tracking. The motion sensing and position tracking depth camera was a Microsoft Kinect (Redmond, WA, USA), which was used in both the preliminary and the patient studies. The HMD used in the preliminary study was a Development Kit 1, Oculus Rift, (Oculus VR, LLC, USA), which had a 110° diagonal field of view and a combined resolution of 1280×800 pixels, or 640×800 pixels per eye. The Development Kit 1 was shown to have 10° accuracy within each rotation axis [38], and this potential accuracy error was reduced by periodically "zeroing" the target position at the start of each trial. Development Kit 2 Oculus Rift (Oculus VR, LLC, USA) became available and was used at the time of the patient study, which had 100° diagonal field of view and a combined resolution of 1920×1080 pixels, or 960×1080 pixels per eye.

The VR scenario was written in C + + and it was based on OGRE, an open source 3D graphics rendering engine (www.ogre3d.org). Visuals were retrieved from an open source 3D model repository (Trimble 3D Warehouse, Google, Mountain View, CA, USA) and modified in SketchUp (Trimble Navigation, Ltd., Sunnyvale, CA, USA).

C. Experimental Procedure

1) Asymptomatic Study: Ten healthy, college-age individuals (6 females and 4 males) were recruited from the University of Wisconsin-Madison campus under IRB approval and informed consent. Participant mean age was 23± 3 (range 19–29) years. The asymptomatic study provided valuable data on visual-proprioception mismatch and the tolerance of mismatch in asymptomatic individuals, and also helped to refine the range of C-D gain to be used with chronic neck pain patients. The enrolled participants completed the study in one session that lasted approximately 40 min.

Asymptomatic participants performed a JND task, which involved two consecutive head rotation movements and then comparing whether the two head movements were the same or different. One head rotation movement had a unity gain

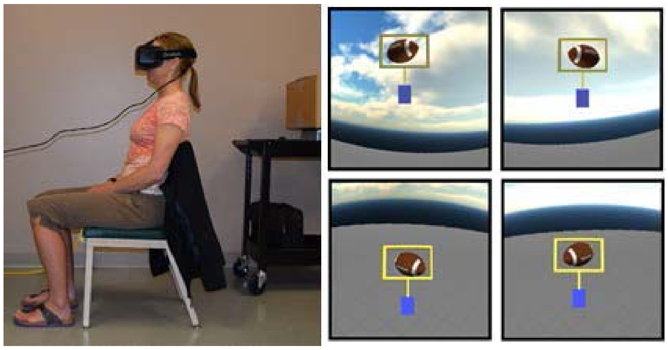

Fig. 1. (Left) Participant wore the HMD in a seat in front of a Kinect motion tracker. (Right) Participant was presented with four possible locations of the target football, shown with the secondary object (goalpost). The four possible locations were upper left and upper right corners, and lower left and lower right corners.

(C-D gain = 1) and the other rotation movement was at C-D gain $\neq$ 1. In one trial, for example, visuals in the HMD first instructed the participant perform a 45° head rotation movement, and the participant actually rotated the head 45°. Hence, the intended head rotation movement directed by visuals in the HMD and the actual participant head rotation were at 1:1 mapping, or, unity gain. Following the first head rotation movement, visuals in the HMD then suggested the participant perform another 45° head rotation movement, but instead the participant would need to actually rotate the head 50° to achieve the movement displayed in the HMD. In the case of the second head rotation movement, there was not a 1:1 mapping and therefore the C-D gain $<$1.

At the start of the JND task, participants faced the tracking camera while seated in a stationary chair with a backrest, but without armrests, and wore the HMD (Fig. 1). A target object image (i.e., a football) and a secondary object image (i.e., a goalpost) were displayed in the HMD (Fig. 1). The target was stationary and it randomly appeared in one of the four corners of the HMD field of view. The four target locations were based on the average allowable range of motion (ROM) demonstrated during a diagonal head–neck movement [39]. A diagonal head–neck movement includes a neck flexion or extension motion, followed by a left or right rotation [39].

