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The effect of pain on balancing behavior: Complexity analysis of mediolateral force trajectories

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ABSTRACT

Background: Postural instability is a prevalent and deleterious consequence of aging. It is unclear how the occurrence of chronic pain augments balance issues as age progresses.

Research question: We investigated how postural stability is influenced by aging and chronic pain.

Methods: Fifty-five participants with and without recent chronic pain balanced on one foot while performing three tasks, a standard balancing task with no challenge, a mental task in which participants answered arithmetic questions while balancing on one foot, and a knot-tying task in which participants tied knots in a ribbon while balancing on one foot. General linear models were used to assess the relationship between age, sex, BMI, and pain category for the three different balancing tasks. In addition, a multivariate analysis of variance was used to test the effect of age and pain category on Hurst exponents from all of three different balancing tasks.

Results: Our results show that aging changes the control strategy of balancing from less persistent to more repetitive. The strong feedback elements intrinsic to healthy stability ensure quick reactions and strong capacity to compensate for balance checks; this reactive state changes into a less reactive and more predictable balance strategy with age while balancing on one foot. Mental tasks during balancing also decreased the feedback in balancing strategy. Balance strategy during the knot-tying task was correlated with age, but unaffected by chronic pain. Overall, the chronic pain group had a worse balance strategy while performing the mental task in comparison with healthy people, but were not differentiable from controls in the standard or knot-tying tasks.

Significance: Scores from balancing while engaging in cognitive tasks may provide evidence of health decline, and contribute to our knowledge about how pain affects feedback mechanisms.

1. Background

Advancements in understanding postural stability, the ability to maintain an upright stance, are of great importance; falls often result in catastrophic injury and death, especially in the elderly [1,2]. There are many physiological reasons for declining stability, including neural receptor desensitization, slower central pattern generators in the brain, and slower motor unit recruitment [3–5]. In addition, nonlinear interactions of control nodes may result in altered complexity of balancing movements and a further decline of this complexity when a person is given mental challenges while balancing [6]. One condition which often results in impaired postural stability and may provide a framework for further understanding of the mechanisms at play in age-related decline in stability is chronic pain [7].

It is estimated that more than 100 million Americans suffer from

chronic pain, caused by a combination of physiological and psychological issues [8]. In addition to loss of function, a dangerous problem associated with chronic pain is postural instability, which can lead to permanent injury and death [7,9]. Besides lower extremity pain which would logically affect stability, chronic lower back pain has been shown to change the postural control of both young and older adults by changes in angle of trunk tilt and altered perception of lower extremity muscle excitation [10,11]. Surprisingly, even upper body pain such as shoulder pain has been shown to affect postural stability, possibly due to the coincidental pathway of muscular inhibition and the central nervous system [12,13]. Further, Mann et al. [9] showed that women who suffered from chronic lower back pain had significantly impaired postural control strategies, as evidenced by increased center of pressure velocity. The removal of visual feedback (eyes closed condition) further impaired the postural stability [9]. Lee et al. [7] also showed postural

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instability in patients with chronic lower back pain when compared with controls in the eyes closed condition. Although this connection between postural instability and chronic pain sufferers has been drawn, it is unclear how the control strategy of balancing changes due to pain, which balancing tasks result in impairment, and whether or not these balancing changes still exist once an individual is treated and sees a reduction in significant pain levels. In addition, Rashiq and Dick [14] showed that 2/3 of chronic pain sufferers who expressed pain levels of greater than 3 on a scale from 1 to 10 showed decreased cognitive functioning. Identification of specific balancing tasks that create balance difficulty in people with chronic pain will reveal altered control strategies and provide a framework for future quantitative evaluation for diagnostics and treatment. In addition, if individuals with a history of chronic pain show differences in balancing ability during tasks requiring extensive focus, it will provide evidence for cognitive changes related to pain.

