Learning Curves Observed in Establishing Targeted Rate of Force Application in Pressure Pain Algometry

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ABSTRACT

Purpose: To determine whether learning curves can be observed with deliberate practice when the goal is to apply a consistent rate of force at 5 N/second during pressure pain threshold (PPT) testing in healthy volunteers. **Methods:** In this prospective study, 17 clinician participants completed PPT targeted rate-of-application testing with healthy volunteers using three different feedback paradigms. The resultant performances of ramp rate during 36 trials were plotted on a graph and examined to determine whether learning curves were observed. **Results:** Clinicians were not consistent in the rate of force applied. None demonstrated a learning curve over the course of 36 trials and three testing paradigms. **Conclusion:** The results of this study indicate that applying a consistent 5 N/second of force is difficult for practising clinicians. The lack of learning curves observed suggests that educational strategies for clinicians using PPT may need to change.

Key Words: hyperalgesia; learning curve; pain measurement; pain perception; psychomotor performance.

RÉSUMÉ

Objectif : Déterminer si une courbe d'apprentissage se dégage en réponse à un entraînement délibéré visant à appliquer un taux de force constant de 5 newtons par seconde (N/s) lors de tests du seuil de douleur à la pression (PPT pour *pressure pain threshold*) auprès de participants en santé. **Méthodes :** Dans cette étude prospective, 17 cliniciens ont réalisé des tests sur des participants en santé au moyen de trois modes de rétroaction. La variation du taux de force observée sur 36 essais a été représentée graphiquement afin de déterminer si une courbe d'apprentissage se dégageait chez les cliniciens. **Résultats :** Le taux de force appliqué par les cliniciens n'était pas constant. Une courbe d'apprentissage n'a été observée chez aucun d'entre eux au cours des 36 essais, peu importe le mode de rétroaction. **Conclusion :** Les résultats de cette étude indiquent qu'il est difficile pour les cliniciens praticiens d'appliquer un taux de force constant de 5 N/s. L'absence de courbe d'apprentissage donne à penser qu'il pourrait y avoir lieu de revoir les stratégies de formation des cliniciens appelés à mesurer le seuil de douleur à la pression.

For both physical therapists and occupational therapists, consistent psychomotor skills are a professional necessity when completing clinical pain measures. Health care educators have suggested focusing on deliberate practice to develop essential psychomotor skills.¹ Boe and colleagues^{2(p.309)} have defined motor learning as a “process where improvements in performance are seen over a series of discrete training sessions, and following a delay and subsequent consolidation of the skill, similar levels of performance are observed on a retention test.” Sigrist and colleagues³ have described three phases of psychomotor skill acquisition. In the most cognitively demanding stage, the motor programme is developed; in the second, or associative, phase, error recognition and corrective attempts are noted; and, finally, in the

automatic phase, performance demonstrates a steady state of efficient and coordinated movement without feedback.³ Because this transition from performance to learning is influenced by a wide variety of internal and external factors, deliberate practice with concurrent or terminal augmented feedback³ has been reported to be imperative for psychomotor skill acumen to develop via performance modification.^{1,4}

When the optimal amount of feedback and trials is unknown, deliberate practice has been mapped on a learning curve, which is a graphical representation of the change in performance over the number of practice trials (see Figure 1).⁵ The initial flat line represents the cognitive stage, in which repeated trials produce minimal improvements in performance.⁵ The subsequent

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Figure 1 Ideal learning curve.⁵

upslope indicates movement into the associative stage,⁵ and the start of the second flat line indicates that the associative phase of learning has been reached, with no further improvement in performance. The number of trials corresponding to this point on the curve is recorded as the recommended number.⁵

Interest in evaluating altered somatosensory processing via quantitative sensory testing (QST) tools has grown. Pressure pain threshold (PPT), defined as the point when the intensity of the pressure algometer “becomes linked with that of pain,”^{6(p.637)} has been studied in various acute and chronic pain conditions, including low back pain,^{7–9} jaw pain,¹⁰ patellar tendinopathy,¹¹ knee osteoarthritis,¹² whiplash-associated disorder,¹³ and neck pain.¹⁴ PPT is a method-of-limits test (i.e., the participant must respond to stop the application of the test),¹⁵ which makes the participant’s response time an influencing variable.¹⁵ The neurophysiological changes that occur during musculoskeletal pain can also influence PPT; for example, temporal summation can occur in response to repeated application of a stimulus (i.e., although a single application of the stimulus may not be painful, the same stimulus repeated can result in increased pain).¹⁶ A study specific to PPT demonstrated a decreased threshold when the same force intensity was applied with less time allowed between applications.¹⁷

