Ten guiding principles for movement training in neurorehabilitation

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Abstract
Clinicians and researchers in neurorehabilitation continue to have difficulties with reporting and describing the many active components used within physical therapy interventions. People with neurological conditions can present with cognitive, perceptual, behavioural and physical impairments that require individual consideration within their training program. Current knowledge from the areas from motor control theories, neuroscience and clinical evidence from neurological and musculoskeletal rehabilitation all inform the design of movement training programs. Such a diverse field of theoretical, scientific and clinical knowledge makes it difficult to agree upon a consistent way to label the many components relevant to training. This article proposes the use of ten guiding principles of movement training that can provide terminology for use in neurorehabilitation clinical practice that could be used by both professionals and individuals with neurological conditions. The ten Movement Training Principles could potentially improve interdisciplinary collaboration, enhance teaching of the clinical reasoning process and drive innovation for future therapies.

Keywords: exercise, training, movement, rehabilitation, learning

Introduction

Movement training within neurorehabilitation utilises knowledge from the fields of theoretical motor control and learning, exercise science and rehabilitation. Rehabilitation has embraced the International Classification of Functioning (ICF) as a useful conceptual framework to identify impairments, activity levels and participation, in addition to facilitators and barriers to the rehabilitation process (Health Organisation, 2001). Movement training in neurorehabilitation can aim for restoration, adaptation, maintenance and prevention, themes likely to have relevance across all areas of physical therapy (Lennon et al., 2018).

There is, however, no clear classification system for movement training interventions that could provide an organised way of identifying and labelling the many active ingredients for training (Hart et al., 2014). Treatments can be listed under many labels such as; disciplines (physical therapy, exercise physiology), functions (walking, balance), symptoms (pain, tremor), body parts (knee, trunk), impairments (strengthening, cognitive training), sensory systems (vestibular, proprioceptive), techniques (mobilisation, facilitation), philosophies (Tai Chi, Yoga), researched protocols (Constraint Induced Movement Therapy), equipment (Treadmill training, Robotics), orthosis/prosthesis (Splints, Braces), actions (isometric, ballistic) approaches (Action Observation, Task Specific Practice) and original concept inventors (Brunnstrom, Bobath).

In the current climate of evidenced based learning, inconsistent labels such as these can make information dissemination very challenging. These problems with interdisciplinary rehabilitation terminology have been described as inevitable 'growing pains' which can lead to misinterpretation and conflict (Levin et al., 2009). Clinicians rarely use isolated interventions (Hayward et al., 2014; Kleynen et al., 2017), which creates an immediate divide between clinical practice and many singular or simple research design protocols. Poor intervention reporting is a common theme that limits the interpretation and implementation of research findings. For example, improved standards in the reporting and design of future stroke rehabilitation research has been recognised as a high priority (Bernhardt et al., 2019). As various clinical disciplines and research fields combine, a common language of movement training principles could help facilitate clinical reasoning, guide research toward specific problems encountered in practice (Esculier et al., 2018) and improve communication and coordination across disciplines (Hart et al., 2014).

The use of guiding principles can be an effective way of categorising relevant themes in neurorehabilitation. Important principles for neurological rehabilitation have been previously summarised and include patient centred care, the ICF, teamwork, prediction, neural plasticity, motor control, functional movement reeducation, skill acquisition,

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self-management and health promotion (Lennon et al., 2018). These principles can help guide evidence-based clinical practice by providing a broad conceptual framework. While some of these principles address movement, there is still scope to provide further detail and guidance with respect to movement training.

While 'neuroplasticity' is an important physiological process for motor learning, the term itself is often exploited as a popular buzzword that lacks specific meaning to guide clinical practice. Neuroplasticity refers to the ability of the central nervous system (CNS) to make structural and functional changes in response to internal and external stimuli (Cramer et al., 2011). Clinicians often refer to basic principles of plasticity such as specificity, intensity, time and age in the hope that it can inform clinical practice to improve rehabilitation interventions (Kleim & Jones, 2008). These principles are likely to be important yet remain limited in their ability to guide specific movement training at an operational level.

With respect to movement training, there is an opportunity to provide even further guidance to the way we describe and prescribe training principles in clinical practice. Movement training components taught in neurorehabilitation education are often sourced from theoretical areas that include motor control theories and motor learning, exercise science and self-management.

Theories of human motor control should also inform clinical practice. The Generalized Motor Program theory proposed by Schmidt (Schmidt, 1975) suggests the CNS stores generalised programmes used for certain types of actions. The Systems model theory theorises that movement evolves from an interaction with multiple systems in order to meet our functional goals and provides a theory on how movement synergies can influence control over the Degrees of Freedom 'problem' originally described by Bernstein (Bernshteĭn, 1967). More recent follow up work on the uncontrolled manifold hypothesis has emphasised the 'abundance' of solutions to a movement, as these provide a rich sensory learning experience that can improve adaptability - perhaps a key part in our evolution (Latash, 2018). Future physical rehabilitation research is already gaining insight from these ideas (Vaz et al., 2019). Computational theory highlights the feedforward predictive abilities of the CNS (Wolpert et al., 2011), while the Dynamic Systems theory proposes that movement constantly adapts to both individual and environmental constraints (Corbetta & Vereijken, 1999; Kamm et al., 1990). These are just some theories that provide valuable information to include within training principles.

Motor learning has a long history within neurorehabilitation and refers to the process of skill acquisition and problem solving that can be promoted through various types of practice (Kleynen et al., 2020; Krakauer & Thomas Carmichael, 2017; Maier et al., 2019). Motor learning includes several types of sensorimotor learning, cognitive strategies and other variables that we should consider to intensify our interventions to optimise the learning process (Guadagnoli & Lee, 2004).

Exercise science integrates knowledge from biomechanics, functional training, strength and conditioning, pain and injury management. These themes have important implications for movement training that include information about exercise type, frequency, intensity, time (American College of Sports Medicine, 2017) injury, and load management (Drew & Finch, 2016).

Self-management has become an integral part of neurorehabilitation (Jones & Riazi, 2011). Patients themselves also need the opportunity to become active learners in the rehabilitation process where they can understand and identify important components for training. Clear and simple training principles without complicated professional jargon, could help engage patients in the design of their own physical rehabilitation over the longer term (McKenna et al., 2015).

The importance of a common language to describe the movement system within physical therapy has been recognised as a priority (Association & Others, 2015). The aim of this paper is to briefly summarise the relevance of ten 'Movement Training Principles' (MTPs) in the context of movement training in neurological populations and discuss their potential in facilitating a common language to support education, research and valuable collaborations for neurorehabilitation (see online figure). These principles originate from the areas of motor control/learning, exercise science and self-management, and can be used across all health disciplines involved in movement training, including Physiotherapists, Exercise Physiologists, Occupational Therapists and Personal Trainers. These principles are likely to be relevant for movement training for many clinical populations, however this paper will focus on neurorehabilitation.

The movement training principles

1. Actual and predicted bodily state

Multiple, congruent sensory inputs from vision, proprioception, vestibular, auditory and even arterial baroreceptors (Mittelstaedt, 1996; Ogoh et al., 2018) give perceptive information about body location. It has been stated that we must learn to predict the sensory consequences of movement, before we can control our movements (Wolpert et al., 2011) possibly through a process of Bayesian inference - a statistical model of probability which updates as more sensory information becomes available (Samad et al., 2015; Wolpert, 2014). Feedforward prediction leads to sensory attenuation of self-initiated movements (Blakemore et al., 1998) and explains why we cannot tickle ourselves. These predictive abilities assist in developing a sense of body ownership, self-identity (Dogge et al., 2019), and a sense of agency, which are important parts of the motor learning process (Sato & Yasuda, 2005). For example, Functional Neurological Disorders show reduced sensory attenuation, which may help explain dissociative symptoms and an unwanted shift in movement behaviour (Pareés et al., 2014).

People with schizophrenia can demonstrate changes in sensory predictive abilities that may well contribute to conflicts in body ownership (Frith et al., 2000). Parkinson's Disease (PD) patients demonstrate lower sensory attenuation with reduced intake of dopaminergic medication (Wolpe et al., 2017). Whiplash and concussion patients show deficits in cervical position awareness of the head in space when vision is removed (Cheever et al., 2016; Chen & Treleaven, 2013; Treleaven et al., 2006) which may drive ongoing symptoms, while many stroke patients with 'Pusher Syndrome' show altered perceptions of verticality and/or graviception that may contribute to the action of pushing toward the hemiplegic side (Karnath, 2007). Spatial cognition helps determine the locations of body parts in relation to the surrounding environment with known deficits in physiological aging (Gazova et al., 2012), stroke (Lunven & Bartolomeo, 2017) and neurodegenerative conditions (Possin, 2010). Spatial awareness of depth, vertical perception, surrounding boundaries and landmarks could be an important consideration for movement training. Extra sensory inputs, spatial orientation and interaction with the environment might assist in priming motor activity (Stoykov & Madhavan, 2015).

2. Feedback

External feedback can provide information about the ultimate success or outcome of the movement, which is termed Knowledge of Results (KoR). External sensory feedback is often termed augmented feedback, and can be used as extra information used to coach movement and includes verbal or non-verbal instruction, manual facilitation to block or guide movements (Normann, 2018), visual feedback via laser pointers or mirrors to provide information about speed, size and direction of movement. Electromyogenic biofeedback can provide auditory or visual feedback about muscle activity during movement. Virtual reality can also provide extra information about movement (Ferreira dos Santos et al., 2016). Internal sensory feedback about movement kinematics and kinetics, can guide movement quality control and provides a Knowledge of Performance (KoP).

Feedback can be provided constantly, intermittently, or randomly with the aim of enhancing learning. Feedback can be provided 'live' during movement or can be used later to review movement performance - such as via video review. Feedback can be gradually reduced as motor control improves as too much feedback may be considered if the learner is becoming reliant on this extra information to move effectively, in what has been termed the 'guidance effect' (Salmoni et al., 1984). However, this effect may not apply to all situations, with ongoing feedback learning mechanisms shown to be beneficial in some situations (Buchanan & Wang, 2012). In neurorehabilitation it may be important to consider different feedback learning strategies to maintain function and quality of life in some neurological conditions (Donchin & Timmann, 2019).

3. Error-based learning

If the actual sensations from a movement differ from what was anticipated by feedforward prediction, it is referred to as a sensory prediction error (SPE). These can be errors in timing, direction or force. As control improves, SPEs reduce with practice through a process of unconscious, error-based learning, which is likely to be important for skill acquisition. An example can be reducing the SPE of retinal slip with head movements following vestibular gaze stability exercises (Migliaccio & Schubert, 2019).

Error-based learning with reaching arm movements may be motion referenced, by comparing SPEs with actual motion states (Gonzalez Castro et al., 2011) or perhaps more importantly, SPEs are compared with the cognitive plans and intentions linked to the reaching movement (Day et al., 2016). Error-based learning such as split-belt treadmill adaptation can even occur in combination with other simultaneous conscious feedback learning strategies (Statton et al., 2016). Clinicians can consider both implicit and explicit motor learning strategies with training (Kleynen et al., 2015). This concept of dual-learning has exciting implications for gait retraining strategies in populations such as stroke (Cherry-Allen et al., 2018).

4. Reward-based learning

Reward links closely to the idea of salience - what is important to the individual? The resulting behavioural reactions might positively reinforce the selection of a new movement and improve skill retention (Galea et al., 2015). New sensations might drive a form of 'playful exploration' to seek out some variability in the hope of reward (Pekny et al., 2015). It is difficult to be sure what an individual person might interpret as rewarding (Schultz, 2015) but incorporating rewards into movement training is likely to be important for movement selection.

Interactive video 'gamification' has been shown to be feasible within neurorehabilitation (van den Berg et al., 2016) and could assist in driving motivational behaviour, increasing practice dose and physical activity for some people (Hassett et al., 2016, 2020; Krakauer & Cortés, 2018). Future technology could possibly make obtaining rewards more achievable such as using virtual reality to provide an illusion of amplified arm movements in order to achieve reward more easily (Ballester et al., 2016).

Internal rewards such as stability and perceived safety may also attract movement habits such as slow, asymmetrical gait patterns, despite making progress with speed and symmetry in therapy. If training is to provide alternative movement selections and carry-over into real life, both external and internal rewards will need to add value for each individual patient (Roemmich & Bastian, 2018).

5. Cognitive selecting and planning

Movements include many sequential parts that are grouped together in a process called 'motor chunking'. These motor chunks are probably distributed throughout the cortex as motor plans and retrieved via memory processes involving basal ganglia and cerebellar networks (Diedrichsen & Kornysheva, 2015). Freezing of gait in Parkinson's Disease may indicate problems accessing motor plans (Heremans et al., 2013). Task specific dystonia may also demonstrate a corruption in selecting movement plans for specific tasks (Sadnicka et al., 2017). Apraxia may also result from selecting and planning deficits. Innovative visuo-motor training to improve movement ideation and planning such as Action Observation may have potential for training (Pazzaglia & Galli, 2019) as well as motor imagery (Eaves et al., 2016; O'Shea & Moran, 2017; Silva et al., 2018), mirror therapy (Thieme et al., 2019) and movement with music (Srinivasan & Bhat, 2013; Zhang et al., 2017).

Metacognitive processes involved in evaluating feedback and the level of thinking and self-awareness required to make decisions and choices about movement are important. Reflecting on real world hemiplegic arm use with the transfer package in Constraint Induced Movement Therapy might be an example of how important this can be (Taub et al., 2013). Training of visuospatial tasks, attentional set-shifting and working memory has shown promise with reducing freezing of gait in Parkinson's Disease (Walton et al., 2018), while training metacognitive awareness might also assist with transference of skills across tasks in stroke (McEwen et al., 2014). Opportunities to make choices about the type of practice might also further enhance the motor learning process (Lewthwaite et al., 2015).

6. Practice and variability

'Dose' of practice has been gaining increasing attention, particular in populations such as stroke where interventions with higher doses of practice have shown promise in animal studies (Kleim et al., 1998; Nudo et al., 1996; Nudo & Milliken, 1996) and early human trials (Birkenmeier et al., 2010; Hsu et al., 2010; Lang et al., 2015; Lohse et al., 2014; Moore et al., 2010). Dose in this context refers to the number of movement repetitions, or time spent actively engaged in practice. For some movements, very high movement repetition numbers may be needed to drive neuroplasticity, improve strength, activity levels and functional change.

In populations of stroke patients, there is a growing consensus that dose of practice needs to increase in inpatient rehabilitation (Dorsch & Elkins, 2020). However, there is no evidence for a dose-response effect of high repetition upper limb task-specific practice leading to increased functional capacity in chronic stroke patients (Lang et al., 2016). This has prompted some reflection on how to further intensify interventions in other innovative ways (Bernhardt et al., 2019; Winstein, 2018; Winstein & Varghese, 2018). For many neurological patients, high repetitions are not possible due to weakness, fatigue, reduced attention span or musculoskeletal load restrictions (see physical capacity), so alternative ways to define 'intensity' and engage in practice could be explored.

Variability is known to influence motor learning (Dhawale et al., 2017) and was termed - 'repetition without repetition' by Bernstein (Ito, 2015). It highlights the importance of building multiple movement solutions to deal with unforeseen changes in internal or external conditions. Early variability in training can be a necessary way to map the possibilities of movement for a task (Harbourne & Stergiou, 2009). Random practice might take longer for skill acquisition when compared to blocked practice, but retention of a skill may be superior (Shea & Morgan, 1979). Random practice (Lee & Magill, 1983; Merbah & Meulemans, 2011) and distributed practice (spaced repetition) might also enhance the learning process (Gerbier & Toppino, 2015). Rest intervals can also allow for recovery, and sleep has even been shown to help 'off-line' motor skill learning in stroke (Gudberg & Johansen-Berg, 2015; Siengsukon & Boyd, 2009). As movement becomes more successful the expert learner may seek further variability to build a higher level of skill (Harbourne & Stergiou, 2009) for an optimal 'challenge point' for learning (Guadagnoli & Lee, 2004). Movement training might also allow learners to choose for themselves how they vary their own practice (Wu & Magill, 2011).

7. Biomechanics

Movement training can aim to either increase or decrease the movement degrees of freedom in order to improve performance. For example, an ankle foot orthosis can provide an external constraint to provide stability at the ankle, knee and might help with toe clearance in gait (Tyson et al., 2013). For some suitable candidates, carbon fibre AFOs can provide propulsion and improved energy efficiency (Aboutorabi et al., 2017) and ankle dorsiflexion assistive devices can mitigate against fatigue effects on strength and balance in people with Multiple Sclerosis (McLoughlin et al., 2014). For optimal functional movement, biomechanical trade-offs around stability versus mobility will need to be considered with the prescription of all these devices (Cattaneo et al., 2002; Meyns et al., 2020).

Internal constraints such as muscle and joint contracture, viscoelastic stiffness of muscles, velocity dependent hyperexcitability in spasticity can also alter biomechanics (Glazier & Davids, 2009). Training may consider increasing active range (if possible) and exploring optimal ways of controlling any new range to adapt and improve performance.

Robotic exoskeletons can provide biomechanical support and assistance to enable function and increase practice. Features can include impedance control of the device as it interacts with the environment, and adaptive control, which adjusts to a person's needs (Krebs, 2018). Potential advantages in enabling movement are anticipated in terms of reducing disability, but important questions around the design requirements to enhance motor learning still need to be answered (Rodgers et al., 2019; Tejima, 2001). Even so, novel robotic technology if paired with virtual reality may have potential to provide a variable and enriched motor learning experience (Krakauer & Cortés, 2018).

8. Physical capacity

Strength training can be undertaken for specific functional actions that may involve combinations of concentric, eccentric, isometric or ballistic contractions. The functional need for power and/or endurance will influence prescription and progression of load, repetitions and perceived intensity. Common barriers that require consideration with strengthening include; engaging very weak muscles, musculoskeletal injury, motor and perceived fatigue, and sensitivities such as spasms or dystonia (McCambridge et al., 2019). Progressive resistive training is gaining clear evidence on improving strength for Multiple Sclerosis (Kjølhede et al., 2012), stroke (de Sousa et al., 2018; Flansbjer et al., 2012; Harris & Eng, 2010; Mehta et al., 2012; Morris et al., 2004), Parkinson's Disease (de Farias et al., 2020) and Cerebral Palsy (Ross et al., 2016; veloso Fernandes et al., 2017). Resistance training can even have a positive effect on brain volume and cognitive functioning (Herold et al., 2019).

Load on musculoskeletal structures is also very relevant. Tendinopathy, osteoporosis and osteoarthritis exercises all need individualised management of load, in addition to those recovering from ligament sprains, stress fractures and muscle strains. An increase in training load is related to injury in athletes (Drew & Finch, 2016) and could also be measured and monitored in neurological populations. The amount of practice may need slow incremental progression to minimise the risk of injury and subsequent setbacks in rehabilitation.

Cardiovascular fitness within a movement training program can improve function and quality of life (Ellis & Motl, 2013; Stoller et al., 2012). There is a long list of other health benefits of fitness that cannot be ignored, particularly in neurological populations where activity levels are often very low (Rimmer & Lai, 2015). Brain health with aerobic exercise is also important and might be used to prime neuroplasticity for learning (Mang et al., 2013, 2014; Moriarty et al., 2019; Schwenk et al., 2014) and over time, could be neuroprotective for some degenerative conditions such as Parkinson's Disease (Schenkman et al., 2017; Zigmond & Smeyne, 2014).

9. Attention

Attentional focus refers to how the person attends to selective sensory stimuli to help initiate and regulate movement performance. If attention is drawn to the movement quality of body parts and characteristic techniques or bodily sensations - this is termed 'internal focus'. This might be useful to initiate and recruit movement, but can be detrimental if it over-complicates movement planning by deviating away from the automatic selection of desired motor plans (Lohse et al., 2014; Song, 2019), possibly worsening outcomes in Functional Neurological Disorders (Espay et al., 2018), dystonia (Sadnicka et al., 2017) and might even explain 'choking' under pressure in sport (Cappuccio et al., 2018). Internal focus might also increase pain perception via pain hypervigilance (Vossen et al., 2018).

An 'external focus' is more commonly used in movement training and directs the learner to information about movement effects on the outside environment. There is an accumulation of evidence that supports an external focus of attention in preference to an internal focus for motor learning (Wulf, 2013). Multiple types of external sensory attentional cues can help facilitate movement in Parkinson's Disease (Cassimatis et al., 2016). In stroke, however, the relative roles of internal versus external focus are less clear (Kal et al., 2018). In neurorehabilitation clinicians may well need to be prepared to use different types of attentional focus to improve motor learning.

Dual tasking using another simultaneous movement or cognitive task might increase movement automaticity by forcing the brain to continue to execute movements while attentional demands are focused elsewhere. This may have advantages for simulating real life scenarios, but care must be taken if performance decays enough to reduce motivation or lead to falls and injury (Heinzel et al., 2016).

10. Beliefs and self-efficacy

Confidence in one's ability and the belief that training will help improve performance and function is possibly the most important MTP. Major barriers that prevent people engaging in exercise include 'low expectation' from exercise and 'fear of falling' (Ellis et al., 2011). Beliefs drive behaviour both in and outside the training environment so neurorehabilitation may need to consider strategies around motivation and behaviour change (Ellis & Motl, 2013; Michie et al., 2011). Training programmes might utilise measures of self-efficacy as these have been shown to be better predictors of mental health, disability and quality of life in neurological conditions (Shulman et al., 2019).

Fear of movement in pain states and beliefs around certain 'safe' or 'correct' postures can result in movement avoidance in what has been termed kinesiophobia (Kori, 1990), which may limit opportunities to train and explore all movement options. In chronic pain, a vicious cycle of limited motor control can persist, and future movement training interventions in chronic pain may need to target many MTPs. A movement training programme should consider building choice, autonomy and confidence in an individual to create what has been termed a 'virtuous cycle' of positive learning (Wulf & Lewthwaite, 2016).

Discussion

The aim of this paper is to summarise the relevance of ten 'Movement Training Principles' (MTPs) in the context of movement training in neurological populations and discuss their potential in facilitating a common language to support education, research and valuable collaborations for neurorehabilitation. The MTPs categorise ten interrelated factors that impact physical therapy that can be targeted in training programmes using various possible strategies (see Table 1 on pg. 15). The MTPs bring together relevant principles from the areas of motor control and motor learning, exercise science, and self-management, and are intended to assist neurorehabilitation practice and research by:

- Encouraging a common terminology used to educate and empower patients, which can be used across all health professions and students involved in movement training.
- Providing principles that can be updated as evidence grows.
- Identifying training components affected in individual patients to inform clinical decision-making.
- Using principles to evaluate and design innovative rehabilitation treatments (from past, present and future practice), including rehabilitation technology.

The MTPs can stimulate discussion about how and when principles can be targeted with interventions. Debates regarding interventions based on MTPs, rather than philosophical or historical approaches, could provide more constructive conversations about ways to improve outcomes in rehabilitation. Some interventions or protocols might be stronger in some principles than in others. If principles are then identified as useful additions, these might be added into the programme, included in additional treatments, or planned for a later time during the rehabilitation journey.

Experienced physiotherapists tend to use a diverse selection of treatment options in neurorehabilitation (Kleynen et al., 2017) but have difficulty articulating the clinical reasoning process (Hart et al., 2014; Vaughan-Graham et al., 2019). The MTPs may help guide this process and future work in the implementation of these principles in clinical teaching and practice is warranted. Every principle included in this paper is interrelated with all the others, with no hierarchical level of importance. The MTPs should only provide options for consideration and are therefore not prescriptive. This more simplified strategy may help train new professionals by providing useful training principles to consider, while more experienced clinicians can use the MTPs to articulate and justify their rehabilitation plans, especially when an intervention combines multiple training principles.

As neuroscientific and clinical evidence regarding specific clinical populations continues to grow, the relevance of the MTPs for each of these populations will hopefully become clearer. Detailed justifications and descriptions of training principles within interventions could improve research methodology reporting (Hoffmann et al., 2014) and assist with the design of future technology (Brackenridge et al., 2016). Rehabilitation technology could benefit from a more structured approach. Current research around virtual reality has been described as the 'wild west' with a lack of clear guidelines and a temptation to focus on the technology itself rather than the theories behind its use for training (Birckhead et al., 2019). Robotic devices have also been recognised for their potential to drive recovery, yet need to consider relevant components of neuroplasticity and learning for future successful evaluation and design (Brackenridge et al., 2016). Current devices can be reviewed in terms of what training principles they might contribute towards enhancing outcomes, which could then inform improved updates and designs in the future.

Researchers in stroke rehabilitation have recently recognised the importance of identifying the interaction of many training components that are likely to be important in driving recovery (Hayward et al., 2014). The need to identify more usable ingredients to help bridge the gap between motor learning principles and clinical practice in stroke has recently been highlighted (Maier et al., 2019). In clinical teaching, the MTPs can discourage the use of vague or non-specific terminology. For example, recent discussions around the importance of 'dose' and 'intensity' in promoting neuroplasticity, could refer to more specific principles about practice of repetitions, amount and type of variability, type of attentional focus and specific active learning strategies used in a particular intervention. The next step is to investigate the potential use of MTPs in assisting clinical reasoning and design thinking in various clinical settings with different neurological populations.

There are several limitations to the ten MTPs. The principles are derived from a variety of theoretical origins, many of which have yet to be proven scientifically. This makes it difficult to provide certainty about their importance in specific clinical scenarios. Evidence regarding MTPs in specific neurological populations will take time, however, a common language could potentially support this process through improved research methodology and critical analysis of clinical research. The MTPs could also be misinterpreted, particularly in terms of the level of importance of each principle and the fact that each of the principles are interrelated in many ways. As guiding principles, support will need to be provided, with further work underway to determine the usability and helpfulness for students, health professionals, patients, and researchers.

Finally, the MTPs do not currently include adjunct interventions that may play an important role in the future of movement training in neurorehabilitation, such as brain stimulation techniques (Rothwell, 2016), vagus nerve stimulation (Engineer et al., 2019) and pharmacological treatments such as fampridine (Valet et al., 2019). The effect of these interventions on MTPs will need to be considered as more evidence becomes available.

The MTPs also have relevance for movement training in musculoskeletal and sports rehabilitation. It is hoped a common language will assist with much needed collaborations between the fields of neurological, vestibular and musculoskeletal physical therapy (Snodgrass et al., 2014), injury prevention (Low, 2018) and sporting performance (Glazier, 2017). Exchanging ideas becomes much easier when we are speaking the same language!

Conclusion

The ten MTPs presented in this article aim to provide a common language to support the design of movement training interventions. There is a considerable amount of shared knowledge from the areas of motor control and motor learning, exercise science and self-management that has the potential to guide clinical practice, teaching and research methodology. It is hoped the ten MTPs provide a usable and relevant language that will facilitate clinical reasoning and encourage future innovation in movement training for patients, health professionals, students, and researchers.

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Table 1: A summary of the Movement Training Principles with possible examples for each.

Movement principle	**Definition**	**Examples to consider**
1. Actual & predicted bodily state	Awareness of intrinsic body positions and the surrounding space. Multiple incoming sensations during movement become predictable and reliable, with a sense of ownership and agency (Wolpert & Flanagan, 2001).	• Provide congruent sensory stimulation to increase proprioceptive awareness • Load bearing • Weighted vests, belts, cuffs • Tight garments • Tactile stimulation • Mobilisation • Visual orientation • Active movements • Sensory exploration • Sensory priming before activity such as vibration, electrical stimulation, brushing, tapping, bouncing, or shaking • Orientation or 'tuning in' to body parts and the surrounding space
2. Feedback	Knowledge of Performance is information about movement execution via verbal feedback and non-verbal sensory cues from tactile, proprioceptive, auditory and vision (Shumway-Cook & Woollacott, 2006). Knowledge of Results provides explicit information from external verbal, non-verbal, visual coaching about the outcomes of the movement, or goal achievement (Shumway-Cook & Woollacott, 2006).	• Tactile feedback • Visual feedback via mirror or laser pointers • EMG auditory/visual feedback • Dynamic/textured insoles • Taping • Feedback can also be reduced/removed such as closing eyes • Explicit coaching information about technique can be verbal or non-verbal (e.g. video review) • Task completed successfully? • Timing of completion • Accuracy of movement • Number of mistakes, or number successfully completed • Feedback can be provided continuously, intermittently, and gradually removed as skill improves • Is the person becoming over-reliant on feedback such that it is limiting progress?
3. Error-based learning	Implicit information comparing predicted versus actual movement sensations produce sensory prediction errors during practice. These errors reduce as skill acquisition improves (Wolpert et al., 2011).	• Sensory information about movement precision in terms of • Timing • Direction or force • Consider contrasting sensations that give information about accuracy such as • Visual targets • Proprioceptive or visual boundaries with movement • 'Practice by doing' using task specific and functional practice exercises
4. Reward-based learning	A form of achievement or reward as a result of the movement (Xiuli Chen et al., 2018).	• Consider novel sensations • Feeling secure and safe • Emotional gains • 'Showing off' • Success in reaching a goal or • Pleasurable rewards on completion • Consider ways to incentivise training through choosing tasks that are achievable, using coercion, prizes and gamification
5. Cognitive selecting and planning	The process of consciously thinking, planning and choosing from a variety of movement options in order to complete the required outcome. This may involve problem solving, selection, sequencing or guided discovery of movements	Cognitive training to monitor and adapt via conscious choice and planning. This includes: • Spatial cognition • Navigation • Pre-planning/ideation

	(Diedrichsen & Kornysheva, 2015; McEwen et al., 2014).	● Metacognitive awareness to check and self-monitor movements via graded discovery ● Executive functions such as working memory and flexible thinking ● Consider video reviews to analyse movement performance ● Action observation, mental practice and motor imagery ● Regular self-monitoring (such as real-world arm use in the transfer package in Constraint Induced Movement Therapy)
6. Practice & variability	Practice can be determined using a select number of repetitions of a movement or time spent actively practicing (Lang et al., 2015). Variations can include subtle changes in speed, timing and direction in movement performance and rest intervals between repetitions or sessions (Dhawale et al., 2017).	● Repetitions ● Time engaged in practice ● Rest intervals ● Massed or distributed practice ● Task specific, part-practice or non-task practice ● Blocked or random practice Consider variations in: ● Speed ● Distance ● Power ● Direction and sequence of movements Variation can be added via: ● Coaching instruction ● Setting the nominal difficulty of the task ● Adding uncertain external variables such as unexpected perturbations, or different environments
7. Biomechanics	The physical science of stationary and moving body parts (LeVeau, 1984). Does the training provide opportunity to enable or constrain movement kinematics or kinetics in order to enhance activity and the learning experience?	● Splints ● Braces can limit ROM for stability to enable functional movement ● Mobilisation with movement and active movement to increase functional ROM ● Functional Electrical Stimulation may increase active ROM with orthotic benefit to increase activity ● Propulsive energy in carbon-fibre AFOs to improve energy efficiency with walking ● Active, passive, or active-assisted supports such as pulleys, body weight supports ● Constraints to block movement and force other strategies e.g. Trunk restraint with reaching, mitt/glove in Constraint Induced Movement Therapy ● Manual facilitation and guidance, buoyancy in hydrotherapy or physical capacity ● Robotic exoskeleton to provide active assistance against gravity for weak muscles to allow more movement practice
8. Physical capacity	The actual or potential ability to perform movements or physical activity (Kasper et al., 2017). Training protocols for: ● Muscular strength, power, endurance and/or ● Cardiovascular fitness ● Load management ● Brain health and neuroprotection	● Resistive training, increase/decrease loads, repetitions, exertion (repetitions in reserve), power outputs, rest times, set numbers, per day/week, type of muscle action (concentric, eccentric, isometric, ballistic) ● Monitor load on tendons, muscles, ligament, bones and joints with injury or pathology ● Aerobic exercise, time and training distance. High/low or intermittent levels of intensity, actual (Heart Rate) or perceived exertion

9. Attention	Internal focus on the body parts, sensations and actual technique of movement performance (Wulf, 2013). External focus on the result of the movement or other related factors. Cues to help the initiation, sequence or timing of a movement (Wulf, 2013). