The role of errors in learning new surgical skills: Using a high-speed burr in cervical laminoplasty as an example

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Abstract

Traditional methods of surgical skill-learning tend to take the form of impromptu hands-on teaching, mainly through explicit learning. In explicit learning, skills are learnt via trial and error, and there is a significant amount of time spent learning and correcting movements until a skill is mastered. In contrast, an alternative form of learning, implicit learning, is the antithesis of the above. Currently, a small amount of literature supports the introduction of implicit learning to the health sector (dentistry and laparoscopic surgery). One method of encouraging implicit processes is to reduce errors in the initial learning of a novel motor task.

The research presented here compares implicit (errorless) learning versus explicit (error-ful) learning in the development of skills with high-speed burr in tasks that simulate cervical laminoplasty. This is the first study to investigate the application of implicit learning principles to spine surgery education. In addition, this study seeks to contribute to evidence for a potential alternative, sustainable means to train surgeons in the future.

The results from this project did not show a significant difference in performance scores or time to the completion of surgical tasks following either errorless or error-ful learning. However, it has demonstrated that skills learnt were transferrable between initial learning tasks to performing a simulated laminoplasty. Further research is needed to confirm a suitable implicit learning protocol for use in surgical training. Advancement in this field is relevant and important in contemporary practice, where 'hands-on' learning opportunities in the clinical context may become limited.

Keywords: errorless learning, error-ful learning, implicit learning, explicit learning, surgical education

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Table of Contents

List of Tables and Figures

Chapter 1 INTRODUCTION

1.1 History of surgical training

Surgical ability is built upon the development of practical skills, which experts perform more quickly and effortlessly. Depending on the learning methodology, different cognitive processes are involved in motor skill learning. Understanding these learning processes is of interest in contemporary surgical practice in order to increase the efficiency of training. Traditional 'hands-on' learning opportunities in clinical settings are becoming increasingly limited due to the increasing number of surgical trainees per centre, demand for shorter training pathways, restricted working hours and a constant need to ensure service delivery. Hence, there is a need to determine ways to enhance skill learning and development in order to produce suitably trained surgeons (1,2).

Traditionally, the performance of surgery was regarded as a craft passed down from expert to novice in the form of an apprenticeship model (3). The apprentice observed and assisted with a surgery that the expert performed. The learned skills can then be utilised when the apprentice completes similar tasks in the future. Elements of this ‘on-the-job’ learning method within surgical training are still observed today, despite the continual changes towards more regulated training and the certification of surgeons. William Halsted (1852-1922) was a United States surgeon who proposed the 'principles of surgery', established a 'school for safety in surgery', and initiated the modern regulatory system for surgeons (4). He emphasised the gradual increase in trainee responsibility with close supervision by a more experienced surgeon within his surgical training programme soon after his promotion to surgeon-in-chief of the Johns Hopkins Hospital in 1889 (4), influencing how surgical skills were taught.

Surgical education has strong historical influences. Many skills are still taught to novices on a one-on-one basis by more experienced surgeons. For example, surgical heuristics describes the 'rule of thumb' judgements an expert retains from their lifetime of experience. These judgements apply to many aspects of a surgeon's daily practice, whether it is accurate dissection through tissue planes to reach an anatomical position of interest, application of appropriate pressure to safely manoeuvre instruments or even more simply, selection of a suitable surgical instrument for the task at hand. It has been proposed that there are three main types of heuristics concerning surgical dissection: motor, perceptual and cognitive (5). The most important of these are motor. In the past, these heuristics were passed on explicitly to trainees in written material form (5,6). Tips and guidance from experts can also be passed down verbally. However, there is often a lengthy learning process before this information can be automated into a learner's daily practice.

Methods of practical learning of surgical skills are of interest due to their potential to improve the efficiency and efficacy with which surgery is taught. Structured training is now in place for most surgical specialities, requiring surgical trainees to obtain sufficient experience in performing essential cases before their training completion (7,8). However, inequalities can still occur in providing training opportunities for environmental or personal reasons. For example, trainees in different centres (e.g., urban versus rural) observe and are involved in different cases of varying complexity. Each training centre offers unique caseloads and pathologies based on different patient demographics or local geography. The standardisation of surgical training can be helpful in the early stages of surgical training to ensure a foundation on which trainees can build more advanced skills, which could occur via learning outside of the operating room. Recent studies support a simulation for the acquisition of surgical skills (9). Simulations could improve operating safety and provide suitable opportunities for junior trainees in a more controlled learning environment (9). The literature provides evidence to support the efficacy of simulation-based surgical training, yielding results more effective than observational (video-based) learning alone (10,11). Understanding the cognitive processes underpinning the teaching of practical skills can enable the continual improvement of surgical education.

1.2 Learning theory

Part of being an expert surgeon is having the ability to perform individual manual tasks proficiently. In the past, surgical skills were generally learned explicitly (4). However, there is now an increasing understanding of an alternative and opposing method referred to as implicit learning. The following section will discuss theories behind how these methods were developed and their applications in real-life specific settings.

1.2.1 Explicit Learning

Explicit learning is so named because it involves learning verbal knowledge (including detail of the steps of the task and how it should be performed) associated with motor performance. Fitts and Posner (1967) described stages of learning that were thought to explain how a learner progresses from a cognitive stage to a more automatic stage of performance (12). The transition from explicit to implicit knowledge occurs via distinct stages (12,13):

Initial stage: Slow performance under close sensory guidance, irregular shape of movements, and variable time are taken.

Second stage: Gradual learning of the sensory-motor map increases speed.

Late-stage: Rapid, automatic, skilful performance, isochronous movements, whole field sensory control.

The traditional method for motor skills learning thereby begins with a verbal-cognitive phase (12). During the initial stages, an individual is new to the task, therefore unskilled, and each movement is highly feedback-dependent and cognitively demanding (14).

In this initial stage, learning is essentially by trial and error. There is a need to focus and anticipate mistakes and be prepared to respond to them (15). Time is spent in this highly cognitive learning phase whereby errors are made; it is also considered error-ful learning (14). During the learning period, neural circuits link sensory input to motor output. Sensory input from the action is retained in the learner's working memory (16) to be translated into motor output (17). Cognitive processing during this stage leads to the slow performance of actions by the learner. However, the learner will have an excellent verbal recall of the steps involved in the action.

The learner then progresses to practical advancement of the movement skill whilst being highly cognitive regarding their movements. Finally, they reach an autonomous phase, in which they are less cognitively aware of the fine steps in their actions but can perform them with more ease. It is then considered that they have attained the 'expert' motor skill level at this stage (12,13).

A vital issue with explicit learning is that the learner may find it challenging to progress from the initial to the final stage of automation. For example, memorising the steps of the action and the actual generation of the action are two very different stages of explicit learning, requiring different skills. In addition, there may be challenges with understanding the content, particularly for a novice, thereby limiting knowledge retained. Furthermore, not all motor movements require active thought about the regularities and facts of how the action should be executed. Different acquisition methods have been proposed and compared against explicit learning.

1.2.2 Implicit learning

More recent research has challenged the traditional approach to surgical skill acquisition via the explicit learning pathway (18-22). Not all motor movements require active thought about regularities and facts of the action. Research indicates that this form of learning may not proceed in a set sequence, as Fitts and Posner (1967) proposed previously (18-22). It has been proposed that implicit motor learning may even bypass cognitive stages of learning (18-22).

Implicit learning is thought to be the opposite of explicit learning. For example, a group of participants learnt a sequence of letters generated by a specific set of grammatical rules (unbeknown to the participants). At the end of the session, they were asked to determine whether new sequences were generated using the same set of grammar rules (23). They demonstrated the ability to accurately determine which sets fitted in with the previous grammar rules they were exposed to without conscious knowledge of the rules themselves (23).

During implicit learning, the skill is acquired by a learner in a non-verbal manner and with little conscious awareness at the time of learning (21). As a result, a learner will have more difficulty verbally recalling how the task was carried out, for example, being able to ride a bicycle but not knowing how to explain it verbally to someone else. This type of learning focuses purely on the motor side of the skill being taught without first translating it into words. Thereby, learners are proposed to learn it implicitly or without verbalising what they are doing (20-22). Outcome measures such as the ability to function well under stress (24,25) and during multitasking situations (18,26) can be used to determine whether learners have learned the skill implicitly.

Implicit learning is less reliant on working memory, providing an alternative to poor working memory functioning (27,28). Once automated procedural knowledge is attained, a learner can perform the task with minimal cognitive awareness, which also benefits from freeing up their working memory and preventing them from being easily distracted. For example, a study of laparoscopic surgeons noted that implicit learners could perform the same task with fewer brain regions activated than explicit learners (29). There are situations in real-life operating rooms where surgeons may need to multi-task or work through unexpected interruptions. For example, colleagues' dialogue, equipment malfunction or changes in a patient's condition. These interruptions occupy the working memory of a surgeon; hence, implicitly learnt skills that are less reliant on working memory could yield more consistent or stable performance. A downfall of implicit learning is that a learner has less of a verbal recall of the steps in their motor task. Knowing how to perform procedural skills without verbalising to others may limit an individual's ability to perform in examination situations or teach the skill to others.

Implicit learning is not simply how one learns without instructions or feedback. A concurrent secondary task to load working memory is needed to hinder the generation of declarative knowledge from the learning task to achieve implicit learning. It needs to be carefully planned out to achieve it. A variety of efforts to develop other methods of inducing implicit learning have been made, including dual-task, analogy learning or errorless learning (21,30).

1.2.3 Working memory

Motor memory is formed through practice. When optimising motor skill training and practice, we should also consider how memory is stored. Atkinson and Shiffrin (1968) proposed the first well-known working memory model (31). Information in working memory is forgotten as new incoming items displace it. Atkinson and Shiffrin (1968) explained this concept through their generalised model in which a variety of "sensory registers" can temporarily gather and hold large amounts of perceived information from the environment (31). Only a few items are transferred to a longer-lasting short-term memory store. There are multiple opportunities for control or input from higher cognitive centres in the short-term memory store before information passes into long-term memory. In this model, information can flow bi-directionally; hence, there is a constant flow of information between short and long-term memory stores. Working memory is the short-term system in this model, controlling what information flows into and out of long-term memory, thereby crucial in learning and cognitive functioning. Most attempts to encourage implicit learning to occur have focused on the role of working memory (23,32-35). Working memory plays a role in motor task performance, including storing and identifying information about the task at hand and correcting errors or changing movement patterns in the hypothesis testing phase of motor learning (36,37). Therefore, these cognitive processes lead to a learner acquiring explicit knowledge regarding the task. Hence, these tend towards explicit learning. Most movements in real life are probably a composite of both implicit and explicit learning, with very few forms of learning that are purely one type or the other. Evidence from studies conducted in motor learning usually has participants reporting some verbal knowledge of the task (22,38). However, implicit learners tend to report less than explicit learners at the end of the experiment (21).

1.2.5 Methods of achieving implicit learning

Implicit processes are thought to be more efficient at controlling movements than explicit processes, and specific types of motor learning can be used to activate implicit motor learning (39). The following sections will elaborate on the main methods used to verify the efficacy and practicality of these approaches in various sporting or clinical settings.

1.2.5.1 Dual-Task Approach

Working memory plays a vital role in generating and applying declarative knowledge (facts or information stored in memory and expressed verbally by a learner) (40). Masters et al. (1992) carried out a study where learners completed a random letter generation task while performing a golf putting task (21). Participants in this study were assigned to groups. They were either discovery learners (proceeded to putt with no specific instructions) or explicit learners (taught with specific instructions prior to completing the golf putt), or dual-task learners (given a letter generation task whilst golf putting). The dual-task learners were required to call out a random letter whenever they heard the click of the electric metronome (set to go off every 1.5 seconds). Dual-task learners had to use their working memory to think of a letter to call out. The letter generation task effectively burdens the working memory so that it cannot be used to accumulate explicit knowledge about the putting task (21). The dual-task learners were found to demonstrate traits characteristic of implicit learning, including little attainment of verbal knowledge of the task (compared to explicit learners). However, their performance was more stable under pressure (compared to discovery and explicit learners). Dual-task learners also reported that they performed the task 'by feel' or intuition, which is also a key feature of implicit learning (21).

Results from the above experiment demonstrated one method of encouraging implicit learning. It should be noted that it is also essential to prevent a learner from attaining explicit skill-specific knowledge to promote implicit learning, whether in research or practical settings. Cessation of verbal instructions and feedback will not automatically render the learning process implicit. However, the application of this concurrent task slows the learning rate of the skill due to taking attention away from the motor task itself. Therefore, there has been a shift away from using dual-task methods to achieve implicit learning in experimental and practical settings (21). Other methods of inducing implicit learning, such as via errorless learning or learning with an external focus of attention, have been reported (21,30). Subsequent sections will further discuss the potential role of errors in the learning of a novel motor task.