Clinically, a lowered PPT, or hyperalgesia, may suggest underlying sensitized peripheral nociceptors when found at a site local to the injury or central sensitization when found at sites distal to the injury.¹⁶ PPT has also been proposed to be helpful in clinical decision making and prognosis.^{8,13} In people with whiplash-associated disorder, lowered PPT demonstrated distally in the leg was predictive of increased self-reported disability.¹³

Reliability is integral to the clinical interpretation of

PPT. Early researchers recommended a consistent rate of force application,^{18,19} but only recently has a protocol specified this rate to be 50 kPa/second (5 N/s).²⁰ Other studies have found that the inability to maintain a consistent rate of force application influences terminal PPT.^{18,19} In the temporal muscles of healthy participants, mean terminal PPT varied from 115 (SD 122) kPa/cm² when the algometer was applied at a slow rate (0.07 N/s) to 253 (SD 155) kPa/cm² when it was applied at a fast rate (0.68 N/s).¹⁹ In people with craniomandibular pain, the rate of force application significantly influenced the final threshold.¹⁸

The reliability of terminal PPT has generally been reported to be good in a variety of clinical and research settings.^{9,21–24} Intra-rater reliability has been reported to range from an intra-class correlation (ICC) of 0.94 (standard error of measurement [SEM] 4.5) to 0.97 (SEM 18.2);²¹ in the same cohort of testers, interrater reliability varied from an ICC of 0.79 (SEM 52.5) to 0.84 (SEM 59.2),²¹ and in another cohort it reached a high of 0.91 (SEM 6.7).²³ Finally, test–retest reliability ICCs have ranged from 0.76 (SEM 48.9)²¹ to 0.98²⁴ These findings meet the cutoff threshold for good reliability (ICC ≥ 0.75).^{25(p.595)} However, the large SEMs reported limit precision and invite caution with this interpretation.

Two recent studies have examined the rate of force application.^{23,26} Rolke and colleagues^{26(p.40)} found that the actual mean rate of force application, when “checked in a few subjects,” was 55 (SD 5) kPa/s. In one of the most detailed descriptions of training, the participants blinded to the rate of force application were considered to have demonstrated reliable rate of force application when they applied a fixed-angle algometer at a rate of 5 N/second over 10 seconds in 5 consecutive trials.²³ “On the first attempt,”^{23(p.762)} all participants applied the algometer at the target rate of 5 N/second in five consecutive trials.

Previously identified methodological limitations include a lack of detail on rate of application and on tester training.²⁷ Interestingly, three of five studies^{9,22,24} did not report the amount of training, and the remaining two reported training to be 1 hour²¹ and a “single day.”^{23(p.761)} The lack of details on training in PPT testing is not consistent with other medical education for psychomotor skill learning.¹ The currently reported training protocols for PPT testing^{21,23} may be insufficient for the psychomotor skill of applying targeted rate of force during PPT testing.

Although practising clinicians need to learn how to use QST tools, the literature contains few descriptions of actual educational strategies for rate of force application. The purpose of our study, therefore, was to determine whether learning curves could be observed with deliberate practice when the goal was to apply a consistent rate of force of 5 N/second during PPT in healthy volunteers.

METHODS

Clinician participants

In this prospective, cross-sectional study, participants were practising clinicians working in an outpatient rehabilitation department. Before the study, all clinicians participated in a departmental in-service aimed at improving the management of patients with chronic pain, which included a 1-hour tutorial on QST that allowed the opportunity for practice time. The clinician participants were instructed to use PPT at their discretion during their clinical practice. Approximately 12 months later, after reviewing and signing written informed consent approved by the institutional review board (2012-0780), all clinician participants completed a demographic data sheet that included questions on their use of PPT in clinical practice. Clinicians were included in the study if they were interested in participating, had worked in the clinic for at least the past year, and had attended the in-service described earlier.

Healthy volunteers

Healthy volunteers were recruited from among the entry-level Doctor of Physical Therapy student interns assigned to the clinic as part of their clinical education requirement and were included if they reported no musculoskeletal disorders within the previous 6 months. The volunteers reviewed and signed the written informed consent.