The secondary object was affixed to the center of the field of view and its position was controlled by the participants' head–neck movements.

Participants assumed the ready position at the beginning of a trial, which was a neutral posture sitting upright and facing forward with the shoulders relaxed. They had to change the location of the secondary object (i.e., to overlap the goalpost with the football) using head rotation and indicate that they have completed the movement by pressing a pre-programmed button on the controller, and then return to the ready position. After they had returned to the ready position, the experimenter pressed a key on the computer keyboard to reinitiate the target object for the second head rotation movement. The first target disappeared and another target reappeared at the same location as the first target. Participants aligned the secondary object against the new target (i.e., to overlap the goalpost with the football) and pressed the controller button, and then returned to the ready position. Following the second alignment movement, the experimenter verbally asked "Were the two head-neck movements the same or different?", and the participant verbally responded. The response was recorded either as 1 or 0, which corresponded to yes or no, respectively. Participants were welcomed to provide any feedback regarding their perception after each trial, but it was not mandatory. Also, the VR scenario (i.e., anything that was displayed to the participant) was visible to the experimenter on a computer screen and therefore the experimenter could follow the activity of participants, and verify if they actually overlapped the goalpost with the football.

A 15-s rest break was provided between each trial and participants could request longer rest breaks if needed. Participants completed a brief demographic questionnaire including questions on age, gender, ethnicity, and hand dominance during a 3–5 min break that was provided half-way during the session. Each participant was provided a small monetary compensation.

2) Chronic Neck Pain Study: Nine patients with chronic ($>$3 months) neck pain (7 females and 2 males) were recruited from a University of Wisconsin clinic under IRB approval and informed consent. Participant mean age was 58 $\pm$ 11 (range 39–75) years. The mean years since neck diagnosis by a physician was 9.8 $\pm$ 12 (range 4 months to 35 years) years. The inclusion criteria were pain in the neck or shoulder region for at least 3 months. All participants in this study were referred patients of author J. L. as potential volunteers. Patients interested in participating were screened for eligibility via phone using the inclusion/exclusion criteria and the Generalized Anxiety Disorder 7-item (GAD-7). Patients scoring less than or equal to 10 out of 21 (maximum) on the GAD-7 were eligible to participate [40]. Eligible participants were scheduled for a one-time study session.

Chronic neck pain participants performed two tasks: the JND task that was the same as the JND task in the asymptomatic study but with less trials (20 trials), and the evaluation task (12 trials). The JND task involved performing two head rotation movements and then comparing whether those two head movements were the same or different. The evaluation task consisted of one head rotation movement when the C-D gain was set at the JND, which was experimentally determined for each participant during the JND task. All VR visuals of the target and the secondary objectives were identical to the asymptomatic participant study. Both the JND and evaluation tasks were performed in a stationary chair with a backrest but without armrests (Fig. 1).

Participants indicated their pain level using a 10-point visual analog scale (VAS) at the beginning of the session. Standard neck ROM was measured at the start of the session using the HMD. After a 5-min rest break, participants completed the JND task with a 15-s rest break between each trial. Extended rest breaks were provided upon request. Participants rated their pain on the VAS after the JND task. They took a 15-min rest break while completing the demographic, Tampa Scale for Kinesiophobia 11-items (TSK-11), and the Neck Disability Index (NDI) questionnaires before the evaluation task.

For the evaluation task, participants visually located a target object and then aligned it with a secondary object, which was