In this study, we quantify balancing data from patients receiving treatment for chronic pain, for the purpose of detecting balance differences between people with pain patients and healthy controls. Chronic pain from all sources has been shown to affect the brain similarly, with increased gray matter volume in the hippocampus and parahippocampal gyrus, regardless of the source of the pain [15]. In addition, upper-body pain has been linked with balance disturbances, but the degree of pain was not correlated with the balance sway widths [12]. We wanted to test whether there were overall differences between controls and people with a recent history of chronic pain, without regard for the musculoskeletal source.

Most participants in the pain category experienced back, hip, or neck pain, and many patients had multiple origins of their pain. It is known that the existence of chronic pain raises the likelihood of additional pain elsewhere in the body (central sensitization), and there remains a high prevalence of uncertainty in diagnosis of and identification of the cause of chronic musculoskeletal pain [16]. In this study, our goal was to compare patients with pain and no pain in general, therefore, we pooled all treated patients into the “pain patient” category. Future targeted studies might address the role of the origin of the pain.

We have shown a significant difference between controls and patients with chronic pain in balancing during a mental task. We suggest further research regarding the mechanism, and speculate that with chronic pain, individuals are unable to balance as mechanically efficiently as healthy people, due to pain signals from sensory neurons disrupting the most efficient energy dissipation capability [17]. We predict that aging will result in a decrease in complexity in balancing behavior and this pattern will interact with pain treatment. We predict that the effect of pain can override the declining age-related trend and the loss of complexity in balancing strategy will emerge also in younger patients.

2. Methods

Twenty subjects, both sexes (10 males and 10 females) aged between 18 and 59 with body mass index averaging 30.31 (BMI 23.8–45) voluntarily participated in this study; data were collected on site at the Johnson City Chiropractic Clinic and East Tennessee State University [18]. Pain is generally immediately treated when it manifests, therefore we studied patients who are currently under treatment via chiropractic practices, and only one patient took any pain medication. The patients were asked to verbally describe what sort of pain they experienced chronically and the amount of pain that they felt prior to trials. Affirmed pain levels were low during trials; participants did not express that they felt significant pain during trials. For controls, thirty-five age and BMI-matched subjects, (18 males and 17 females) aged between 18 and 72 with body mass index averaging 27.5 (BMI 20.5–42.8) from East Tennessee State University campus were included [18]. All control patient claimed good health, had no recent lower extremity injuries, and were without treatment for pain. Every participant

signed an informed consent document; the study was approved by the Institutional Review Board of East Tennessee State University. Before commencing trials, participants performed a ‘timed get up and go’ test in which they were seated in a chair and upon hearing ‘go’, they were asked to stand up and walk 10 ft., then pivot, walk back to the chair, and return to a seated position. If they were unable to accomplish this task within 10 s, they were not permitted to participate further. A Pasco two-dimensional force plate (PS-2142) was used to measure medio-lateral force trajectories. Mediolateral force trajectories from single foot stance were collected at 100 Hz. Force trajectory data have been adequately used for complexity analysis when collected at 100 Hz [1,19,2].

Three different actions were studied: standard test, the mental test, and the knot-tying test [18]. For the standard test, participants initially stood with the dominant foot on the force platform, and the other foot on a support platform with the same height as the device. Upon the start of each trial, the participant would shift his or her weight onto the foot which was on the force plate and maintain balance on that foot for a total of 12 s, including the shifting phase. The shifting period and static standing periods were linked together and analyzed simultaneously in order to test the time dependency of the latter parts of the balancing tasks. We considered that the balancing strategy is a process which consists of a shifting period and the balance maintenance, therefore we did not separate these 2 phases, and we used the Hurst exponents instead of a measurement like time-to-stability, so that we can ascertain the nature of the feedback instead of just how wobbly or tentative the person appeared to be.

Interestingly, it has recently been shown that consistent Hurst exponents estimates have been acquired from collections as low as 5 s in duration [1]. To allow for sufficient time to see differences but to prevent fatigue and motor learning of these unusual tasks, we selected 12 s as long enough to see differences but short enough to avoid the fatigue and learning issues.