Testing procedures

To assess the learning curve for applying rate of force at 5 N/second, the authors predetermined a cut-point of 40 N/cm², which allowed for 8 seconds of testing per trial. A handheld 500 N capacity pressure algometer with a 1 cm² rubber tip (ForceTen FDX; Wagner Instruments, Greenwich, CT) is commonly used in the clinic and was therefore used for this study. We chose a target of 40 N/cm², which is below lumbar PPT thresholds previously reported in people without back pain (45.5 [SD 25.82] N/cm² on the right side and 44.7 [SD 22.93] N/cm² on the left)²⁸ and within the range of anterior tibialis (AT) PPT thresholds in a healthy female population (33.41 [SD 15.7] N/cm²).¹⁴ Three sites were tested bilaterally, in random order chosen by rolling a die: the quadratus lumborum, the lumbar paraspinals, and the AT. The quadratus lumborum sites were measured 5 cm lateral to the fourth lumbar spinous process; the paraspinal sites were measured 3 cm lateral to the first lumbar spinous process; and the AT sites were measured 5 cm inferior to the tibial plateau and 2.5 cm lateral to the tibial crest. Three feedback paradigms were used, during which two different sites were assessed on the volunteers. At each site, the clinician participant applied the algometer six times, with each trial starting 30 seconds after the previous trial ended. The testing schedule

ensured that no one volunteer was involved in testing more than twice in 1 week or on consecutive days.

Feedback paradigms

Clinician participants were instructed to apply the pressure algometer at a rate of force of 5 N/second until the 40 N/cm² target was reached. In the first two paradigms, they received concurrent feedback during each of the 12 trials; in the third paradigm, which also consisted of 12 trials, they received terminal feedback if their performance missed the target. The feedback paradigms were consistently completed in the same order: audio-visual (AV) feedback, then visual feedback, then no audiovisual (no AV) feedback.

In the AV paradigm, clinician participants listened to a metronome set at 60 Hz (i.e., chiming once per second) and could observe the visual display on the pressure algometer. We hypothesized that the ability to hear the target rate while observing the actual force applied would facilitate the motor programme development phase² as learners received instruction (pacing) and feedback (visual display). Audio feedback had previously been used to help participants maintain a standard pace¹² and would be analogous to the concurrent audio feedback discussed in other psychomotor studies.³

In the visual paradigm, clinician participants could observe the visual display on the pressure algometer, as described in previous studies.²³ We hypothesized that at this stage the learner might be able to correct any errors if the 40 N/cm² target was reached too quickly or too slowly, through the learner's own interpretation.

In the no-AV-feedback paradigm, clinician participants could no longer see the visual display, as in a previous study in which participants were blinded to the visual display.²³ They were instructed to apply the algometer until they thought the maximum of 40 N/cm² had been reached; in an effort to protect the volunteers, the investigator stopped the trial (essentially providing negative feedback) if force application went on for too long or with too much intensity.

Force-sensing resistor

The force-sensing resistor (FSR) was constructed and calibrated following the instructions of Tuttle²⁹ (Figure 2), who developed this device as a way to provide accurate real-time or archived feedback of force applied between 5 and 45 N ($\pm 20\%$).²⁹ Our version of the device used a Flexiforce A201 1 lb sensor (Tekscan, Inc., South Boston, MA) attached to an 11 mm diameter washer and software to quantify force intensity to the thousandth of a second. Pilot study findings indicated that the pressure algometer's visual display and the FSR findings were comparable. To optimize accuracy, the FSR was calibrated before each clinician participant was tested and after approximately every three trials during the testing sessions.²⁹

Figure 2 Force-sensing resistor used with pressure algometer.

Data analysis

We graphed the data generated by each of the 36 trials, with intensity of force generated on the y axis and time on the x axis. The graphs were qualitatively examined via visual analysis.⁵ For each trial, we monitored a graph of the observed increase in force intensity on a second-by-second basis. If the intensity of force in a trial increased by a total of 5 N/cm² by the beginning of the subsequent second during 7 of 8 seconds, that trial was dichotomized as “accurate,” meaning that the target force application rate had been met (see Figures 3a and 3b for examples).

To determine whether a learning curve was demonstrated over the course of 36 trials, we would have needed to analyze the exact rate of force application over each second for each individual trial. However, because the FSR records force to the thousandth of a second, the actual force recorded varied greatly, with large positive-to-negative swings within each second, which would have influenced the final calculated rate. We therefore chose an alternative method, the time to maximal force. Measuring the time to maximal force mimics a clinical situation, in which PPT testing would be halted at the maximum amount of force the patient could tolerate. Using this method, we calculated the rate of force application for each trial and plotted it on a graph, with force per second on the y axis and number

of trials on the x axis. These graphs were then qualitatively examined to determine whether participants’ performances demonstrated an initial flat line, an upslope, and a final flat line, indicating a learning curve.⁵

RESULTS

We recruited 22 clinician participants (17 women, 5 men), of whom 17 were included in the final analysis (see Table 1); the remaining 5 were removed from the final data analysis because of technical difficulties with retrieving the archived data. Of the 17 clinician participants with complete data, 5 reported using PPT testing 3–4 times per month; the remaining 12 reported using it rarely or never. We also recruited six volunteers (all female) to act as patients for the testing process. The testing sites and number of trials for each paradigm are described in Table 2.

Rate of force application

AV paradigm

The mean maximum force applied, according to the pressure algometer’s visual display, was 40.57 (SD 2.31) N/cm² for testing site 1 and 40.53 (SD 0.75) N/cm² for testing site 2. None of the clinician participants was able to achieve 5 N/second in at least 7 of 8 seconds. Although four clinician participants were able to apply a consistent force during the majority of the testing trials, the rates applied did not meet the criterion standard.

Visual paradigm

The mean maximum force applied, according to the pressure algometer’s visual display, was 40.83 (SD 1.23) N/cm² for testing site 1 and 40.62 (SD 0.70) N/cm² for testing site 2. Although no clinician participant achieved 5 N/second during at least 7 of 8 seconds, five were able to apply a consistent force, though not at the criterion standard.

No-AV-feedback paradigm

The mean maximum force applied, according to the pressure algometer’s visual display, was 41.59 (SD 2.72) N/cm² for testing site 1 and 39.54 (SD 3.96) N/cm² for testing site 2. A single clinician participant was able to achieve 5 N/second during at least 7 of 8 seconds; five were able to apply a consistent force, but not at the criterion standard.

Learning curves

Of 17 clinician participants, 1 demonstrated no learning curve because a steady state of the performance was observed over all three testing paradigms; the other 16 showed no overall learning curve across trials because their performance was inconsistent from one feedback paradigm to another.

In the AV paradigm, four clinician participants showed the initial components of the curve (the initial flatline), indicating that a stable rate of force application was

Figure 3 Examples of consistent (a) and inconsistent (b) rate of force.

being reached, although it was either faster or slower than the target 5 N/second. It is interesting that performance began to worsen in the visual paradigm for those same four participants. Because performance worsened after trial 24 (at the initiation of the no-AV-feedback paradigm) for six participants, there was no final upslope of the curve (see Figure 4).

DISCUSSION

To our knowledge, this is the first study to examine the learning curves associated with deliberate practice of the psychomotor skill of applying a consistent 5 N/second of force during PPT testing. The graphs shown

in Figures 3 and 4 are also novel because they give us insight into how the performance of force application changed in each trial. Because the actual rate of force application during PPT testing can now be quantified, our results suggest that practising clinicians—even those who report more frequent use of PPT—do not consistently achieve a rate of 5 N/second. The clinical impact of this finding is that the reliability of PPT, which is increasingly popular, may need to be improved through more systematic and nuanced educational strategies. The consistent terminal PPT observed in all three paradigms suggests that terminal PPT and rate of force application

Table 1 Participant Demographics

Clinician Participants	Mean (SD)*
Physical therapist, no.	13
Occupational therapist, no.	4
% female	82.35
Age, y	36.86 (10.55)
Time in practice, y	12.65 (10.30)
Practice in an orthopaedic setting, y	10.85 (9.19)

*Unless otherwise indicated.

Table 2 Number of Trials at each Testing Site per Feedback Paradigm

Site	No. of trials					
	AV		Visual		No AV feedback	
	1	2	1	2	1	2
AT						
Right	4	1	2	3	5	4
Left	0	6	4	3	1	3
QL						
Right	3	4	3	3	1	4
Left	3	4	2	2	2	4
PS						
Right	1	1	4	5	6	2
Left	7	2	3	2	3	2

AT = anterior tibialis; QL = quadratus lumborum; PS = paraspinals.

are two distinct aspects of PPT that should both be assessed when examining reliability.

Learning curves can be used to identify not only the optimal number of trials required for deliberate practice⁵ but also, perhaps, the style of feedback that is most effective. In our study, learning curves reflected poor performance. Participants' poor performance may have been due to the moderate number of trials in our study (36), which may have been insufficient. Even in the AV paradigm, only four clinician participants were able to demonstrate the initial flat line of cognitive performance during the first 12 trials. The institutional review board acceptance was dependent on demonstrating the welfare of the volunteers; the number of trials we chose was designed to minimize their spatial or temporal summation.