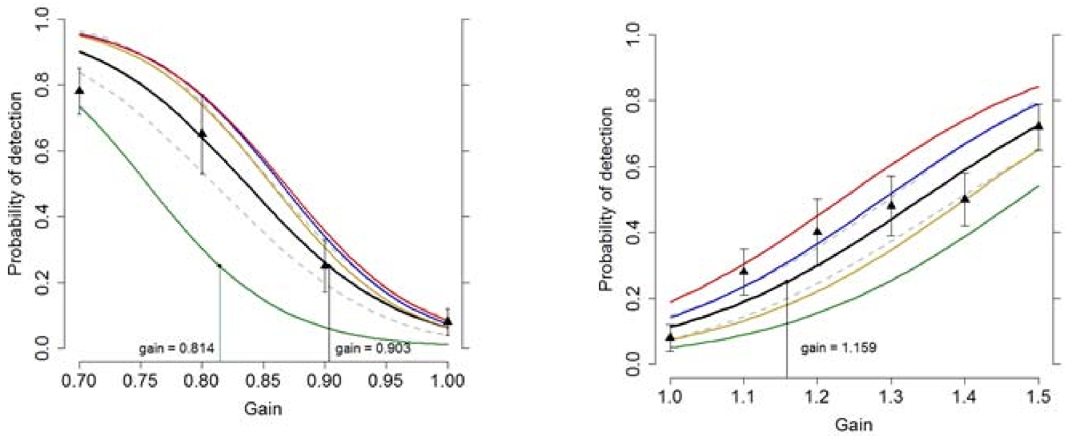

Fig. 2. Lower bound (left) and upper bound (right) detections plotted against gain for asymptomatic participants. Black line depicts the probability of detection of the overall model (dashed lines representing ± 1 S.E). Blue and red lines indicate the probability of detection during neck right- and left-extension movements, respectively. Tan and green lines indicate the probability of detection during neck right- and left-flexion movements, respectively. The black triangles depict the mean probabilities across all participants at each gain.

similar to the JND task. However, the four locations of the target object were customized to the neck movement capability of the participant. The locations of the target object were determined using a diagonal head-neck movement described by Piva et al. (2006). Once the participant aligned the secondary object against the target, the experimenter verbally asked the participant whether the movement was "feasible as expected, feasible but slightly challenging, or challenging and not feasible." The participant returned to the neutral posture before the next trial. The patients were reminded to stop performing the task if they felt pain. The participant rated their pain on the VAS at the end of the session. The experimental session took approximately 75 min and the participant received a small monetary compensation.

D. Variables and Analysis

1) Asymptomatic Study: For the neck JND task, a 9×4 (gain $\times$ target location) within-subjects experimental design was presented for a total of 36 trials. The independent variable were C-D gains ranging from 0.7 to 1.5 in 0.1 increments. The dependent variables were gain detection (same/different) and neck angle during target alignment. The detection threshold (DT) was defined as a 0.25 probability of detecting a difference from unity gain [41]. Logistic regression models were used to analyze the effect of gain and target location on the probability of detecting the visual-proprioceptive mismatch. The significance level was set at $p < 0.05$ for all analyses.

2) Chronic Neck Pain Study: The JND task was a 5×4 (gain $\times$ target location) within-subjects design. Upon the analysis of the JND from the asymptomatic study, we identified that individuals noticed the C-D gain when it deviated 0.2 from unity (e.g., gain= 0.8). In considering the ability and potential fatigue when working with the patient population, we narrowed the range of C-D gains. In the patient study, the independent variables were C-D gain ranging from 0.8 to 1.0 in 0.05 increments. We did not test gains above 1.0 because in those cases the patients would not exceed their demonstrated limits, but rather turn their neck less. Logistic regression models were used to analyze the effect of gain and target location on the probability of detection.

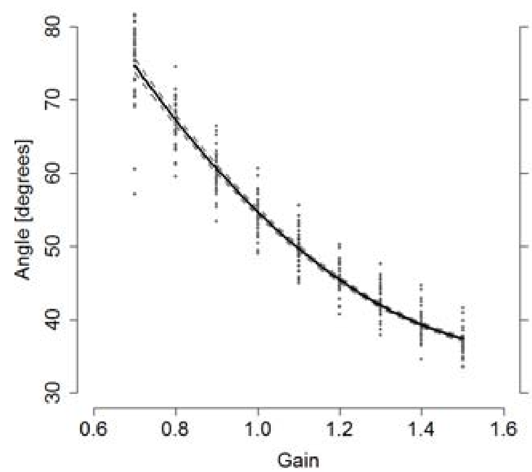

Fig. 3. Neck rotation angle for asymptomatic participants across the range of gains (0.7 to 1.5). The dashed lines represent ± 1 S.E., with the raw data points plotted.