Dominant legs were determined by the participant’s verbal affirmation of his or her dominant leg. Hands were placed at the hips for these trials. The other 2 tests are based on these standard setup, but an extra action was implemented. For the mental test, participants were asked to balance on one foot for 12 s while verbally responding to simple addition and subtraction questions, (i.e. What is 1 + 1... - 2... + 4... - 2... + 5, etc.). For the knot tying test, participants were asked to balance on one foot for 12 s while tying two knots in a 20-cm long piece of ribbon.

3. Mathematical methods

We used the Generalized Hurst Exponent method to analyze the mediolateral force trajectories (Equation 1).

$$\frac{\langle |X(t + \tau) - X(t)|^q \rangle - \tau^{q(H(q))}}{\langle |X(t)|^q \rangle} = \frac{1}{v} \quad (1)$$

where $X(t)$ is the time series for each participant, q is the q th order moment (1 in this case), v is a time resolution, which is the time between data points (0.01 s), τ indicates the time interval, which can vary from v to a selected maximum number (the maximum used was 19), and the angle brackets indicate the mean of the observation window. The Hurst exponent is $H(q)$ [20,21].

This method has given results with the largest effect size when observing the effect of age on balancing behavior, in comparison with other methods, such as Lyapunov Exponents, Root Mean Square Displacement, and Fractal Dimension [19]. A Hurst exponent between 0.5 and 1 is assumed to be persistent; A Hurst exponent between 0 and 0.5 is anti-persistent. Overall, this method allows for the analysis of the model in time intervals of differing length, with the assumption that there is a power law which those observation window means follow, which can be related to the Hurst exponent.

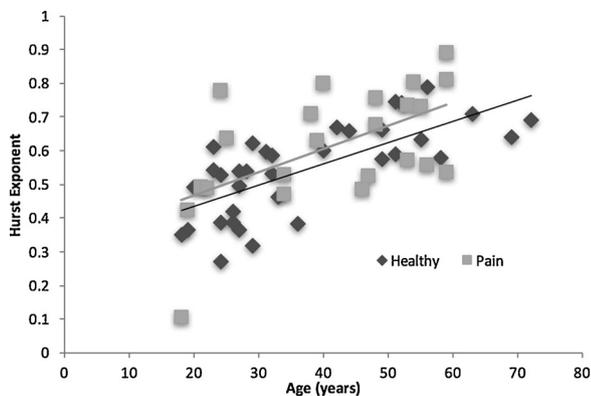


Fig. 1. Control strategy as a function of age for dominant stance in standard task. Generalized Hurst exponents for the mediolateral force trajectories while balancing on one foot, unperturbed as a function of age. Control: black; pain patients: grey. Persistence increases with age for controls and chronic pain patients; GLM: $\text{persistence}(H) = 0.0065 \cdot \text{age} + 0.3207$, $r = 0.64$, $p < 0.05$, $N = 55$; the pain group does not significantly differ from controls ($p > 0.05$); therefore the data were pooled for the overall model.

4. Statistics

We used general linear models (GLM) type III for each of the three tasks to test the relationship between the chaos parameter Hurst exponent as a function of a participant’s age, BMI, health category (chronic pain or control), and sex. The GLM belongs to a statistical modeling technique in which continuous and categorical variables can be analyzed at the same time. We evaluated the linear fits via residual plots of residuals vs. fitted values. We also performed a multivariate analysis of variance to test the effect of age and pain category on all three tasks simultaneously and used the Wilks’ lambda test statistic. The alpha value was set to 0.05 (SPSS, MATLAB 2017).