It was interesting that of the five clinician participants who reported relatively frequent use of PPT testing (3–4 times per month), only one showed a steady state of performance over the 36 trials; that is, this clinician had already learned this psychomotor skill and was able to establish a consistent rate of force in varying feedback paradigms. This finding may suggest that a higher number of trials is needed than was used in this study (i.e., this participant completed a minimum of 144 trials, assuming three applications per testing session and a

Figure 4 Learning curve with change in performance in the no-AV-feedback trials.

maximum of four sessions per month for 1 year). However, the other clinicians who reported the same level of PPT use in the previous year did not demonstrate a learning curve. It would appear, therefore, that the actual number of trials is not the only contributor to learning. Further research is needed to identify factors other than number of trials that may be required for optimal psychomotor skill learning.

Our study may not have identified the optimal feedback style for learning this skill. We expected that the transition to the visual paradigm would result in an upslope of the curve, suggesting an associative phase of learning. Although some clinician participants were able to demonstrate a more consistent ramp rate, the upslope of the learning curve was not identified in this paradigm. In the no-AV-feedback paradigm, six clinician participants demonstrated worse performance. Although the no-AV-feedback paradigm could be considered a test of performance rather than deliberate practice, participants still received terminal feedback if intensity was too high or duration of testing was too long. Interruption of the trial indicated non-optimal performance (i.e., negative feedback). Therefore, although the style of feedback changed, clinician participants were still completing deliberate practice. Nonetheless, the final acquisition phase of true psychomotor skill learning was not reached; this phase requires executing the skill without feedback, in varying paradigms and over varying durations of practice.³

The value of demonstrating accurate ramp rate in the no-AV-feedback paradigm can be relevant in clinical practice as well as in research. If terminal PPT is known, the clinician may be biased and may adjust the ramp rate as the known terminal threshold is reached. An interesting future study could take the number of trials required to demonstrate a learning curve with a visual display and examine performance with the same number of trials without a visual display.

Emerging understandings of the neurophysiological changes that occur during nociceptive processing and technical advances in methods of examining in vivo

ramp rate make it possible to reconsider the influence of noxious stimulus parameters (intensity of force and speed). In our study, terminal PPT was consistent, but the rate of force application was not. Contrary to previously published findings,^{21,23} our results indicate that achieving a consistent rate of force application requires more deliberate practice, and they do not support the currently reported protocols. The inconsistent rate of force application has practical clinical relevance in that PPT is considered a tool to assist clinical diagnostic and prognostic decision making. As the use of PPT becomes more commonplace, the current educational guidelines should be adjusted on the basis of a scientific method for establishing a consistent rate of force application.

LIMITATIONS

Our study has several limitations. The first relates to the equipment used in the trials. The FSR, designed for easy and inexpensive use in the clinic, has a reported error rate of $\pm 20\%$.²⁹ On one hand, a more sensitive FSR might help to minimize the variability observed within each second of testing, perhaps allowing for actual calculation of the rate of force application for every second of the trial. On the other hand, the device was able to minimize artefacts between the pressure algometer and the volunteer, replicating the clinical setting. Furthermore, the testing equipment used a convex washer glued to the strip, which is practically similar to assessing PPT on a bony surface. Although the perpendicular algometer was aligned to the testing surface,²⁰ it was difficult to maintain the incongruent surfaces. The unequal pressure required frequent readjustment of the convex surface; the FSR was recalibrated after the adjustments and between clinician participants to minimize error.

Second, because clinician participants demonstrated poor overall learning, it may be that the testing scenarios were not ideal. We attempted to replicate the conditions of clinical practice with algometer choice and volunteers (i.e., in vivo simulation change in normal tissue resistance as the algometer was applied at greater depth). This approach limited the number of trials we were able to include.

Third, all feedback paradigms were completed in one testing session. Although this was a practical choice, designed to limit the study's impact on productivity during clinical hours, a future study could examine deliberate practice with the different feedback paradigms over varying days or weeks. A similarly designed study that included both short-term (i.e., 1 day) and long-term (i.e., 1 month) follow-up could investigate whether any of the participants' learning curves could be demonstrated or maintained over time.

CONCLUSION

Our results indicate that applying a consistent rate of force at 5 N/second during PPT testing is difficult for

practising clinicians over the course of three different feedback paradigms. Therefore, we recommend using increased deliberate practice with varying feedback paradigms to ensure that the optimal rate of force application is achieved in PPT.

KEY MESSAGES

What is already known on this topic

Reliability of assessment of terminal pressure pain threshold has been established.

What this study adds

This study quantifies the force per second of the ramp rate and highlights the difficulty clinicians had in consistently applying the recommended rate of force application at 5 N/second, which suggests that current educational strategies may be insufficient.

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