The dependent variables were gain detection (same/different) and neck angle during target alignment. A linear model was used to analyze the effect of gain and target location on neck motion with the same detection threshold as the asymptomatic study.

The evaluation task was a 3×4 (gain $\times$ target location) within-subjects design. The independent variables were C-D gains at unity, patient-specific JND, and a "nudge JND" that was 0.5 less than JND. The nudge JND was tested to explore the potential of creating greater visual-proprioceptive mismatch and the demonstrated tolerance of the patients. The dependent variable was neck rotation angle. A linear model was used to analyze the effect of gain and target location on neck rotation angle. The significance level was set at $p < 0.05$ for all analyses.

III. Results

A. Asymptomatic Study

All recruited participants completed the study. Detection was significantly affected by gain ($\chi^2(1)= 26.91$, $p < 0.001$) for the lower bound, while statistically controlling for target

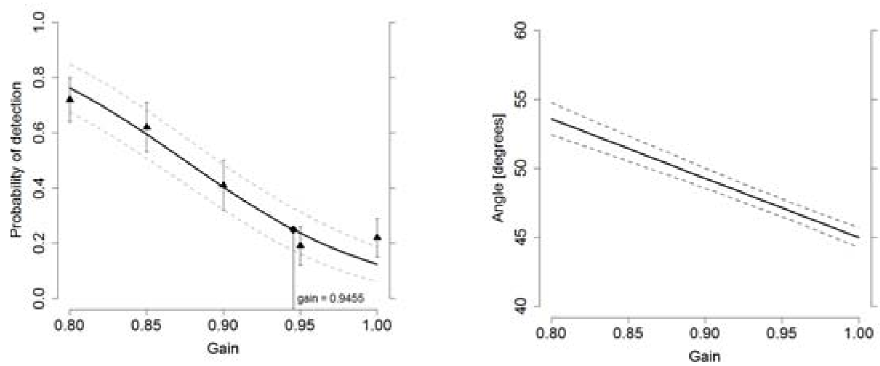

Fig. 4. (Left) Probability of detection plotted against gain for symptomatic participants, with black triangles depict the mean probabilities across all participants at each gain. (Right) Neck rotation angle across the range of gains (0.8 to 1.0) for symptomatic participants. Dashed lines represent ±1 S.E.

location. The detection threshold gain was 0.903 for the overall model of the lower bound (Fig. 2). There was a significant effect of target location ($\chi 2(3) = 8.60$, $p = 0.035$) on detection, while statistically controlling for gain at unity. Post-hoc analysis with Holm-Bonferroni correction revealed that the detection of the gain during left-flexion (i.e., looking over the left shoulder) was significantly different from neck left- and right-extension movements ($p < 0.05$). The DT for neck left-flexion was modeled to gain = 0.814. There was a significant effect of gain on detection ($\chi 2(1) = 34.52$, $p < 0.001$) for the upper bound of C-D gain, while statistically controlling for target location. The DT gain was 1.159 for the overall model of the upper bound (Fig. 2). However, target location did not have a statistically significant effect on detection ($p = 0.22$).

A generalized model was used to analyze the effect of gain and target location on neck rotation angle (Fig. 3). There was a significant main effect for gain ($F(2,8) = 1282$, $p < 0.001$) but not for target location ($p = 0.51$). At unity gain, the neck angle was 54.28°, and it was expected to be 5.45° less or more for every 0.1 change in gain ($F(1,9) = 1786$, $p < 0.001$), respectively.