5. Results

5.1. Control strategy

Neither sex nor BMI were significant indicators of persistence (H) for any trial (GLM, $p > 0.05$). For the standard task, persistence (H) was not affected by pain; only age dependency was detected in the standard test (Fig. 1). For the knot tying test, the trend was similar; pain was not significant and we only detected age dependency in balancing strategy (Fig. 2). Pain, however, had a significant effect on the mental

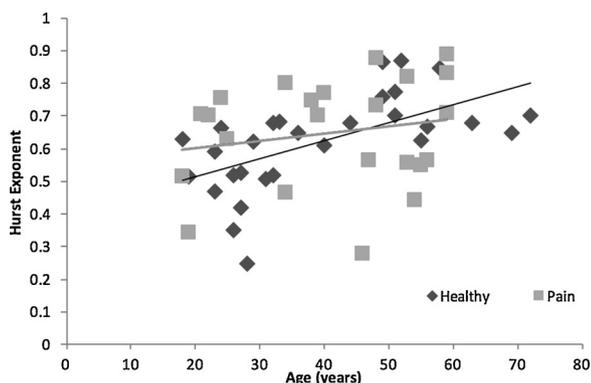


Fig. 2. Control strategy as a function of age for dominant stance in knot-tying task. Generalized Hurst exponents for the mediolateral force trajectories while balancing on one foot as a function of age. Control: black; pain patients: grey. Persistence increases with age for controls; GLM: $\text{persistence}(H) = 0.0043 \cdot \text{age} + 0.461$, $r = 0.42$, $p < 0.05$, $N = 52$; for pain patients, the slope is insignificant ($p > 0.05$); therefore the data were pooled for the overall model.

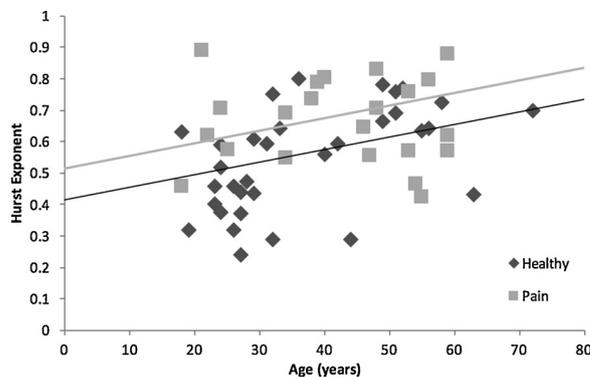


Fig. 3. Control strategy as a function of age for dominant stance in mental task. Generalized Hurst exponents for the mediolateral force trajectories while balancing on one foot as the function of age. Control: black; pain patients: grey. Persistence increases with age and with pain, GLM:

task and significantly increased persistence in balancing (Fig. 3). The pain thus does not alter balancing strategy for the task involving an additional motor control challenge (knot-tying) but affects that strategy for the task involving mental stimulation.

5.2. Dependencies of the persistence of the 3 tasks

There is a significant correlation (Pearson’s correlation coefficient, $p < 0.05$) between all of the combinations of task persistence scores (standard vs. knot-tying $r = 0.34$; standard vs. mental, $r = 0.44$, and knot-tying vs. mental, $r = 0.59$). To test how the balance performances under different tasks relate to each other and pain, we performed a multivariate analysis of variance with all three task scores simultaneously. The results of the multivariate analysis of variance showed that for the healthy people, there was a significant difference between tasks (Table 1, Fig. 5). People with chronic pain do not have a difference in competence (persistence) between tasks, and healthy people have a more structured change in persistency between tasks (Figs. 4 and 5). Marginal means from the MANOVA are shown in Fig. 6; upon multiple post-hoc comparisons of the model, with Scheffe correction, there are no differences between any combination of tasks for the pain group, and for the healthy control group, there is a significant difference between the mental and knot-tying tasks, $p < 0.05$. Healthy people are thus most competent (using feedback mechanisms) at the standard balancing task and the worst at the knot-tying task.

6. Discussion

6.1. Balancing strategies

There is feed-forward balancing strategy which emerges with age, even in apparently healthy people [19,18]. Recent studies have shown prominent differences between young and old people in mediolateral sway [1,22,18]. We have also shown an age-related increase of persistence of balancing behavior with age in both healthy individuals and those with a recent history of chronic pain, which indicates the slowing of feedback processing [3,4]. In our study, the mental and knot-tying tasks are affecting the people of different ages similarly in terms of increased persistence in balancing strategy. Our results showed that

Table 1
MANOVA table by group (Pain vs. Control).