1.2.5.2 Feedback manipulation

Movement production may be viewed as a link between a mental, behavioural objective and desired mechanical output by activating appropriate muscles (41). Mental models have been proposed to explain this, comprising two main components: Sensory input and motor output. Sensory information regarding the proposed movement – for example, the room conditions, equipment available, and distance to object – in the current environment is relayed to higher motor centres in the brain. These stimuli are integrated, and output signals are relayed to generate the desired precise movements. Exact matching of sensory and motor information is crucial to responding appropriately and effectively to environmental stimuli (42).

Sensory feedback from the current movement is usually used in hypothesis testing and the formation of changes needed to make subsequent movements. Visual feedback is the primary sensory information used to formulate the movement outcomes (43). Therefore, it was thought that learners are more likely to learn implicitly if there was a lack of visual feedback of the action because, then, hypothesis testing would be inhibited as they cannot determine the current movement's success (34). However, Maxwell et al. (2003) conducted an experiment in which visual feedback provided to the individuals was limited, and they were found to have still learnt explicitly rather than implicitly. This phenomenon was thought to be explained by using proprioceptive and tactile feedback in place of visual feedback (44).

1.2.5.3 Analogy learning

Analogy learning aims to make declarative knowledge more easily understood by manipulating instructions (45)(46). It is thought to be closely related to implicit learning. The focus of instructions is on the learners themselves and away from the tools and technicalities. Alternatively, another proposed cognitive process is aimed at short-circuiting the traditional approach to allow learners to attain the desired stage of automation without going through the verbalised process first. Instructions given to learners are information that can be understood as a metaphor rather than focusing on the technical aspects of the task. For example, studies have trialled giving out instructions for playing tennis by providing analogical instructions whereby an individual is taught to complete a series of movements in terms of activities of the individual's body. For example, "imagine the racket is the hand of a watch that goes clockwise from 9:00 to 3:00" as an analogous instruction versus "move the racket first down then up" as an explicit instruction (45).

Studies of analogous learning show similarities to implicit learning: Being less reliant on cognitive resources, less verbal knowledge accumulated during early phases of education, leading learners to have better motor responses and perform during multitasking (34,46). The reduction in explicit instructions seems to induce implicit learning in learners.

Analogous learning benefits the learning of diverse types of motor tasks, including table tennis (47,48), basketball shooting (49) and balance tasks (28,50). In addition, analogous learning protocols also appear to benefit a broad age group. For example, it has been used successfully for teaching rope-skipping to children (51) and badminton to older adults (52).

1.2.5.4 Errorless learning

Learning occurs passively when errors are minimised (53). The reduction of errors during practice is thought to cause implicit motor learning by reducing the amount of active cognitive engagement in the learning process (19). When tasks are performed well, a learner will become less aware of their performance, and confidence will increase. Allowing more errors to occur during learning will evoke explicit learning as learners will need to consciously identify and eradicate the mistakes, which requires a high level of cognition (19).

In a golf putting experiment, an errorless group of participants putted from distances starting close to the target; hence, they were less likely to miss (19). Another group of participants started far from the target and frequently missed; therefore, they were error-ful learners. The errorless group moved incrementally onto greater, more difficult distances, whereas the error-ful group moved onto closer, easier distances in subsequent trials. The errorless group committed fewer errors in golf putting than the error-ful group across the whole range of distances tested. The errorless group also demonstrated more accurate performances in a delayed retention test. Their performances were also unaffected by a concurrent tone-counting task. Stable performance despite introducing a concurrent secondary task is evidence that working memory was not needed for the golf putting task and was available for use in the secondary task (19). These all suggest the occurrence of implicit learning in the errorless group. However, the errorless group did not report less task-relevant knowledge than the error-ful learners.

In a second experiment from the same study, participants putted from increasing distances of 25cm, 50cm and 75cm or decreasing distances of 175cm, 150cm, and 125cm (19). The first group evoked a low frequency of errors and is the errorless learning protocol. Whilst the second group was prone to a high frequency of errors during learning and is, therefore, the error-ful protocol. The final performance assessment was conducted at 100cm (average distance across the two learning groups). Again, the errorless learning group demonstrated superior performances to the error-ful learning group. Their performance was also unaffected by the addition of a secondary tone-counting task. Video analyses of performances in the assessment task also showed that the errorless group was less likely to test the hypotheses about their movement (by demonstrating less visible movement adjustments during the golf putting task).

Furthermore, advantages of implicit learning processes persist if the environment is such that errors are reduced early in the motor learning phase, even if there is the accrual of explicit task-specific knowledge as the learning progresses. For example, in the above golf putting experiment, errorless learners exhibited the benefits of learning implicitly despite accruing some task-specific knowledge. In another experiment, probe reaction times (PRT) (whereby participants were timed whilst they completed a secondary task at the same time as the primary motor task as a means for testing the cognitive load that the primary task places on the individual) did not slow as the golf putting distances were increased, according to the errorless protocol (19). As distances increased, there was inevitably an increased tendency for learners to commit errors and, therefore, a need for hypothesis testing. The above observation indicates that in the errorless group, an increase in hypothesis testing during learning did not change attention requirements for the task. Hence, it did not increase the time taken to complete the task.

Timing of instruction also impacts the efficacy of errorless learning. Movement instructions for the task were given either before commencing errorless learning (top-down) or after an initial brief period of errorless learning (bottom-up) in an experiment by Poolton et al. (2005) (54). The bottom-up approach promoted a stable performance after introducing a concurrent tone-counting task compared to the top-down group. Despite accrual of explicit knowledge of the task later in their learning, the bottom-up group demonstrated a stable motor performance (55). However, stable, comfortable movement solutions are frequently adopted at the beginning of motor learning. Hence, the practicality of a bottom-up approach in clinical teaching of surgical skills may be limited, as these movements often require choreographed movement solutions for best practice (56). Nevertheless, in both experimental and practical applications, incremental, errorless learning protocols with graduated increases in difficulty of the motor task appear to be sufficient to encourage implicit learning processes to occur.

Errorless learning has been shown to benefit motor learning of young, healthy novices (57) and skilled athletes (33,58), as well as older adults (59) and children (60-62). It has also been shown to be beneficial to the rehabilitation of patients with Alzheimer's disease (63) or cerebral palsy (64). Furthermore, reducing errors during learning increases learners' self-efficacy and enhances their decision-making skills during motor learning (65). An errorless approach to implicit learning has been applied in healthcare with evidence for superior performance outcomes in implicit learners compared with explicit learners. These will be explored in section 1.4.

1.3 Role of errors in learning

Movement errors or unsuccessful trials are processed differently from accurate movements or successful trials. An example of this is an experiment whereby simple verbal responses to auditory probes (words or phrases that requires a specific response) during the preparation and execution of a golf putting task were slower following an unsuccessful trial than a successful one (32). The delayed verbal response in the individuals following unsuccessful trials was thought to be due to their attention being diverted to an explicit construction of a motor hypothesis to correct the previously committed errors in practice and test the new hypothesis (66). Conversely, increased brain activity has been found in individuals in trials following an unsuccessful attempt. This was thought to be evidence of the increased cognitive efforts to prepare for the new movement considering the hypothesis testing required to make corrections from the old, inaccurate movement (67).

Learners are typically more prone to making errors when faced with a novel task, as they have not yet formed a motor memory of the task (14). Learners are also cognitively attuned to any potential corrections needed in their movement in every step of the task. Whether the occurrence of these errors is beneficial or detrimental to the learning and subsequent performance of the individual is controversial. Several theories have outlined the impact of mistakes during the learning phase of motor skills, such as schema theory and reinvestment theory.

1.3.1 Schema theory

The central concept behind schema theory is that the generation of movements and feedback processes associated are not necessarily based on previous experience but formulated based on probabilities through the memory of similar actions in the past (68).

These memories help generate an internal set of rules and allow projected extrapolations when planning and executing novel tasks. To develop a robust schema system, an individual must practice the motor skill frequently and focus on the breadth of practice. Schema theory was developed on the assumption that a single memory representation can be used to control a wide range of movements (within a class of actions), not just a single model for each activity. Therefore, this theory views errors as positive to learning; albeit successful or unsuccessful, all attempts in practice serve as building blocks (68).

Both error-ful (explicit learning) and errorless (implicit learning) actions are considered equally important for forming a schema during the learning phase. When there are few errors during the learning process, the range of movement experienced with a task is smaller, reducing the subsequent extrapolation process. Hence, explicit learning with errors is beneficial to motor learning under the schema theory (68).

Task variability during practice requires learners to have multiple tasks occupying their working memory and obliges them to compare tasks with each other. They also must reconstruct their motor action plan for each specific task during variable practice, enhancing their learning. This is otherwise known as contextual interference effects (69). Contextual interference effects can be increased by interchanging between tasks controlled by different motor programmes rather than using minor variations of a task governed by the same or similar motor control centres (70).

The strength of schema theory is its ability to explain the transfer of a previously practised skill to novel tasks or novel versions of the task. Several studies compared results from varied learning to specific practice to examine the assumptions of this theory. Motor studies involving both children and adult participants demonstrated positive effects of diverse and specific practice on long-term motor learning outcomes (up to two weeks after the initial learning phase) (71-74). Motor tasks included in the study involved throwing bean bags at different distances or pushing on the coloured switches in response to the instructions provided in the colour panel (visual input). Studies have demonstrated that random variable training is more beneficial than blocked variable training for yielding these positive impacts on motor learning (75,76). Random variable training was thought to induce more errors during the learning phase. Hence, this was valuable to build up the motor schema, which can be later used to control similar movements. However, some studies have not found any difference between varied practice and focused practice for motor learning (77,78). Furthermore, there were no significant differences in performance between varied and focused practice in the short term (within an hour of completion of learning) (79).

1.3.2 Reinvestment theory

The theory of reinvestment suggests that the performance of previously learnt motor skills can be disrupted if the individual attempts to control these movements by conscious internal control using declarative knowledge. For example, if the learner re-focuses a high amount of attention on their task, they can reverse the automatisation of that movement. (20,21,80,81). This effectively disrupts processes of motor control that have become automatic. Reinvestment can, to some extent, be viewed as a regression from the automatised, expert stage back to an earlier, novice stage of motor learning.

Reinvestment by individuals is impacted by anxiety or stress (20,81). Furthermore, specific individuals are more prone to exhibiting reinvestment than others (80). For example, reinvestment tendencies exist amongst individuals who are more likely to use conscious motor processing or have higher levels of movement self-consciousness. A high level of reinvestment can be measured by a standardised scale: The 'Reinvestment Scale' (80) or the Movement Specific Reinvestment Scale (82). High scores can impair overall motor performance under stress, even in trained tennis players (83). In addition, patients with higher reinvestment scores were observed in post-stroke rehabilitation to have less gait stability and be more likely to fall (84). Further evidence of the detrimental effects of reinvestment can be found in a range of studies involving dart-throwing tasks (85), golf putting (86) and laparoscopic skills in surgery (87).

Reinvestment impacts explicit learners preferentially (88). The propensity to reinvest was correlated with the amount of verbalised technical rules acquired during the learning phases (80,81). Hence, one of the benefits of implicit learning is protecting individuals from reinvestment when placed under pressure. Prevention of reinvestment would be of greater significance to the individuals with a high reinvestment score. Some contradictory evidence is available whereby internal conscious processing was not shown to impact overall performance (88). However, as measured by self-reported conscious processing, reinvestment increased more in the explicit than the implicit group. Hence, errors made during practice would be detrimental to learning under the assumptions of the theory of reinvestment. Errors during learning induce explicit learning in the trainee; thus, formed skills are prone to be impacted by reinvestment during stressful stimuli (81).

1.4 Potential implications for surgical training

Implicit learning of motor skills demonstrates benefits over traditional, explicit learning methods. Some research has investigated its application in the health sector, namely dentistry (35,89) and surgery (focusing on general surgery and its laparoscopic simulators) (29,90-92). Further research into the implicit learning protocols to determine what may work in surgical education is necessary before considering introducing it in a formal capacity to training.

Implicit learning has been applied in some aspects of health care. For example, pre-clinical research into the teaching of motor skills in dentistry schools has been published regarding implicit versus explicit learning. University students from outside the School of Dentistry were recruited: Eight into the explicit group and eleven in the implicit learning group (35). The study showed that students who learnt hand-piece handling via implicit learning methods performed more accurately in a retention test and multitasking scenarios. In addition, implicit learners prepared a cavity more accurately, showing that skills acquired during implicit learning are less attention-demanding than those obtained via explicit learning (35). Surgical skill learning has also been researched concerning suturing and knot tying (93). Medical students were either allocated to an observation-only, an instructed-observation, or a guided-observation treatment condition. Students who learned suturing by observation alone or by observation accompanied by guidance (to reduce the number of committed errors) tended to learn implicitly and have a stable performance during multitasking (93).

There are increasing pressures on the healthcare system to train a growing number of surgeons (1,2). In addition, doctors' expert performance of procedural skills is an expectation from patients and their families. Therefore, incorporating implicit learning into the curriculum may be a method to train learners efficiently and safely in procedural skills. Improvement to surgical training methods by incorporating elements of simulation at an appropriate level of difficulty and containing aspects of implicit learning could enhance the process of acquisition of the fine motor skills required for operating (18,19,21,93). Controlling the task's difficulty level may benefit a learner during skill acquisition, for example, by matching the task difficulty to the learner's current skill level. This avoids over or under-challenging them during training (94) and promotes learners' task engagement (95). That would be logistically possible with the utilisation of simulation-based skill acquisition.

Studies have shown that implicit learners could reach the expert autonomous stages without accompanied verbal knowledge of each of the steps (21). Therefore, if implicit learning is incorporated into surgical training, a potential implication for the future could be that more acquired skills are in the form of non-verbal knowledge. These changes could impact whether the learner could then verbalise their steps. It could also mean that methods of examining their knowledge would require alterations.

1.5 Premise and thesis outline

The implicit learning process, which has been shown in some settings to yield resulting motor skills that are more robust, has many elements which would be favourable in the training of future surgeons. However, there are currently limited attempts at replicating the results found in previous studies in other areas of surgery. This thesis will, therefore, further examine the application of errorless learning to acquire orthopaedic surgical skills.

1.6 Aims

This research project investigates how medical students' performance differs in motor tasks simulating spinal surgery (using a high-speed burr to prepare a spine model for a cervical laminoplasty) after learning via an errorless or error-ful approach.

1.7 Questions

1. Can we validate previous findings showing improved skill performance in dental students who learnt by errorless methods? (35,89)
2. Does errorless or error-ful learning result in the more accurate use of the high-speed burr in cervical laminoplasty preparations?
3. Does errorless or error-ful learning result in more robust or stable skill acquisition under conditions of duress?

Chapter 2 METHODS

2.1 Study overview

This project was a randomised prospective study comparing errorless and error-ful learning of surgical skills using a high-speed side-cutting burr, a skill demonstrated in bone preparation for a cervical laminoplasty. Medical students with no experience in surgical procedures were recruited (n=30) and then randomised into one of two groups. One group learnt the burr handling skills via an errorless protocol, whereas the other group learned via the error-ful protocol. The primary outcome measures were the accuracy and safety of the cuts made on the cervical saw bone models, the ability to perform under pressure, and overall skill (scored by expert spine surgeons). Please see Figure 2-1 for a flow diagram depicting this process.

2.2 Participant recruitment and selection

Medical students at the Waikato Clinical Campus in their 4^{th} – 6^{th} year of medical school were recruited for this study after ethics approval from The University of Auckland (Reference Number UAHPEC22187). Recruitment flyers with the study information were posted in the library and other common areas in the Waikato Clinical Campus during the study recruitment, and an email was sent to all clinical students by the University of Auckland administration team with the participant information sheet (see Appendix 1) and consent form (see Appendix 2). Students were also recruited in person while completing their orthopaedic clinical placement at Waikato Hospital. Further students were recruited by word-of-mouth. Potential participants were screened for eligibility via an online questionnaire (see Appendix 3). Students were excluded from participating if they had previous surgical training or exposure similar to the procedure in this study. This was determined via their responses to the pre-trial questionnaire. Baseline characteristics of the participants, such as age and sex, were also collected, as well as their previous level of surgical experience.

Both study participant groups attended the same briefing before taking on any motor learning. In addition, they were provided with the same information regarding the rationale for the research project: A written explanation of the steps involved in the bone preparations in cervical laminoplasty (see Appendix 4), the importance of preserving surrounding tissue, the tasks they will be expected to perform, a safety briefing, and introduction to the use of the high-speed side-cutting burr.

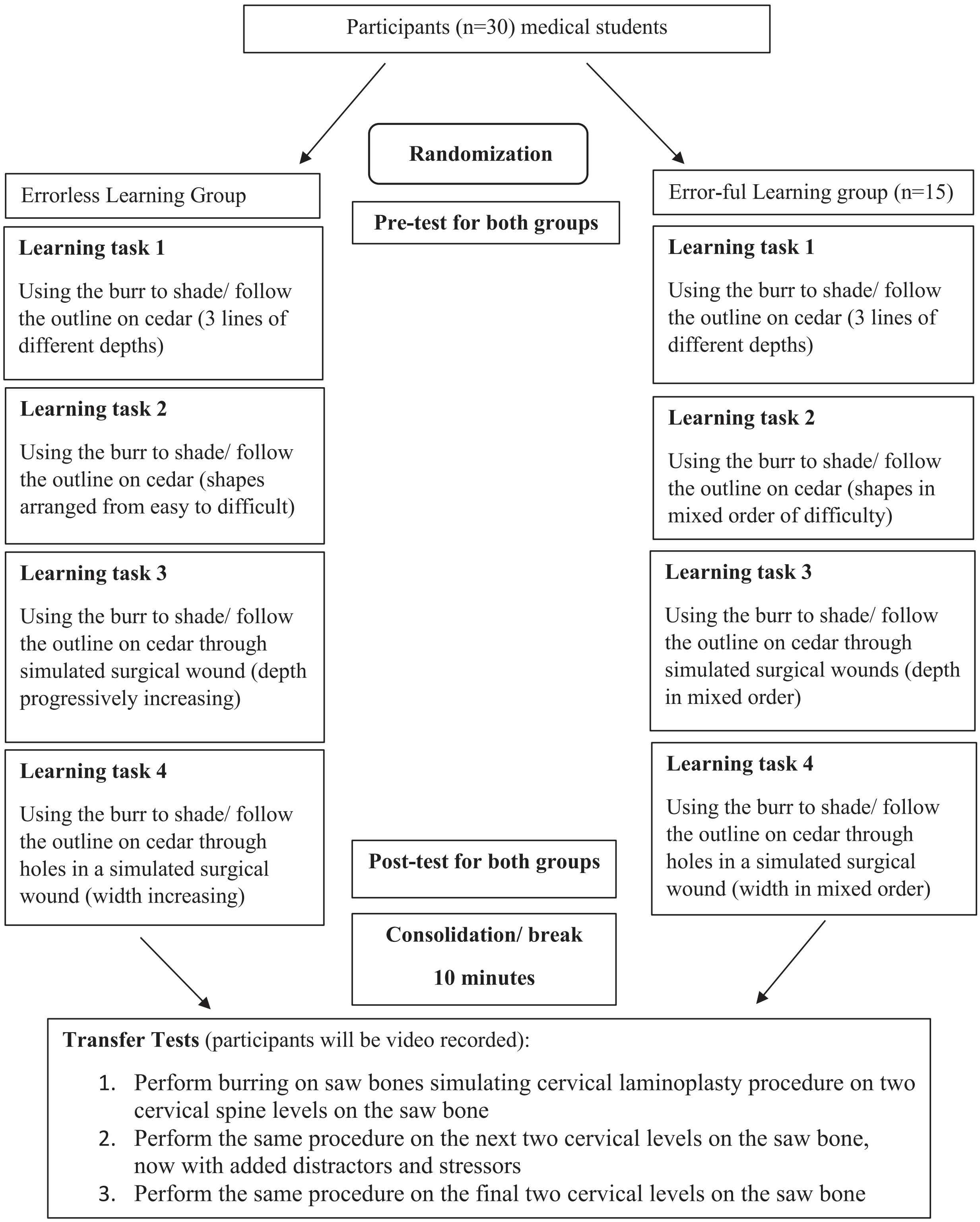

Figure 2-1: Project study design

2.3 Participant information

Thirty medical students were recruited from the Waikato Clinical Campus (n=13 males and 17 females). The mean age was 23.7 years (standard deviation 1.1) in the errorless group and 24.3 years (standard deviation 1.8) in the error-ful group. Please see the results section for detailed baseline participant information.

2.4 Study design

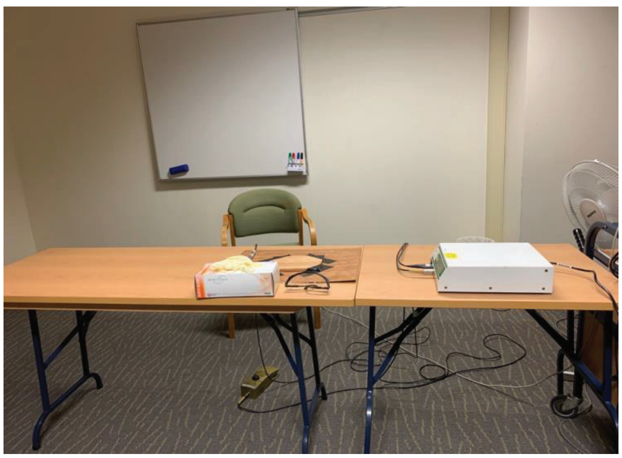

Figure 2-2: Experimental set-up for the learning task: showing the cedar board, burr, stylus, foot pedal, safety goggles and gloves

Figure 2-3: Close up of the burr head

Figure 2-4: Example of a participant completing the learning task

2.4.1 Study apparatus for the learning tasks

The experiments were conducted in study rooms in the Waikato Clinical Campus library or meeting rooms. These rooms were solely used for the experiment to ensure a quiet environment, free of external distractions. The experimental set-up above was utilised for the learning tasks.

The experimental set-up included the use of a table, a chair, a fan, a Medtronic Midas Rex EM200 Legend EHS Stylus with a 10AN drill attachment, a 3mm match head (10MH30 burr attachment) on the stylus, and a footswitch: EF100 for the entire experiment. The first part, the learning phase, utilised the cedar board with shapes drawn with a pencil from a standardised template. The final assessments (transfer tests) were completed on the cervical sawbone models placed on a holder simulating a patient's neck in an operation. Appendix 5 lists all equipment used.

For initial testing, participants were required to burr the outline of a shape stencilled on the cedar board. These boards were approximately 20cm x 15cm. The cedar was taped to a larger plywood board and securely placed on the table (as shown in Figure 2-2). Three different learning tasks were completed involving the burring of shapes on the cedar wood.

The cedar boards were 1cm thick and chosen due to their perceived similar density to cervical sawbones (from www.sawbones.com), which were also used later during the final surgical skill assessment. The learning tasks aimed to train participants to use the high-speed burr and build skills useful for the last task on cervical saw bone models. The high-speed side-cutting burr was connected to a power source and set on the table above. The foot pedal was connected to the main unit and placed on the floor. The burr handpiece was connected to the unit and tested before being placed on the table next to the cedar board. Safety equipment, including gloves and safety goggles, was provided.

A different order of shapes was used for the errorless and error-ful groups. The burr stylus was connected to the main machine to one side of the participant, and the foot pedal was used to control the burr speed. Participants were instructed to push down on the pedal and ensure the burr stylus was at full speed (60,000 rotations per minute) before completing the tasks. A fan was also used for the duration of the learning task to clear away smoke/wood debris from the burring to prevent obscuring the vision of the cedar boards.

The technique of holding the burr stylus was slightly different from the conventional technique used by spine surgeons in the operating theatre. The height of the burr stylus from the cedar boards meant that students had no place to rest their hands or wrist to steady them during the task. This was a problem identified during the initial testing of the set-up. An adaptation was made to allow students to hold onto and direct the drill with their dominant hand, whilst the opposite hand could grip onto their wrist or forearm. Students were able to rest their arms or elbow on the plywood but were discouraged from resting their dominant hand on the cedar board itself, as they were required to burr the shapes with the burr head perpendicular to the cedar board surface (see Figure 2-3 above).

2.4.2 Determination of difficulty of shapes

Before commencing the study, various shapes and designs to facilitate learning were assessed by two expert spinal surgeons adept at the use of the high-speed side-cutting burr. Shapes were traced out and then graded by the surgeons to establish a stepwise progression of difficulty. Six shapes were chosen for the learning tasks (see Figures 2-4 and 2-5). Each shape was traced from stencils and drawn to fit inside a circle with a diameter of 27mm. For the errorless group, the shapes burred during the learning phase were ordered in increasing difficulty, whereas for the error-ful group, the shapes were arranged in mixed difficulty (random order).

Figure 2-5: The sequence of shapes traced by the Errorless group

Figure 2-6: The sequence of shapes traced by the Error-ful group

2.4.3 Pre-test

Both groups then burred a designated shape (star) as a 'pre-test' on the cedar wood surface (see Figure 2-6). Participants were required to burr the shape in one smooth outline at a depth of half a burr head (2mm). The primary investigator timed the pre-test. Figure 2-8 shows an example of the pre-test being completed.

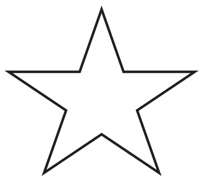

Figure 2-7: Pre-test shape outline

Figure 2-8: Example of a student completing the pre-test on the cedar boards.

(The student used their opposite hand to steady their dominant hand holding the burr stylus; therefore, this depiction shows one hand to allow the shapes to be shown in the figure.)

2.4.4 Depth management learning task

For the first learning task, both groups of participants completed a task involving burring three lines of different depths on the cedar. For the errorless group, the first line was of the depth of just the tip of the burr (approximately 1mm), the second line was half a burr tip deep (approximately 2mm), and the third line was drilled to the depth of the whole burr tip (approximately 4mm) (this is illustrated in Figure 2-9). The error-ful group also completed this task, but the order of completion was half a burr head deep (2mm), followed by a line of the depth of a whole burr tip (4mm), then finally a line at a depth of just the tip of the burr (1mm).

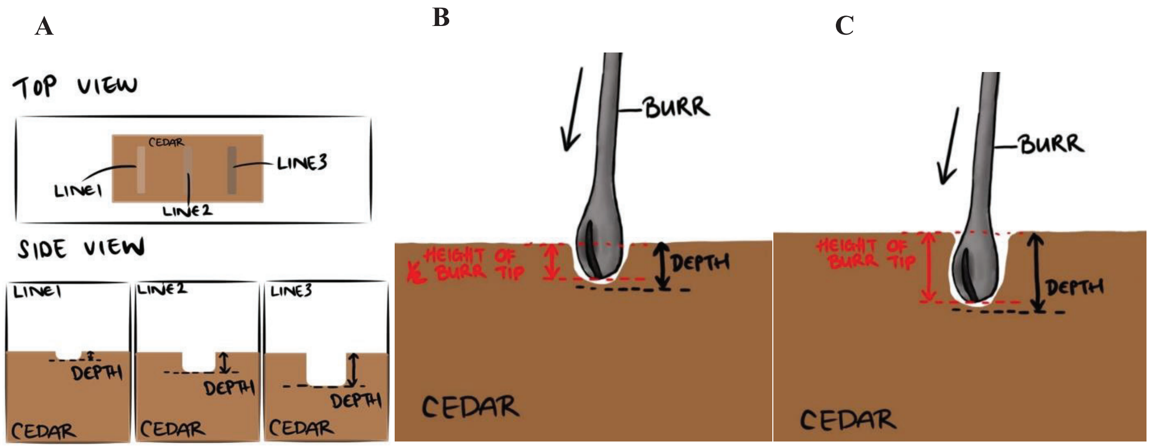

Figure 2-9: Diagram illustrating the depth management task A: Top and side views of the three lines, B: depth of the second line, C: depth of the third line

2.4.5 Shape outlining learning task

The second learning task involved using the high-speed side-cutting burr to cut out shapes (in Figures 2-4 and 2-5) on pieces of cedar boards. The errorless group progressively learned tasks from easy to difficult on the cedar boards. The error-ful group also progressed through the same tasks, but not in order of difficulty. All of the shapes were traced with the burr tips, at a depth of half a burr tip and in one continuous motion.

2.4.6 Learning task simulating wound depth

In the third learning task, participants used the burr to follow the outlines of triangles on the cedar boards, working through 'wounds' of different depths. All of the shapes were traced with the burr tips, at a depth of half a burr tip (2mm) and in one continuous motion. The wound simulator had circles which represented the 'wounds'. They were made at heights of 25mm, 50mm, and 75mm (see Figure 2-10). This task was designed to train participants to complete the task in patients with different body habitus and, therefore, soft tissue depths. The errorless learning group participants completed the burring tasks with pipes in the order of increasing lengths. In contrast, the participants of the error-ful group completed the task of burring shapes on cedar through these simulators, but in the order of 50mm, 75mm, and 25mm.

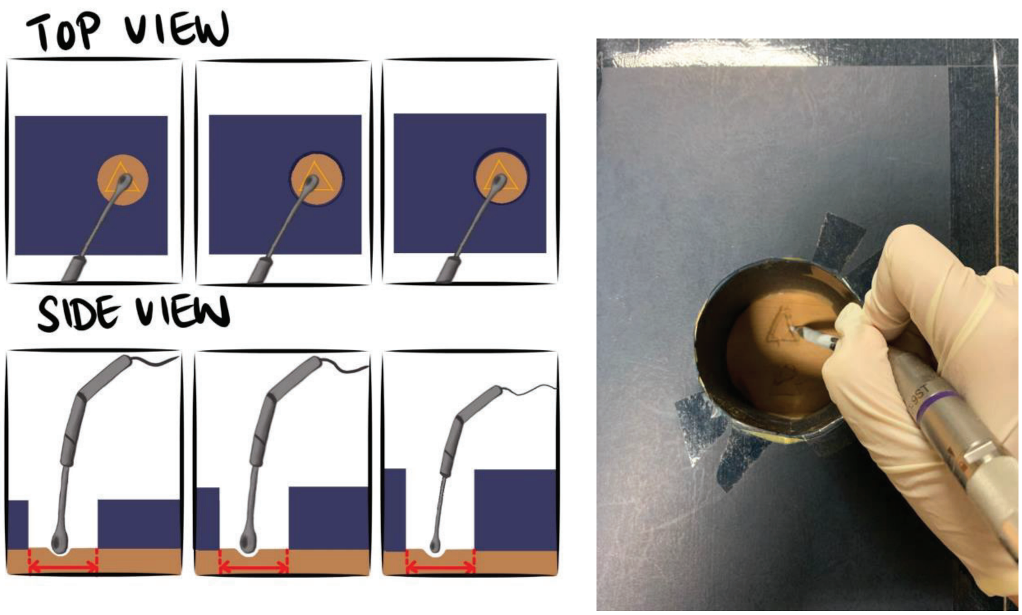

Figure 2-10: Learning task 3: burring the triangle's outline through boxes of different depths. The width of the circles in all three boxes is the same

2.4.7 Learning task simulating wound size

In the fourth learning task, participants again burred triangles on the cedar boards. All shapes were traced with the burr tips, at a depth of half a burr tip (2mm) and in one continuous motion. The wound simulator (50mm deep), with holes cut through it with widths of 40mm, 60mm and 80mm, was placed over the cedar boards (see Figure 2-11), thus limiting the exposure of the shapes to mimic the real-life soft tissue exposure of bone when conducting an operation. The errorless group progressed through the tasks from easy to difficult, from 80mm to 60mm, and then 40mm, whereas the error-ful group progressed from 60mm, to 80mm, and then 40mm.

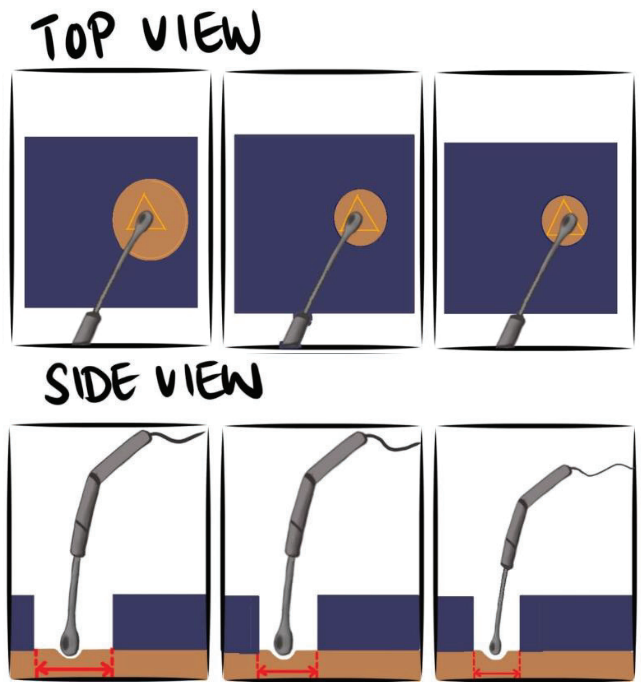

Figure 2-11: Learning task 4, burring outline of the triangle through a box of the same depth but different width circles

2.4.8 Post-test

Both groups then completed the same task as for the pre-test. The participants were all timed in the same manner by the primary investigator (Please refer to the explanation in section 2.4.3).

2.4.9 Rest period

Both groups then proceeded to have a rest period of ten minutes. The time following the initial learning phases was important for retaining previously learnt tasks and gave the participants a rest from using the burr (96). It also served as a time whereby participants rested and prevented muscle fatigue during the assessment tasks.

2.4.10 Transfer tests

All students completed the same tasks for the final assessment following the break, consisting of retention and transfer tests. The experimental set-up on the table was similar to the previous tasks, apart from the addition of the video camera on a tripod aimed at the working field (as shown in Figure 2-12). The same high-speed side-cutting burr as the learning task was used. The retention and transfer tests were designed to replicate an operating theatre as closely as possible. So they were conducted on cervical saw bone models. The cervical saw bone model was held in place with a plastic holder, which simulated the posterior neck in a patient with accompanying blue 'surgical drape' and red 'wound dissection in the same place as the cedar boards from the previous task'. (Figure 2-13).

Figure 2-12: Set up for final assessment task

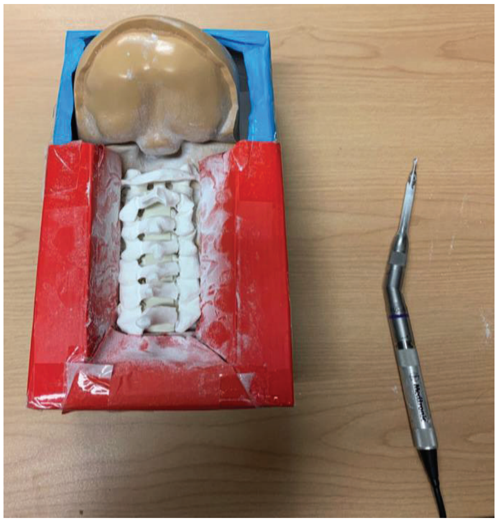

Figure 2-13: Transfer test equipment set up on the table

Each participant prepared the bone cuts on six cervical vertebrae levels on the saw bone models. The hinge cut was prepared on one side, while the trough cut was on the opposite side across all six cervical levels, C2-C7 inclusive. The technique required for preparing a cervical laminoplasty is shown in Figure 2-14. Each participant made a total of twelve cuts on the cervical saw bone models. Participants' hands and the operating field were filmed on video during the transfer tasks. Transfer tasks assessed students' performance of the cervical laminectomy on saw bone models to determine their level of learning from previous stages. Students completed the spinal laminectomy procedure under time pressure and in the presence of distractors during transfer task two to simulate real-life stressors in theatre. A total of four cuts (two hinges and two trough cuts) were performed during each transfer test, with C2-3 corresponding to Transfer test 1, C4-5 to Transfer test 2 and C6-7 to Transfer test 3.

Figure 2-14: Cross-section image of the cuts performed in a cervical laminoplasty *(97)*

Figure reproduced with permission of Wolters Kluwer Health. Figure 4-7, 4-8 in Rhee JM. Editor. Emory's Illustrated Tips and Tricks in Spine Surgery. 1st edition. Wolters Kluwer Health, 2019.

The first transfer task involved using the burrs to create a trough and hinge cuts on C2-3 levels on the cervical saw bone. On the right side of the lamina of the cervical saw bone model, participants were required to make the trough, which involved a cut through almost the entire thickness of the lamina bone. The participants were instructed to avoid plunging into the vertebral canal as that could potentially inflict a spinal cord injury to the patient in a real-life scenario. This was simulated in the assessment task by leaving a thin rim of the far cortex intact. On the left side, participants created a hinge by burring through the near cortex but not the far cortex of the lamina (this arrangement of cuts was consistent throughout all cervical spine levels in the experiment). The cut through the lamina bone was approximately half the thickness of the lamina.

Participants then completed the second transfer task on C4-5 cervical spine levels. This was the same task as before but with a secondary task and a three-minute time limit to complete the task. The participants were required to burr a hinge and trough on a cervical saw bone model (same as above but on C4-5 levels) while listening to a voice recording of a list of nouns (Appendix 6). They were required to count the number of words relating to medicine in the recording (secondary task). Participants listened to the footage with Sony overhead, noise-cancelling headphones provided to them on the day. Participants were also instructed to complete the above task within three minutes. A clock face was displayed on an iPad 10 screen as a full-screen countdown timer to the participant. Following this task, participants filled out a questionnaire reflecting their anxiety levels at the time (see Appendix 7 for the questionnaire).

Finally, all participants participated in a third transfer task on C6-7 cervical spine levels. Again, participants were required to perform the hinge and trough cuts on these two cervical spine levels without additional tasks, time pressure or distractions. This was a repeat of the first transfer test to reassess the participant's ability to perform a cervical laminectomy on cervical saw bone models.

The video recording of the participants during the assessment task was used to determine the time taken for each of the tasks described above. The primary investigator analysed the videos to record a start and stop time for each cut performed on the cervical saw bones. The total time for both hinge and trough cuts on the same cervical level was recorded on an Excel spreadsheet. The time to completion for each task (transfer tests 1,2,3) was determined by the mean time taken to complete the bone cuts on each cervical saw bone level (e.g., for transfer test 1 time was the mean time to complete C2 and C3 levels).

Performance was judged on each of the cedar wood and saw bones (produced by participants during the pre-test and post-test on the cedar and the six vertebrae levels prepared) by assessment by two spine surgeons independently. Judgement of the pre-test and post-test shapes involved a composite score of the depth, smoothness, and control of the burrs during these tasks on a Likert Scale. Saw bone measurements were scored by depth, width, and proximity to the inner cortex on the hinge site, and depth, width, and angle compared with the lamina for the hinge site.

Angle scores were assigned as follows: (1) If the cut was >45º from a right angle or consistent variation in the angle, (2) if the cut was <50% at a right angle, (3) if the cut was >50% at a right angle, (4) if there were only minor variations from a right angle, or (5) if the cut was made at a right angle to lamina throughout the length of trough/hinge.

Depth scores were assigned as follows: (1) For a highly variable depth of trough/hinge throughout, (2) for <50% of the depth ideal, (3) for >50% of the depth ideal, (4) for only minor variations of the trough/hinge are ideal throughout the length and (5) ideal depth throughout the length of the cut.

Width scores are assigned with the following criteria: (1) For a highly variable width, (2) for a <50% width of the burr head, (3) for a >50% width of the burr head, (4) for only minor variations in width and (5) for the width consistently the same as the burr head.

Linearity of the cuts was assessed and scored according to the following standard: (1) For highly variable edges of the trough/hinge throughout, (2) for deviations >50% of the trough/hinge length, (3) for deviations <50% of the trough/hinge length, (4) for only minor deviations and (5) for the trough/hinge created in one continuous smooth line.

The time taken to complete the task and performance in the secondary task (number of medical words identified from the recording) were also recorded. The judges did not know the participants' assigned groups. The overall performance on each cervical saw bone piece was generated from the average scores of the two spine surgeons on a scoring sheet.

Each performance domain was scored out of five in the pre-test and post-test, and an overall score out of twenty was recorded. Each cut (hinge or trough) on the cervical spine models was scored out of five for each domain of performance. There were two spine levels or four cuts conducted by each participant in each transfer task. The maximum score for each transfer test was, therefore, 80. The scores for each participant were divided by four first to generate a score out of 20 to generate a comparable score between the pre-test, post-test, and transfer tasks. Figure 2-15 shows the scoring sheet.

2.5 Statistical analysis

Data were entered into a Microsoft Excel spreadsheet and then converted to SPSS data files. A box plot of all the performance scores was conducted to identify outliers. Descriptive statistics (mean, standard deviation) were generated in SPSS.

To examine the reliability/agreement in performance scores provided by the independent raters (i.e., the expert surgeons), intraclass correlation coefficients (ICCs) were computed for the pre-test, post-test and three transfer tests using SPSS. Repeated measures analyses of variance were used to examine Group (errorless/error-ful) x Block (pre-test /post-test / transfer tests) differences in performance scores and time to completion. A follow-up analysis was conducted when appropriate, using paired samples t-tests. In the event of a significant Mauchly's test of sphericity, Greenhouse Geisser corrections were used. Performance in the secondary task and STAI-S scores were analysed using independent samples t-tests.

Scoring sheet for each cervical spine level prepared:

	1 (Poor)	2	3	4	5 (Excellent)
Angle – trough cut					
Depth – trough cut					
Width – trough cut					
Smoothness of cut					
Angle – hinge cut					
Depth – hinge cut					
Width – hinge cut					
Smoothness of cut					

Overall mark /80

Angle scoring guide (ideal is trough/hinge created at 90 degrees to the surface of the lamina):
(1) – >45º from a right angle or consistent variation in angle
(2) - <50% at right angle
(3) - >50% at right angle
(4) – Only minor variations from a right angle
(5) - Right angle to lamina throughout the length of trough/hinge

Depth scoring guide (ideal is hinge is created at half the depth of the burr head; the ideal is trough is created leaving a thin sliver of inner cortex):
(1) – Highly variable depth of trough/hinge throughout
(2) <50% of depth ideal
(3) >50% of depth ideal
(4) Only minor variations of trough/hinge are ideal throughout the length
(5) Depth of trough/hinge ideal throughout the length

Width scoring guide (ideal is the width of the trough/hinge is the same as the width of the burr head):
(1) – Highly variable width
(2) - <50% width of burr head
(3) - >50% width of burr head
(4) – Only minor variations in width
(5) - Width consistently the same as the burr head

Linearity scoring guide (ideal is the edges of the trough/hinge are smooth and the trough/hinge are straight along their length without lateral deviation):
(1) – Highly variable edges of trough/hinge throughout
(2) - Deviations >50% of trough/hinge length

(3) - Deviations <50% of trough/hinge length
(4) – Only minor deviations
(5) – Trough/hinge created in one continuous line

Scoring sheet for the pre and post-test star shape on cedar:

	1 (Poor)	2	3	4	5 (Excellent)
Angle					
Depth					
Width					
Smoothness of cut					
Overall mark /20					

Angle scoring guide (ideal is cut created at 90 degrees to the surface of the cedar board):
(1) – >45º from a right angle or consistent variation in angle
(2) - <50% at right angle
(3) - >50% at right angle
(4) – Only minor variations from a right angle
(5) - Right angle to lamina throughout the length of trough/hinge

Depth scoring guide (ideal is cut created at half the depth of the burr head):
(1) – Highly variable depth of trough/hinge throughout
(2) <50% of depth ideal
(3) >50% of depth ideal
(4) Only minor variations of trough/hinge are ideal throughout the length
(5) Depth of trough/hinge ideal throughout the length

Width scoring guide (ideal is the width of the cut is the same as the width of the burr head):
(1) – Highly variable width
(2) - <50% width of burr head
(3) - >50% width of burr head
(4) – Only minor variations in width
(5) - Width consistently the same as the burr head

Linearity scoring guide (ideal is the edges of the cut are smooth and the trough/hinge are straight along their length without lateral deviation):
(1) – Highly variable edges of trough/hinge throughout
(2) - Deviations >50% of trough/hinge length
(3) - Deviations <50% of trough/hinge length
(4) – Only minor deviations
(5) – Trough/hinge created in one continuous line

Figure 2-15: Scoring sheet for assessment tasks

Chapter 3 RESULTS

3.1 Baseline characteristics of participants

Thirty medical students were recruited and randomised into the error-ful and errorless learning groups for the study. No statistically significant differences between the two groups were detected from the information collected prior to the commencement of the experiment (Table 1 shows detailed participant characteristics).

Table 3-1: Baseline information of participants in the two groups

	Errorless	**Error-ful**	**P-value**
Age	23.67 (S.D 1.05)	24.33 (S.D 1.84)	0.232
Sex			
Male	8	5	0.269
Female	7	10	
Handed ness			
Right	14	14	0.368
Left	1	0	
Ambidextrous	0	1	
Have you had any experience using power tools outside of the medical setting? (e.g., at home/ recreationally)			
Yes	8	9	0.713
No	7	6	
Have you had any experience in using power tools in theatre?			
Yes	5	5	1.00
No	10	10	
How many times (as an estimate) have you scrubbed into theatre?			
0-1	6	1	0.171
2-5	1	4	
5-10	2	1	
10-15	1	1	
15+	5	8	
How many surgical rotations have you attended so far in your medical training?			
1.53 (S.D 1.60)	1.93 (S.D 1.39)	0.470	

Which year of your medical degree are you currently in?			
IV	11	10	0.884
V	2	3	
VI	2	2	
Have you had any surgical experience (including workshops/ conferences/ skills training sessions)?			
Yes	11	7	0.136
No	4	8	
Have you worked prior to commencing your medical degree?			
Yes	5	3	0.409
No	10	12	

3.2 Performance

Each participant's performance during the pre-test, the post-test, and the three transfer tests were scored independently by two experienced spine surgeons. Intraclass correlation coefficients (ICC) were computed to test for inter-rater reliability. The inter-rater reliability was acceptable (0.698), so the scores were averaged and used for analysis. However, the ICC between each surgeon's score was low (0.365). A separate analysis of the performance scores provided by each surgeon revealed identical patterns of behaviour during the transfer tests, so the scores were averaged and used for final analysis.

Figure 3-1 shows the scores for each group. A 2x5 repeated measures ANOVA (Group x Test Block) revealed a significant main effect of Test Block [F (1.904, 53.394) = 19.070, $p < 0.001$], but no main effect of Group [F (1,28) = 0.005, $p = 0.942$]. A Group x Test Block interaction was not evident [F (1.904, 53.394) = 0.411 $p = 0.656$].

Follow-up analysis of the main effect of Test Block was conducted using paired samples t-tests (groups combined). Post-test performance scores were significantly higher than pre-test performance scores [t(29) = 6.647, $p < .001$]. This finding suggests that, taken together, the groups performed significantly better after practice but that there were no differences between the groups.

For the transfer tests, performance scores during transfer test two were significantly higher than during transfer test one and transfer test three [t(29) = 2.644, p = .013 and t(29) = 2.359, p = .025, respectively]. However, performance scores during transfer test one and transfer test three did not differ [t(29) = .379, p = .708]. These results indicate that, taken together, the groups performed better when asked to multi-task during transfer test two.

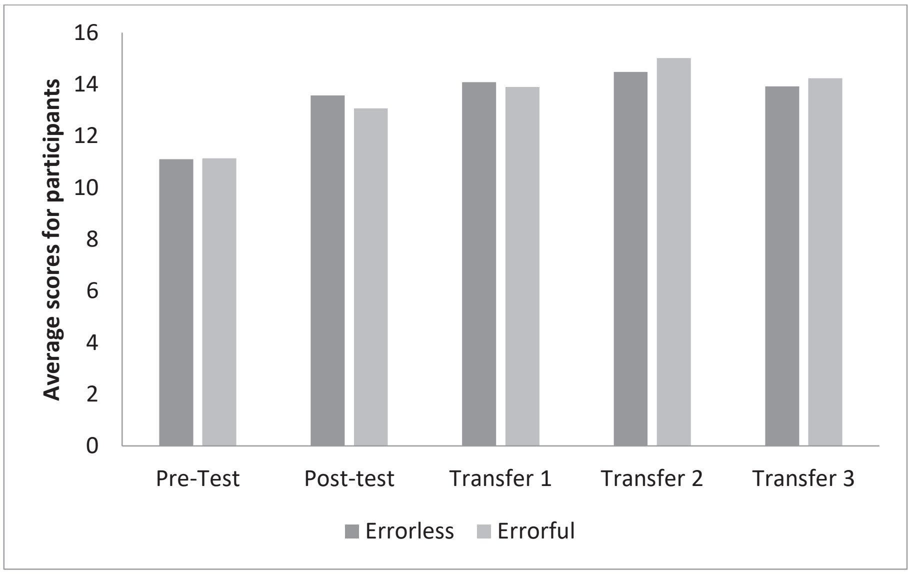

Figure 3-1: Mean performance in the Errorless group and the Error-ful group during each test

3.3 Time taken to complete the pre-test and post-test

Each participant was timed during the pre-test and post-test (burring the star shape outline on cedar boards) with a stopwatch by the primary investigator. These two tasks were identical; hence, the time to complete them was comparable.

Figure 3-2 shows the mean time taken to complete the task during the pre-test and the post-test. A Group x Test Block (2 x 2) repeated measures ANOVA revealed a significant main effect of Block [F(1.00, 28.00) = 27.95, p < 0.001], but no main effect of Group [F(1,28) = 1.085, p = 0.306]. A Group x Test Block interaction was not evident [F(1.00, 28.00) = 0.005, p = 0.722].

The follow-up analysis of the main effect of Test Block was conducted using paired samples t-tests (groups combined). The times taken to complete the post-test were significantly lower than for the pre-test [$t(29) = 5.368$, $p < .001$]. This finding suggests that, taken together, the groups performed the same task more quickly after practice but that there were no differences between the groups.

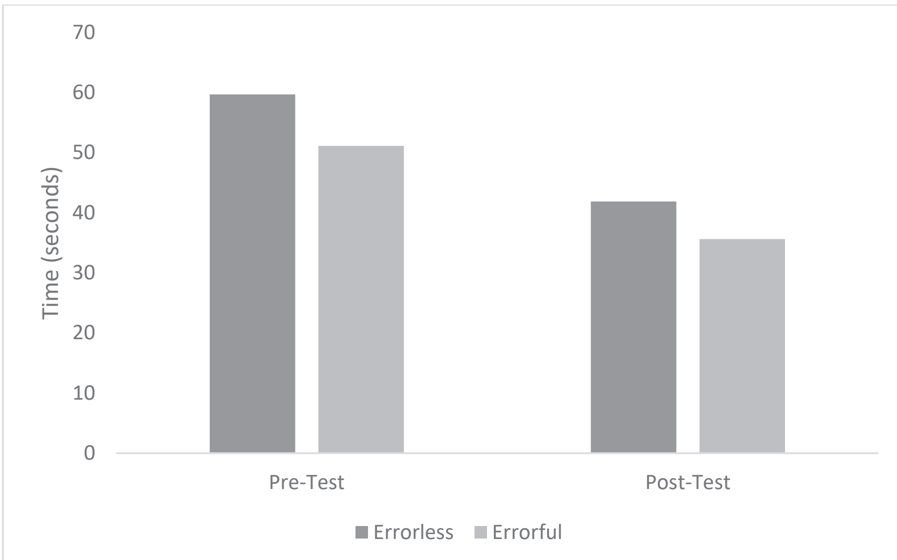

Figure 3-2: Time to completion during the pre-test and the post-test (seconds)

3.4 Time taken to complete the transfer tests

Participants were video recorded during the three transfer tests. The time was extracted from these recordings post-completion of the experiment by the primary investigator. The time analysed here was the time taken to make the hinge and trough cuts on the cervical sawbone models (C2&C3 cut times were averaged for transfer test one, C4&C5cut times were averaged for transfer test two, C6&C7 cut times were averaged for transfer test three).

Figure 3-3 shows the time taken to complete the transfer tests by the two learning groups. A Group x Test Block (2 x 3) repeated measures ANOVA demonstrated a significant main effect of Test Block [$F(1.65, 46.23) = 17.07$, $p < 0.001$] but no main effect of Group

[F(1,28) = 0.157, $p = 0.695$]. A Group x Test Block interaction was not evident [F(1.65, 46.23) = 1.44, $p = 0.247$].

The follow-up analysis of the main effect of Test Block was conducted using paired samples t-tests (groups combined). Time taken during transfer test two was significantly lower than during transfer test one and transfer test three [t(29) = 4.901, $p < 0.001$ and t(29) = 2.686, $p = .012$, respectively]. The time taken during transfer test one also was significantly higher than during transfer test three [t(29) = 3.765, $p = .001$]. These results indicate that taken together, the groups performed more quickly when asked to multi-task during transfer test two. Both groups also become quicker at the same task with practice, as shown by the decreased time taken in transfer test three compared to transfer test one.

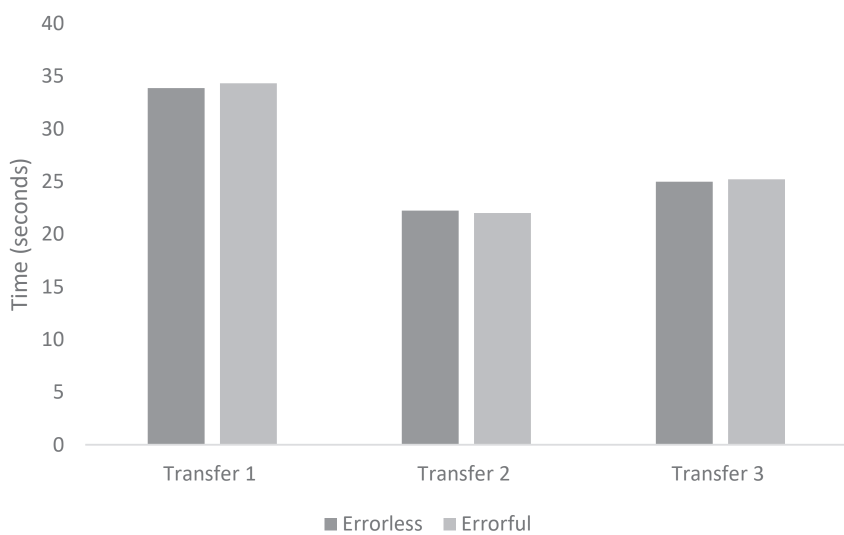

Figure 3-3: Time taken to completion during the transfer tests (seconds)

3.5 Counting performance during the secondary task

During transfer test two, three participants counted the correct number of words (n=14) while completing the motor task (two from the errorless and one from the error-ful group). The mean counting accuracy was 99.05% in the errorless group (13.87; range 9-25 words) and 96.19% in the error-ful group (13.47; range 6-19 words). There was no significant difference in counting accuracy between the two groups [t(28) = 0.260, $p = .797$].

3.6 State anxiety scores during the secondary task

The mean State Trait Anxiety Inventory's (STAI) scores (S subcategory) when multi-tasking during Transfer Test 2 were 42.67 (SD = 12.75) for the errorless group and 38.8 (SD = 11.14) for the error-ful group. The differences were not significant [$t(28) = 0.884$, $p = .384$].

Chapter 4 DISCUSSION

4.1 Aims and key findings

This study is the first to investigate the potential application of implicit learning protocols specifically to spinal surgery training. The reduction of errors during learning was used to encourage implicit learning processes, so the study was designed to compare implicit (errorless) and explicit (error-ful) learning, using cervical laminoplasty as an example. When comparing errorless and error-ful protocols in using a high-speed side-cutting burr for the simulation of bony preparations for cervical laminoplasty, neither protocol was superior with regards to performance or time taken to complete the task (pre and post-tests, as well as in transfer tests).

Both groups of participants demonstrated improved burr handling skills throughout the learning phase on cedar boards. In addition, both groups demonstrated increased performance scores in the post-test compared to the pre-test. Our results showed no statistically significant difference between the errorless and error-ful learners in terms of time to complete the tasks. Regardless of grouping, all the participants demonstrated reduced time required to complete the same task (pre and post-test). In addition, there was a significant block effect in comparing the transfer test performance scores to earlier transfer test scores. These results indicate that motor learning of high-speed side-cutting burr-handling skills occurred over the course of the study. Performance in the secondary task and the mean STAI-S score following transfer test two showed no differences between the two groups.

These results contradict the findings of Maxwell et al. (19), El-Kishawi et al. (89), and Winning et al. (35), as they did not demonstrate superior performance following errorless learning. However, the results are similar to Sanli et al. (98), whereby an easy-to-difficult progression in the learning of a fine motor task did not induce implicit learning. Both El-Kishawi et al.(89)and Winning et al. (35) found evidence of superior performance in cavity preparation for an errorless learning group compared to an error-ful learning group. It prompted us to examine and trial an errorless protocol for training to use a high-speed side-cutting burr in a task simulating cervical laminoplasty. Our errorless protocol did not appear to produce implicit learning, as we did not demonstrate superior performance in the errorless compared to the error-ful group (35).

Although this study also investigated the application of errorless learning to burr handling, the designated cervical laminoplasty procedure was probably more challenging than cavity preparation in dentistry. Final assessment task on the cervical saw bone models required students to complete cuts on either side with sound handing (smoothness) of the burr as well as the concurrent judgement of depth, width and angle. The difficulty of the task could have limited the ability for it to be learnt in a single session by novices. However, it could also mean that both groups, regardless of how they were trained, could have still experienced significant errors in the transfer tests and, therefore, demonstrated similar results.

Sanli et al. investigated in two experiments whether graduated increases in distances or target sizes affected the error rate or final performance in a disc-propulsion task (98). In experiment 1, the errorless group committed fewer errors in the learning phase; however, it did not lead to differences in performance in the transfer test or a dual-task test. Both groups achieved similar final performances regardless of their order of progress through target sizes. Sanli et al. hypothesised that target sizes did not generate significant differences in difficulty and, thus, did not incur mistakes. They observed that there was no significant difference in radial error (defined as the distance between the centre of the target and the actual position of the disc after participants had thrown them) between the two groups during the learning phase of the experiment. In experiment 2, participants' distances from the target were manipulated so that the progression was near-to-far for the errorless group and far-to-near for the error-ful group. The near-to-far group experienced fewer errors at the beginning of learning but performed with a greater number of errors than the far-to-near group on transfer tests. There was a lack of group differences in the dual-task performance test. These were all contradictory results compared to what was expected if implicit learning occurred. Therefore, it was concluded that implicit learning processes might not have been triggered by these learning environment manipulations (target size or distances). Similarly, modifications to the shape progression and wound simulations (size and depth) may not have created distinct errorless and error-ful learning protocols in the current experiment, thus not triggering implicit learning processes. Both groups may have improved their burr-handling and learnt through explicit learning processes. Therefore, they showed similar performance in transfer tests. The number of trials or shapes included in the learning protocol might have been brief compared to similar studies investigating the use of implicit learning in dentistry, which could impact learning time and, therefore, the outcomes measured in the transfer tests.

The experimental set-up with the progression in learning from easy to difficult on the cedar was similar to the methods in the study by Winning et al. (35). However, the burrs used differed in design and our participants were required to trace an outline of the shape rather than shading it in. Furthermore, differences in personal characteristics of medical students compared to dentistry students could impact their respective likelihood to reinvest and, therefore, contribute to differences in experimental outcomes noted.

Previous studies, such as dental burr-handling (35,89), suturing (93), and laparoscopic surgery gaze training (90-92,99), explored the introduction of implicit learning to various health sectors. These provided early evidence for the benefits of learning implicitly. Results here contradicted these previous findings, noting no differences in performance or time taken to complete simulated cervical laminoplasty. Participants were expected to transfer their burr-handling skills learnt on the cedar boards to perform a simulated cervical laminoplasty surgery. There is quite a rapid progression from tracing shapes on a two-dimensional surface to completing a simulated surgery on a three-dimensional cervical spine model. Perhaps the sudden increase in difficulty between the learning tasks and the transfer tests meant that both groups were still forced to learn and perform tasks explicitly. Furthermore, the concentration required for accurate placement of the cuts, and judgement of angle and depth were all decisions that participants had to face. Participants were also informed of the potentially life-threatening complications of real-life spine surgery if the cuts were not completed accurately. Perhaps the simulated spine surgery was a more difficult task requiring multiple steps and higher cognitive engagement to achieve, hence, encouraging them to learn explicitly.

Interestingly, during transfer test two (students were asked to multi-task and were also under time pressure), both groups demonstrated not only a shorter time with the completion of the task but with better performance scores when compared to the other transfer tests. Superior performance during multi-tasking is a trait typical of implicit learning (35). Errors encountered during the learning phase were anticipated rather than measured. If there were no significant differences in the errors encountered between the two groups of learners, then equally, it could be argued that both groups could have learnt implicitly. Furthermore, both groups were indistinguishable in secondary word-counting task performance. These could show stable performances in a concurrent secondary task, which is also characteristic of implicit learning (35).

4.2 Limitations

This study has limitations, which could be improved in future studies investigating the applications of implicit learning to surgical education, particularly spine surgery. Students were recruited to one-on-one sessions outside of their usual clinical hours. They were all given instructions and assessed by the same investigator. They were given written instruction sheets, and attempts were made to prevent instructions from differing between the students. However, some students asked questions to clarify the tasks further. Therefore, these students were given more verbal instructions than others if they did not understand initially – given the nature of the equipment used, such explanations were deemed necessary to ensure participant safety. To improve the consistency of the delivery of the instructions, future studies could utilise a video of the tasks involved as standardised pre-participation information rather than giving verbal instructions during the task. Previous work has been performed to confirm video feedback's efficacy for gaze training in laparoscopic surgery (92) or similar visual gaze training systems with minimum verbal instructions (90,91). Alternatively, future studies could look at implementing guided protocols without oral or written instructions for use within spine surgery.

The experimental set-up was such that the students were trained in a simulated environment. Generally, the burr stylus was held with the dominant hand at the curvature of the burr stylus, and the opposite hand was used to support the dominant hand at the wrist or forearm. This method was adopted due to the distance of the burr stylus from the cedar board, which means that there was not a suitable place for participants to rest and stabilise their dominant hand. In real-life surgical settings, the surgeon would usually grip the stylus with both hands at the curvature of the stylus. The surgeon can rest their hand or wrist on the patient’s neck. In future experiments, further development of the wound simulator blocks or training devices to better simulate real-life operative distances is needed.

Most students under-counted the words in both the errorless and error-ful learning groups, but there was no difference in recall between the groups. The overall recall accuracy was high amongst all participants. This task did not negatively impact performance; in fact, the performance was noted to be higher when participants were required to complete this task concurrently. These indicate that the secondary task may be too easy. Therefore, participants were able to count the words with minimal increased cognitive resources. Nonetheless, both groups were subjected to the same secondary task.

The assessment tasks (pre-test, post-test, and the three transfer tests) were all scored by two spine surgeons who were blinded to participants' group assignment and who completed the assessments independently of each other. Analysis of the scores given by the two assessors showed similarly correlated scores for the pre-test and post-test on the cedar boards. However, the scores were much less correlated for the transfer tests. The subjectivity introduced by having manual scoring of the cervical spine saw that bone models could contribute to a source of bias in the study. We elected to take the mean of the two assessors for use in the final analysis. The possibility of including objective measurements (such as standardised imaging and computer-generated scores or measurements) should be considered in future studies, although this would be expected to come with additional cost (e.g., CT scans of the saw bone models).

A separate, stand-alone control group was not included in this study because the explicit learning group represented the traditional 'trial and error' mode of motor skills learning. Therefore, when participants were given limited or zero information regarding the task at hand, they would be expected to learn via the testing of the hypothesis in an error-ful manner. That is, there was no control group included in the design of the study, as this group would be expected to behave similarly to the explicit learners (this is not uncommon in the literature – see, for example, Poolton et al.(48), or Tse et al. (51)). However, to provide evidence for the occurrence of learning during the study, we opted to introduce a pre-test for all participants before the learning phase on the cedar boards, which provided the basis for comparing the other tasks' performance scores and time taken. There were improvements in performance and time taken when comparing the pre-test and post-test, indicating that learning occurred in the experiment.

Furthermore, movement adjustments are often detectable when learners test hypotheses when encountering errors (19). In the study, the error-ful group would have been expected to experience more pauses and readjustments in their movements during the learning tasks, as they are required to begin the session with more difficult shapes than the errorless group. This could manifest as the drill being started and stopped more frequently as participants adjusted their grip or when thinking or re-thinking their steps. Concurrent movement monitoring would have been helpful in assessing whether there has indeed been a difference in the errors encountered in the two learning groups. The videos obtained of the participants during the transfer test could have been analysed in a similar manner to Maxwell et al. (19).

4.3 Practical applications

In this study, we have also demonstrated that the skills learnt on the cedar boards regarding handling the high-speed side-cutting burrs were stable upon transferring the task over to the cervical spine saw bone models. Therefore, it provides evidence for the training of surgical trainees in an environment quite different from the operating theatre, on practice models which do not necessarily have to have a representation of human anatomy at the initial learning stages. Furthermore, the skills of handling the power tools are still reproducible after the learners have progressed onto different models to practice. This is supported in the literature, where other studies have investigated virtual reality simulators for surgical training (92,99).

4.4 Future pathways

The application of implicit learning to improve efficiency when learning the motor components of surgical skills is a novel field within surgical education. This study is the first to examine the application of implicit learning protocol to teaching the skills involved in handling a high-speed side-cutting burr for use in spine surgery, using cervical laminoplasty as an example. As opposed to similar research investigating the teaching of the use of burrs within the dental industry, our study has not shown a significant difference between errorless and error-ful learners. Although there were no significant inter-group differences, both groups improved throughout their learning and demonstrated stable performance during multi-tasking situations.

It is likely that the protocol used to cause errorless learning (see Figure 2-4) did not result in differences in errors compared to the error-ful protocol (see Figure 2-5), so differences in learning did not occur. Future research needs to use a more suitable errorless learning protocol, one that clearly reduces errors in order to cause implicit learning in the context of burr handling. Other modifications may be required, given the limitations mentioned above to the study. For example, extending the number of repetitions to accentuate the differences in the order of shapes burred or the number of errors encountered or removing the requirement for verbal instructions (which was challenging to maintain constant between participants) by using standardised videos. In addition, the shapes and wound simulators used could be tested and their difficulty verified by a range of people, from novices to experts. Furthermore, the errors encountered could be monitored using motion detectors (counting whether extra hand movements are present when mistakes occur and subsequent compensations made). Performance at a concurrent secondary task (testing for working memory occupation), cognition monitoring (such as electroencephalogram), or brain scans could also be used to confirm implicit learning processes have occurred (29,100,101).

Studies conducted in motor learning usually have participants reporting some verbal knowledge of the task (22,38). However, implicit learners tend to report less than explicit learners at the completion of the experiment (21). The participants' explicit knowledge of the task at the end of the experiment could be recorded and used as another marker to confirm whether groups of learners have learnt explicitly or implicitly.

There are also opportunities to explore other methods to encourage implicit learning of new surgical skills; for example, the dual-task approach and analogous learning, which were discussed earlier in the thesis. Trialling different approaches and then comparing the outcomes is necessary to provide evidence to inform their implementation into the surgical education curriculum. Furthermore, perhaps there are limitations of various approaches and suitability to application to real-life settings would also need to be considered.

4.5 Conclusion

This project compared errorless and error-ful approaches to acquiring high-speed side-cutting burr handling skills. Both groups of medical students showed improved motor skills and performance with practice. However, there were no distinguishable differences between the two groups of participants. There are various explanations for these observations explored in the above section. We may utilise this experience to inform future research in this area, particularly to establish an effective errorless protocol for the induction of implicit learning.

Appendix 1: Participant information sheet

Faculty of Medical and Health Sciences
Address: 503-023, 85 Park Road, Grafton, Auckland
General enquiries: +64 9 923 4888
MAPAS: 0800 20 20 99

PARTICIPANT INFORMATION SHEET

Project title: The role of errors when learning surgical skills in spinal surgery, using cervical laminoplasty as an example
Name of Principal Investigator/Supervisor (PI): Dr Shuwen He/ Associate Professor Joe Baker, Professor Rich Masters

Researcher introduction

Dr Shuwen He – Master of Health Science Student

Project description and invitation

Aim: To compare errorless and error-ful learning using cervical laminoplasty as an example and determine which is superior for teaching surgical skills.

We are comparing two different methods of teaching students' surgical skills required to perform spinal surgery. The two learning methods compared in this study are implicit and explicit learning. During implicit learning, the skill is acquired by the student/ trainee in a non-verbal manner. This type of motor learning is similar to how people learn to ride a bicycle, and once learnt is highly automated. In contrast to implicit motor learning, typical learning modes are explicit and involve a large amount of verbal instruction from the instructor/ teacher. The student/ trainee usually has conscious awareness of how the task is executed, and once the skill is learnt, the trainee can communicate the component steps verbally in detail. There has been research into the benefits of implicit learning, including decreasing the time taken to learn the skill and learned skills being more stable in psychological stress, fatigue, and multitasking.

We would like to recruit medical students who are interested in participating in sessions whereby we teach you (either implicitly or explicitly) the surgical skills involved in the performance of cervical laminoplasty.

Project Procedures

Participants can expect training on using high-speed burrs, first on cedar wood for practice and then on cervical saw bone models. In addition, they will gain practical skills useful for a career such as in surgery.

Participants will be allocated randomly to an implicit motor learning group or an explicit motor learning group to learn a simulated spinal surgery task involving a high speed, side-cutting burr, which is a key instrument for creating the 'trough' and 'hinge' during laminoplasty.

The sessions will be conducted in the Waikato Clinical Campus during the weekend. Participants will be completing a half-day session. The first session is for teaching the skills (approximately 1.5 hours), and the second is the testing session (approximately 1 hour). Participants will be given a $10 café voucher, and refreshments will be provided on-site for your time and participation.

During the learning sessions, participants will be given a safety briefing on the use of the burr and proceed to a 'pre-test' whereby you are required to burr a designated shape outlined on the cedar wood piece provided. Then you will be divided into two groups. First, you will begin learning to burr shapes on the cedar wood pieces under the implicit or explicit motor learning protocol, progressing through three different learning tasks: burring shapes on the cedar, then burr the shapes with wound simulators covering the wood.

In the 'testing' phase of the project, participants will be put under pressure and will be filmed (only hands and body; not face): asked to perform the learned task using a high-speed burr on cervical saw bone models in a time-pressured environment simulating cervical laminoplasty, there will also be distractors to test for their ability to multi-task. You will then be asked to complete a questionnaire (The State-Trait Anxiety Inventory) to report how you felt during the test.

Data storage/retention/destruction/future use

Data collected in this study includes the cedar wood used during the learning phase, the cervical saw bone models used in the assessment phase and the final task's video recording. These will be stored in a secure drive for the duration of the research and six years beyond (according to University of Auckland standards). All data collected (digital and paper data formats) will be stored per the above provisions and subsequently destroyed after six years. After this, the electronic files will be deleted from all drives and devices used to view the files, and all paper forms will be shredded.

Participants have the right to have the recording device turned off during the testing sessions where participants are filmed.

Right to Withdraw from Participation

Participants have the right to withdraw from participation without giving a reason. Participants must be given the right to withdraw their data from the research up to 31st December.

Anonymity and Confidentiality

Data collected will be made confidential. The information provided by the participants will be reported or published as a collective result of the implicit learner and explicit learner groups without identifying specific participants.

As stated, the videorecording will be limited to workstations and hands. Your face will not be recorded. The video recording is accessible only to the primary researcher and the two consultant surgeons scoring the task. This information will be used to analyse and compare the efficiency of movement between the two groups

Coding will occur at the beginning of the assignment of the participants to each group, e.g., implicit A, B, C etc., with the corresponding workstations to the participants but not identifying the names of the participants in the trials. One investigator will oversee the coding process and have the list of codes to which the participants are assigned. The list will be stored securely and not be revealed to other investigators, particularly those in charge of grading the work performed.

The primary investigator will securely store consent forms separate from the research data, and access to the consent forms will be restricted to the primary investigator.

Conflict of Interest

Researchers will be working at Waikato Hospital, where the medical students/ potential participants are based. Please note that although the study is held on the clinical campus, neither grades nor academic relationships with the academic unit or staff members will be affected by either refusal or agreement to participate. For example, suppose you are a student of the researchers. In that case, we assure you that your participation or non-participation in this study will not affect your grades or relationship with the university. You may contact your academic head should you feel that this assurance has not been met.

Contact Details

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UAHPEC Chair contact details:
For any queries regarding ethical concerns, you may contact the Chair, The University of Auckland Human Participants Ethics Committee, Office of Research Strategy and Integrity, The University of Auckland, Private Bag 92019, Auckland 1142. Telephone 09 373-7599 ext. 83711. Email: humanethics@auckland.ac.nz

Approved by the University of Auckland Human Participants Ethics Committee on 10/06/21 for three years. Reference Number **UAHPEC22187**

Appendix 2: Consent form

Waikato Clinical Campus
Faculty of Medical and Health Sciences
Peter Rothwell Academic Centre
Waikato Hospital
Pembroke Street, Hamilton
Telephone: 07-8398750
Facsimile: +64 7 8398712

CONSENT FORM - THIS FORM WILL BE HELD FOR A PERIOD OF 6 YEARS

Project title: The role of errors when learning surgical skills in spinal surgery, using cervical laminoplasty as an example
Name of Principal Investigator/Supervisor (PI): Dr Shuwen He/ Mr Joe Baker, Professor Rich Masters

I have read the Participant Information Sheet and have understood the nature of the research and why I have been selected. In addition, I have had the opportunity to ask questions and have had them answered to my satisfaction.

Data will be stored in a secure drive for the duration of the research and six years beyond (per University of Auckland standards). All data collected (digital and paper data formats) will be stored per the above provisions and subsequently destroyed after six years. After this, the electronic files will be deleted from all drives and devices used to view the files, and all paper forms will be shredded.

Participants have the right to have the recording device turned off during the testing sessions where participants are filmed.

I agree to take part in this research.

I understand that I am free to withdraw my participation at any time and to withdraw any data traceable to me up to 20/7/21

I agree/do not agree to be video recorded.

I wish/do not wish to receive the summary of the findings.

Name: ________________________
Signature: ________________________ Date: ___________

Please provide your email address if you wish to have the recordings returned or to receive a summary of the findings.

Email address: ____

Approved by the University of Auckland Human Participants Ethics Committee on 10/06/21 for three years. Reference Number **UAHPEC22187**

Contact Details

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Appendix 3: Pre-participation survey

1. Have you worked before commencing your medical degree? If yes, what was your previous occupation?
2. Have you had any surgical experience (including workshops/ conferences/ skills training sessions)? If yes, please list them.
3. Which year of your medical degree are you currently in?
4. How many surgical rotations have you attended so far in your medical training? Please list the specialities.
5. How many times (as an estimate) have you scrubbed into theatre?
6. Have you had any experience in using power tools in theatre?
7. Have you had any experience using power tools outside of the medical setting? (e.g., at home/ recreationally)
8. Are you left or right-handed?

Appendix 4: Information sheets for participants

Information for participants

Please read through the safety instructions for using the burr and some general guidance. First, you will learn to use the burr and become familiar with it, doing tasks involving burring shapes on cedar wood pieces. Then you will be performing the bony cuts on the cervical saw bone models provided. If you have any questions, please ask before beginning your tasks.

Safety briefing – Medtronic High-speed burr 10MH30 (3mm Match head, 10 cm attachment)

We will be using the Medtronic High-speed burr for the duration of this project. Please read the following safety instructions before commencing the tasks.

- Keep long hair (longer than shoulder length) tied up/ kept clear of the burr tip
- Please wear safety goggles and a mask during the tasks
- Do NOT touch the tip of the burr or the edges near the tip of the burr
- Stay clear of the pedal when you are handling the burr/ adjusting to avoid accidental activation of the burr
- If you feel the burr tip is not connected correctly/ need help, please ask the instructor in the first instance

General tips with the use of the burr:

- Make sure the burr and attachment are correctly attached. If the tip is loose or sliding out of the burr when you lift it, let your instructor know immediately.
- Make sure the burr direction is "FORWARD". If it is in reverse mode, the unit will say "REVERSE" and make a beeping noise like a reversing vehicle. Let your instructor know immediately if this is the case.
- Hold it like a pen
- The cutting edges are adjacent to the tip. Use it in a light, controlled, sweeping motion
- For the project, please ensure your elbows are not resting on the table when using the burr

– Learning tasks on cedarwood–

With all the shapes/ lines that you are tracing with the burr, please ensure that you make the cuts in one continuous, smooth motion. The depth of the cuts will also need to be controlled. The pre-test and post-test will be timed; the learning tasks will not be.

1) **Pre-test:** Please trace the star shape outline on the board as swiftly as possible, half a burr-head deep. Note this is a timed task.
2) **Learning task 1 Depth management:** Please trace the outlines of the lines drawn on the cedar board provided. For the IL group: The first line is to be shallow – try to use just the tip of the burr to cut. The second line is the depth of half of the burr tip, and the final line is the depth of a full burr tip. (Please refer to diagram 1 below). The EL group: the first line is half a burr head deep, followed by a line of the depth of a whole burr tip, then finally a line at a depth of just the tip of the burr.
3) **Learning task 2:** Please trace the outlines of the six shapes drawn on the cedar board. Try to ensure the outline is burred to the depth of HALF a burr tip.
4) **Learning task 3:** Place the blue boxes of different depths over the board (you will be instructed in which order by the researcher). You can now burr the shapes through the circular windows in the boxes. You may rest your hands on the flat surface of the box whilst completing the task. (Please refer to diagram 2 below).
5) **Learning task 4:** Place the blue box with the three different sized circles over the board. You will be instructed as to which order you move through each of the three windows. Please outline the triangle shapes through them. (Please refer to diagram 3 below).
6) **Post-test:** Please trace the outline of the star shape on the board. Note this is a timed task.

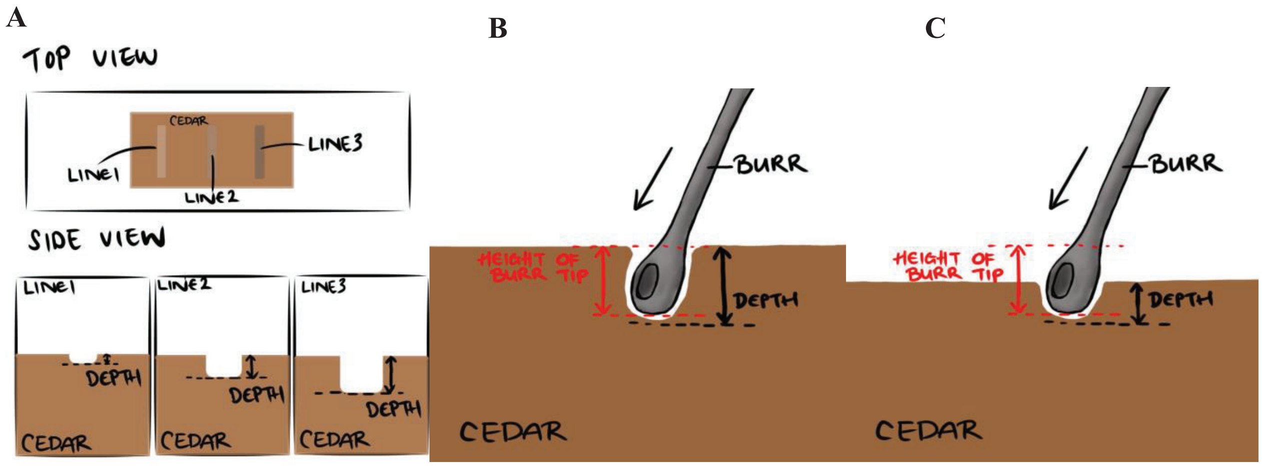


Diagram 1 Learning task 1: A: top and side views of the three lines, B: depth of the second line, C: depth of the third line

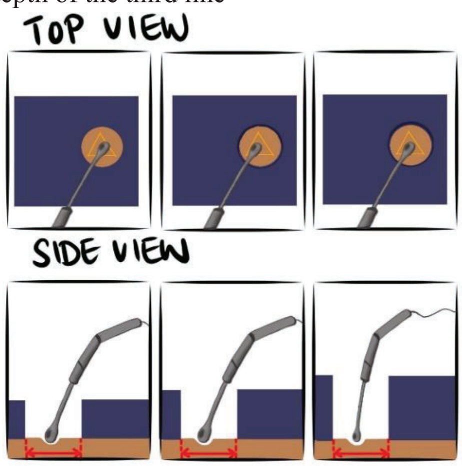


Diagram 2: Learning task 3: burring the triangle's outline through boxes of different depths. The width of the circles in all three boxes are the same

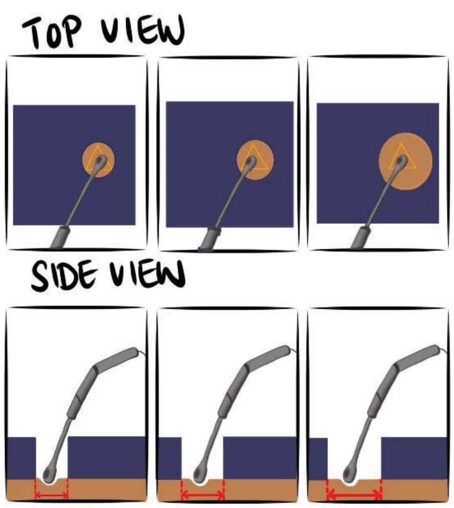
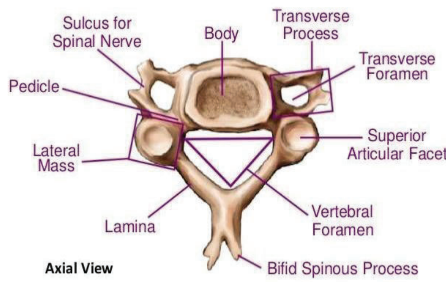


Diagram 3: Learning task 4, burring outline of the triangle through a box of the same depth but different width circles

– Assessment tasks on cervical saw bone models–

Background:
Cervical laminoplasty is a non-fusion, decompression procedure for cervical spondylotic myelopathy (CSM). It is most commonly indicated for patients with multilevel stenosis. Cervical myelopathy refers to compression of the cervical spinal cord from dorsal and ventral lesions, which leads to a distinctive clinical presentation: pain, numbness and weakness in the neck or arms and problems with coordination.

Typical cervical spinal vertebral anatomy:



Terminology:
Near cortex – the part of the hard (cortical) bone that is closest to the outside/ you (the operator)
Far cortex– the second rim of hard (cortical) bone on the other side
In between these two is the space filled in real life with soft, spongy bone (cancellous) and bone marrow.

What you need to do:
You will be making bony preparations on the cervical saw bone models necessary for a cervical laminoplasty procedure. This involves creating a hinge and a trough cut through the lamina of each cervical vertebral level. Therefore, you will be preparing three cervical spine levels during the testing session.

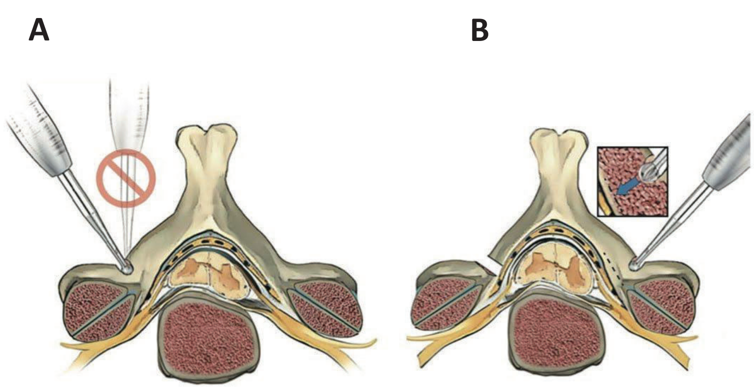


Figure 1: Laminoplasty technique. (A) The opening is created at the lateral mass-laminar junction by angling the burr perpendicular to the lamina—towards the spinal canal—rather than vertically into the facet joint; (B) the trough is completed on the opposite side, leaving the ventral cortex intact and printed with permission from Saadat *et al.*, Cervical laminoplasty. In: Rhee JM. editor. Emory's Illustrated Tips and Tricks in Spine Surgery. 1st edition. Wolters Kluwer Health, 2019.

For each cervical spine level:

1) The **open trough** should be created first (*Figure1*). We perform this on the side with more significant clinical symptoms, although either side can be utilised depending on surgeon preference. (**For today, please complete your opening trough on the LEFT side).** Please ensure you cut through the lateral mass-laminar junction with the burr tip perpendicular to the

lamina and towards the spinal canal (refer to Figure 1, A). **Make your cut, leaving a thin layer of saw bone in the far cortex** (refer to Figure 1b lamina on the left-hand side)

2) The **hinge** is then created on the contralateral side. Preservation of the ventral cortex of bone on this side is important. Again, the burr is placed at the lamina and lateral mass junction. However, it is **only used to remove the dorsal cortex of the bone.** The hinge cut must be deep enough to allow for the opening effect to occur, but not so much that you end up burring all the way through and lose the connection in the far cortex of the bone. (Refer to Figure 1b lamina on the right-hand side)

The surgeon will then open the laminoplasty in real life as per Figure 1, C-D. The surgeon can use instruments to apply dorsally directed pressure underneath the lamina and manipulate the spinous process dorsolaterally to facilitate dorsal and lateral opening at each level. **You are NOT required to do this on the saw bone models.**

You will do this bony preparation in 3 cervical spine levels on the models provided whilst being filmed.
For the 1st cervical level, you will be required to do the above and be timed.
For the 2nd cervical level, you will repeat the same tasks, but there will be a voice recording of a list of objects this time. |You will have to listen to it whilst completing the task. At the end of the task, you will be asked how many objects read out in the recording are medically related. This preparation is also to be completed within 3 minutes; a timer will be provided in the room.
At the end of this task, a simple questionnaire is to fill out.
At the 3rd cervical level, you will be required to repeat what you have done previously **(same as for the 1st level)**. You will be timed. There are no other tasks or distractions.

Appendix 5: List of equipment used

- A Medtronic Midas Rex EM200 Legend EHS Stylus with a 10AN drill attachment, 3mm match head (10MH30 burr head attachment) on the stylus, footswitch: EF100 was used for the experiment
- Canon video camera + tripod
- Cedarwood boards (one per student)
- Stencil (6 shapes + star shape drawn within circles of 27mm diameter)
- Plywood (for the cedar boards to be taped onto)
- Spine, Cervical with Posterior Ligament and White Discs, Solid Foam SKU: 1326-6-1 (https://www.sawbones.com/spine-c1-c7-solid-foam-w-posterior-ligament-white-foam-pads-1326-6-1.html)
- Spine holder, posterior occipital, and cervical spine holder. SKU: 1528-5-1 (https://www.sawbones.com/holder-cervical-occip-2-piece-cervical-holder-w-2nd-piece-attached-via-velcro-1528-5-1.html)
- Black masking tape (stabilise cedar boards onto plywood)
- Safety goggles (one per student)
- Surgical masks (one per student)
- Wound simulators (three per student: heights of 25mm, 50mm and 75mm, the 50mm simulator having three simulated wounds with diameters of 40mm, 60mm and 80mm)
- Desk
- Chair
- iPad 10
- Sony headphones (to play recording)

Appendix 6: Words used in transfer test 2

“**Sutures, needle holder**, shapes, greenhouse, paper, **hypertension, cardiac arrest, troponin,** carrots, potatoes, salad, miso soup**, scalpel,** green beans, potatoes, tea, dried fruit, tomatoes, carrots**, forceps, dissecting scissors**, rice, beef, eggplant, **retractor, suction**, zoo, animals, food, knife, **ECG, creatinine, x-ray**, coffee, soup, chicken, **cannula,** food, knife, cups, chopping board”

All words used above with the 14 medical words in bold.

These words were recorded in this sequence. The final recording was 44 seconds long.

Appendix 7: STAI-S Score

State Trait Anxiety Inventory

Read each statement and select the appropriate response to indicate how you feel right now, that is, at this very moment. There are no right or wrong answers. Do not spend too much time on any one statement but give the answer which seems to describe your present feelings best.

1	2	3	4
Not at all	**A little**	**Somewhat**	**Very Much So**

1. I feel calm	1	2	3	4
2. I feel secure	1	2	3	4
3. I feel tense	1	2	3	4
4. I feel strained	1	2	3	4
5. I feel at ease	1	2	3	4
6. I feel upset	1	2	3	4
7. I am presently worrying over possible misfortunes	1	2	3	4
8. I feel satisfied	1	2	3	4
9. I feel frightened	1	2	3	4
10. I feel uncomfortable	1	2	3	4
11. I feel self confident	1	2	3	4
12. I feel nervous	1	2	3	4
13. I feel jittery	1	2	3	4
14. I feel indecisive	1	2	3	4
15. I am relaxed	1	2	3	4
16. I feel content	1	2	3	4
17. I am worried	1	2	3	4
18. I feel confused	1	2	3	4
19. I feel steady	1	2	3	4
20. I feel pleasant	1	2	3	4

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