B. Chronic Neck Pain Study

The chronic neck pain individuals on average had a self-reported pain level of 2.1± 1.3 on the VAS (0 =no pain, 10 =maximum pain). The Neck Disability Index was 15.3± 4.7 (0 =no disability, 50 =maximum disability). The mean Tampa Scale for Kinesiophobia score was 23± 5.9 (0 =not kinesiophobic, 44 =very kinesiophobic). The mean left and right axial rotation ROMs were 61.8° and 63.4°, respectively.

Detection was significantly affected by gain ($\chi 2(1)= 26.91$, p <0.001) but not affected by target location ($p > 0.05$). The detection threshold was at gain = 0.95 (Fig. 4). There was a significant main effect for gain ($F(1,7)= 44.52$, $p <0.001$) and target location ($F(1,7)= 21.3$, $p =0.001$). At unity gain, the neck angle was 45.0°. For every 0.1 increase or decrease in gain, the neck rotation was expected to be ±4.29° from the neck angle at unity gain (Fig. 4).

For the evaluation task, there was an effect of gain ($F(1,7)= 16.43$, $p =0.005$) on neck rotation angle. There was no statistically significant effect of target location for neck rotation

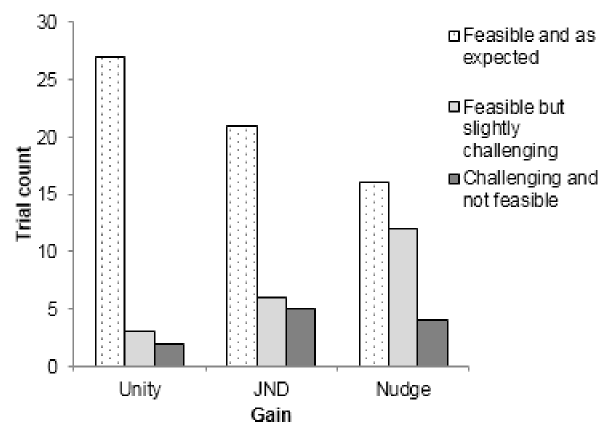

Fig. 5. Symptomatic participant perceived difficulty of neck rotation movement in the evaluation task. Three gains were evaluated: unity, JND, and "nudge".

angle ($p > 0.05$). Participants provided verbal feedback after each trial on their perceived difficulty of the task, and the neck movement was more challenging as the mismatch deviated more from unity gain (Fig. 5).

IV. Discussion

Virtual reality (VR) presents a new physical therapy paradigm, and may be a practical method for rehabilitation. This study examined how individuals with and without chronic neck pain performed exercises in VR under the influence of visual-proprioceptive mismatch. Specifically, the JND gain was determined in both study populations, and the symptomatic participants performed exercise movements with visual-proprioceptive mismatch at JND gain. In general, the VR system was successful in providing altered visual feedback using C-D gain to influence neck movement for both asymptomatic and symptomatic individuals.

The JND task, which was performed by both the asymptomatic and symptomatic individuals, demonstrated that the probability of noticing the altered visual feedback was significantly affected by C-D gain. As the C-D gain deviated from unity, there was a higher probability of detecting the altered visual feedback and this was observed in both healthy and chronic pain individuals. The neck turning angle was also significantly affected by C-D gain in both study populations (Figs. 3 and 4), such that participants did not notice they extended or flexed the neck greater (or less) than how much they would turn at unity gain.

While the influence of C-D gain showed common effects in both groups, the asymptomatic and symptomatic groups had different JND gains, which were 0.903 and 0.95, respectively. The JND gain of the symptomatic group was closer to the unity gain than the asymptomatic group and that mapped to a smaller degree of neck rotation performed when the mismatch was detected. The restricted neck ROM, musculoskeletal pain, or even morphological changes may have led to the difference between the two groups. The symptomatic group was less tolerant to visual-proprioceptive mismatch and discerned the mismatch at smaller degree difference. This lower tolerance did not necessarily associate with poor performance or performance limitations, but it rather suggested greater sensitivity to visual-proprioceptive mismatch. If there were any limitations it would most likely be physical ROM limits in the symptomatic group, which was less than the ROM reported in the literature [42]. However, the JND gains between the two groups did not vary greatly (0.05 difference). It is possible that movements involving cervical spine may not show a large difference in JND gain, and larger differences in JND gain may be seen in other joint movements.