Group	Statistic	Value	F	R-Square	df1	df2	p-value
Control	‘Wilks’	0.843	4.29	0.157	2	46	0.0196
Pain	‘Wilks’	0.968	0.767	0.0323	2	46	0.470

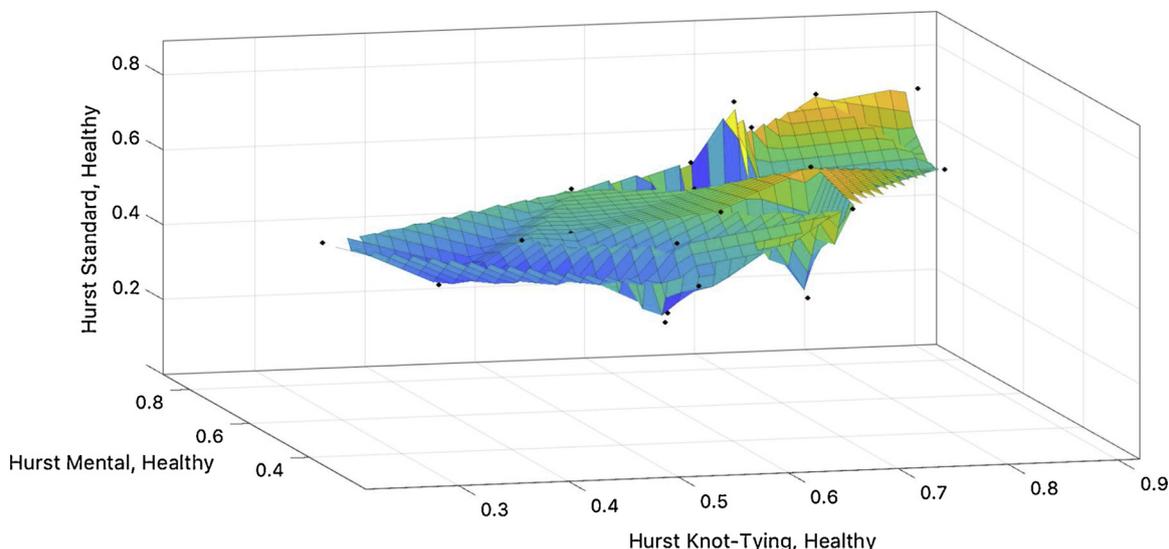


Fig. 4. Persistence during the standard task plotted against the mental task and the knot-tying task for healthy people. Dots represent individual patients with persistency indices (H) of their 3 tasks.

young people, roughly less than 35 years of age, with chronic pain, still have anti-persistent control strategies for all tasks, so age appears to still be a more powerful predictor of balance strategy; it is possible that young people have decreased sensitivity to pain when compared with the elderly. It is controversial how age impacts the perception or processing of pain, but it has been shown that the elderly have decreased sensitivity to cardiac and heat pain but increased sensitivity to nociception when deep tissues are stimulated [23,24,26].

6.2. The effect of pain on balancing

Our results show that chronic pain affects the control strategy during the mental task, but not the knot-tying task. It is possible that the knot-tying task, which is a sensory task, causes a change in concentration which allows for an increased processing load of both the pain and the task, thus reducing the effect of the pain on balancing. It is also possible that the knot-tying task was viewed with less trepidation than the mental task and thus resulted in a less-discernable difference between controls and people with chronic pain. Regarding our results which show a difference between healthy and pained individuals for the mental task, it has been shown that there is a positive correlation between math scores and calculation activation in the bilateral anterior

cingulate cortex [25]. It is thus possible that the processing of pain and mathematical reasoning are largely processed in the anterior cingulate cortex and that a math task is not capable of taking precedence over pain processing. It has also been shown that while performing basic arithmetic, both the agonist muscle (gastrocnemius) and the antagonist muscle (tibialis anterior), which both are integral in maintaining ankle positioning for solid stability, have reduced activity [26]. In addition, the fact that there is no difference between task types for people with chronic pain suggests that these subjects may have begun the tasks with an enhanced level of trepidation and that the complementary postural stiffening intrinsic to nervousness may have caused each individual to respond less predictably to each task than controls. Carpenter et al. [27] showed that there are negative changes such as increased amplitude of center of pressure trajectories during tasks that elicit fear in both young and older participants such as balancing on elevated surfaces; because chronic pain is a result of both physiological and psychological issues, the psychological component may have influenced each pained person spasmodically [8].

6.3. The effect of both aging and pain on balancing

There is decreased amplitude of muscle activity in the

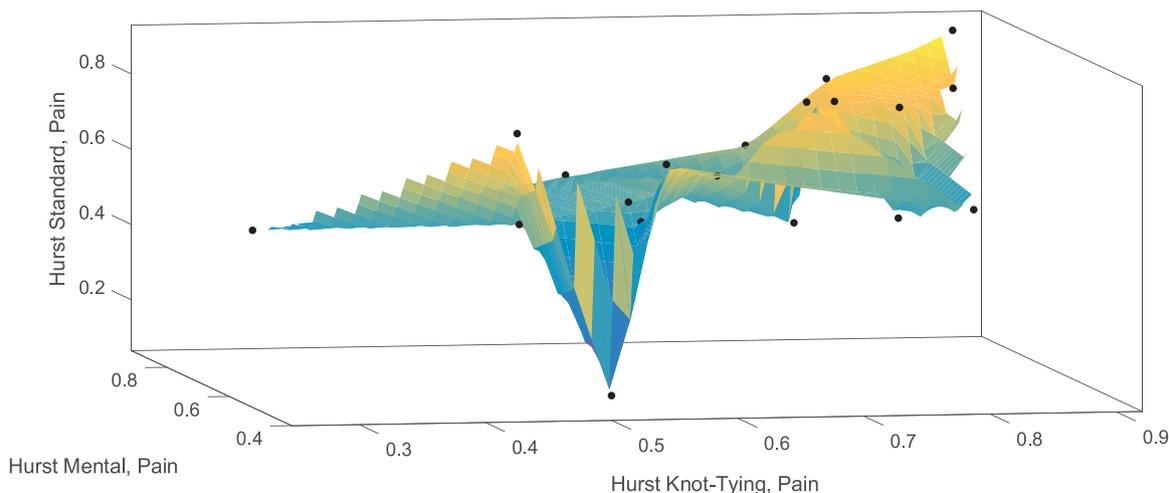


Fig. 5. Persistence during the standard task plotted against the mental task and the knot-tying task for people with chronic pain. Dots represent individual patients with persistency indices (H) of their 3 tasks. The surface is relatively flat for the pain group.

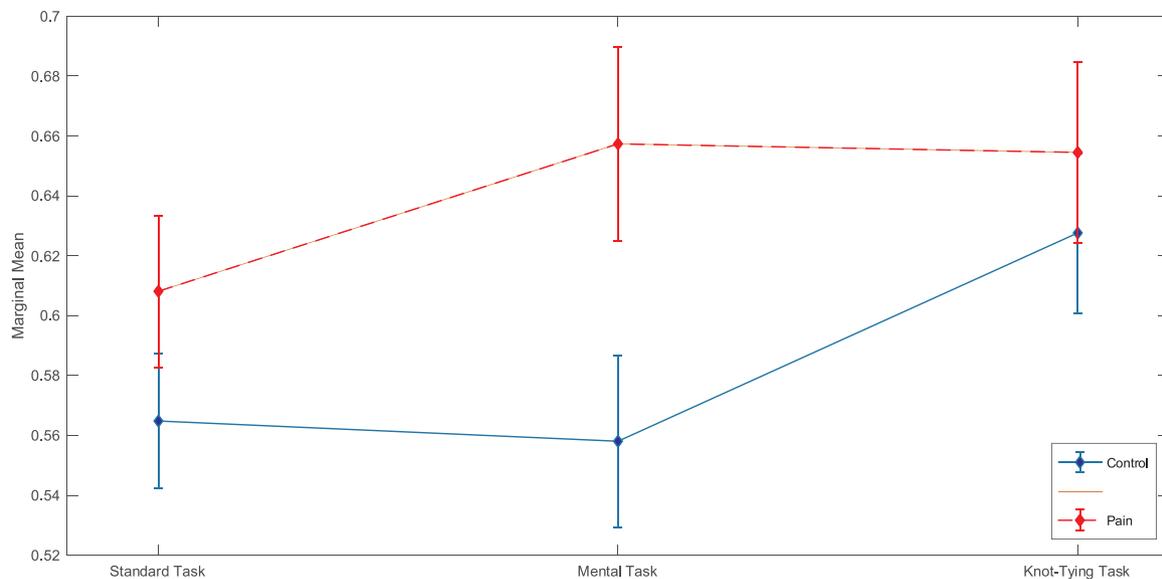


Fig. 6. Marginal means from the multivariate analysis of variance are plotted against the three different tasks, the standard, mental, and knot-tying tasks, respectively. From the results of the MANOVA, there were no significant differences between tasks for the pain group, but there were overall significant differences between tasks for the healthy control group.

gastrocnemius muscle when comparing older people with younger people at time 350–500 milliseconds after beginning balancing [26]. These changes in muscle activity occur too quickly to be a result of the monosynaptic system and thus must originate in higher brain centers [26]. Cognitive functioning is altered with age, thus the increased attentional demands with the perturbing balancing tasks create signal overloads which disrupt the typical balancing capabilities; similar reactions are thus occurring in the people with pain, but it is not until the mental task that the pain signals significantly affect the balancing ability. For healthy people in the mental task, the control strategy passes through a range that is approximately random, around $H = 0.5$, at around age 30. For the people with pain during the mental task, the values are approximately either random or strongly persistent even at a young age, which shows that the pain either distracts from the selection of a solid pattern to follow, or it causes the individual to be even more resistant to feedback mechanisms than their healthy counterparts.

We had hypothesized that those who had experienced chronic pain do not balance as mechanically efficiently as healthy people for the mental and knot-tying tasks and found this to be true only for the mental task. Further, we had hypothesized that the age-related change in balance ability would be removed in people with chronic pain, and this was again only the case for the mental task.

To understand the specifics of this pattern, future studies could focus on specific types of pain and also utilize more accurate pain level assessments than verbal claims from the patients. All but one patient in this study verbally attested to having relatively low pain levels (below a 3/10 and all attested to no pain during trials). And since it has been shown that cognitive challenges accompany chronic pain, the prevalence of previous chronic pain in these patients could indicate that there are long-lasting cognitive defects, even during successful treatment and pain remission [28,30]. Further, we observed the effect of previous pain on people who have been treated for varying lengths of time, and were unaware of initial diagnoses or initial pain levels prior to treatment and thus cannot clearly delineate length or severity of the past chronic pain. Further work should compare cognition between people of varying pain levels against people in pain remission.

The most prominent result in this work is that the age-related predictability of persistence is maintained in people who had previously experienced chronic pain, but that the advent of a mental task increases the persistence of balancing strategy in the pain group in comparison with the controls. We present these findings for the purpose of

enhancing balancing tests in order to better understand the changes intrinsic to the perception of pains so that the predictability of catastrophic falls can be enhanced.

Competing interests

There are no declarable competing interests.

Authors' contributions

All authors contributed in conceiving and planning the study, analyzing the data and writing the manuscript.

Ethics, consent, and permissions

This study was approved by the ETSU Institutional Review Board (IRB#: 0214.27f).

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