In the JND task performed by the asymptomatic individuals, the altered visual feedback was subjected to a wide range of C-D gain (0.7 to 1.5) in order to understand whether there was a difference in how people perform when they were subjected to lower (less than or equal to unity gain) and upper (greater than or equal to unity gain) gains. The mean detection probability suggested that altered visual feedback subjected to upper gains may be less noticeable than lower gains. Specifically, the participants did not detect the altered visual feedback subjected to upper gains until it deviated 0.159 units (upper bound JND gain =1.159) from unity gain, whereas the lower gain had a deviation of 0.097 from unity gain (lower bound JND gain =0.903) and it became noticeable. We propose that people were more likely to notice the visual-proprioception mismatch at lower gains because they had to do more work in order to overlap the goalpost with the football, while less movement was required to accomplish the task with the upper gains. Steinicke et al. (2008) similarly observed that individuals had asymmetrical of gains at detection threshold (DT) for redirected walking, which also suggested people may detect lower and upper gains differently. However, their results showed that people were less likely to notice redirected walking subjected to lower gains.

The effect of target location on probability of detection was observed in the asymptomatic individuals during the JND task. Specifically when asymptomatic participants performed left-flexion movement of the neck, the modeled JND gain was 0.814 for the lower bound, which is almost 0.1 less gain than the JND of the overall model. This may be due to different normal ranges of motion in an extension versus a flexion movement. However, the symptomatic participants had more restricted neck range of motion and neck pain than the asymptomatic individuals, the symptomatic participants' perception of targets in various locations did not affect probability of detection. This finding may influence the design of an altered visual-proprioception task that involves neck rotation for healthy individuals since the perception of neck movement differs by direction.

Although it was beyond the scope of this study, some simple analyses such as correlations were performed to explore a possible relationship between the JND gain of the patients and their pain characteristics, including VAS, TSK-11, and NDI-10. There were no clear correlations between JND gain and the patients VAS, TSK-11, and NDI-10 scores. It be would an interesting future study investigate patients susceptibility to visual-proprioception mismatch in relation to their neck pain symptoms and pain complaints.

In both study populations, some participants were relatively more sensitive to the visual-proprioceptive mismatch and they were able to consistently detect that two neck movements were of different gains. These participants were considered to have a more precise level of detection. Other participants indicated on half of the trials that the neck movements did not feel different. For instance, in one trial the participant indicated that two movements were the same, yet in another trial with the same C-D gain, the participant perceived the movements to be different. Both healthy participants and individuals with chronic pain reported that tightness in the neck muscle provided cues that were used to detect differences when they performed movements beyond their JND, which implies that proprioceptive cues were more noticeable outside of JND. This suggests that when individuals are exposed to C-D gains within the JND, there is visual dominance over proprioception, which was similar to the findings in the proprioception literature [31], [32].

It should be noted that there was not a common JND among the participants. We speculate that the between-subjects JND variation could be related to the participants' regular activities of daily living or exercise habits that may have influenced their ROM, as one asymptomatic participant indicated that she performs yoga and her individual data show wider JND tolerance range. It becomes critical to select the appropriate C-D gain and then experimentally determine the C-D for the planned task and intended population, since the probability of detecting altered visual feedback may vary by the movement and muscles involved.

During the evaluation task the symptomatic participants performed neck rotation movements at a "nudge gain", which was set to be 0.5 gain less than their personal JND gain. This part of the task was to explore tolerance and general responses of patients to increased visual-proprioceptive mismatch. Patients have indicated that the neck rotations were "feasible and as expected" during the movements that had a nudge gain, which provide more insights on the use of gain and visual-proprioceptive mismatch for rehabilitation. In this study, the patients' JND gain was a calculated value from a logistic regression at 25% DT and this DT was adapted from the literature [41]. From the patients response to the nudge gains, it suggested that the patients were able to perform movements at a nudge gain that was beyond the 25% DT.

It is possible that the DT for seated posture upper extremity movements could be greater than 25%, and this piece of information will inform the design of future rehabilitation systems that build on the concept of visual-proprioceptive mismatch. On the other hand, there were some other plausible explanations to the patients' ability to perform neck rotation at the nudge gain. The first explanation is that the VR environment and the football activity distracted the participants from the pain, which was analogous to the SnowWorld scenario that distracted patients with burns during their rehabilitation session [43], [44]. Overall, this provided some more insights on patients' tolerance to perception alteration.

A. Study Limitations

The standard neck ROM test was not used for the asymptomatic participants since it was intended to examine the influence of visual-proprioceptive mismatch on perception. Although this procedure was not needed for the JND gain results, it might have been informative for the understanding the relationship of ROM and JND gain.

As the type of medical and rehabilitative treatment (e.g., massage, physical therapy, cortisone injection) received was not controlled, we cannot assess whether treatment affected JND of the symptomatic participants. Potentially type of treatment may help to explain some variances in the tolerance of mismatch, however this was not within the scope of this study and therefore not assessed.

Target acquisition was determined in the software. Although target positioning error was not explicitly recorded in this study, we should acknowledge that small errors might occur in the measurement devices. The target locations were programmed to be relative to the center of the headset scenario, and at the start of each trial the center was always "zeroed." This way any possible drifting problems of the device was minimized, and therefore location error of the target was minimized.

Although any possible error in target location was not explicitly recorded in this study, we should acknowledge that errors might exist in measurement devices. The target locations were programmed to be relative to the center of the scenario, and at the start of each trial the center was always "zeroed." This way any possible drifting problems of the device was minimized, and therefore location error of the target was minimized.

Another potential limitation existed in the evaluation task. Some chronic neck pain individuals did not indicate difficulty in ROM when they performed the movements at nudge gain, which would have been outside of their indicated feasible range at the start of the evaluation task. It could be possible, as described earlier, that the VR environment distracted the patients from potential pain. However, the JND was operationally defined and calculated to be at the 25% DT of the patient, it was possible that the mismatch from nudge gain was not detected by the symptomatic participants because there was the 25% DT. Moreover, the symptomatic participants could have slightly moved their trunk to compensate for the inadequate neck movement and its associated neck pain. Although they were instructed to restrain from moving their trunk, it was difficult to physically control their bodily movements. This was another potential source of limitation in this study.

Lastly, we were only able to conclude that the calculated C-D is feasible for the neck rotation task described in this study since we did not examine the detection of proprioceptive mismatch in other movements. The JND for other possible rehabilitative exercises will need to be further explored.

V. Conclusion

In VR, neck movements of asymptomatic individuals and neck pain patients were affected by manipulated visual feedback. The visual-proprioceptive mismatch led to increase magnitude of neck rotation movement in VR. However, not all participants were affected by the visual feedback to the same extent since the JND varied individually for each participant. This study also demonstrated that the visual feedback in VR could override muscle proprioceptive cues at or within the JND. It may be possible to use altered visual feedback at JND to encourage patients with chronic musculoskeletal pain to perform therapeutic exercises. The transferability of increased neck rotation magnitude of patients and whether there are any long term clinical benefits to patients, with repeated use of VR, still needs to be explored.

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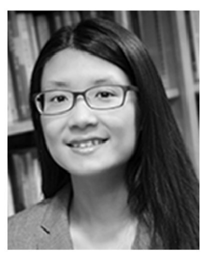

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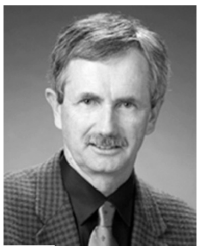

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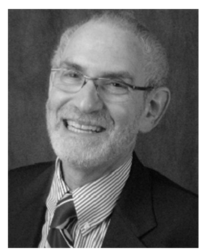

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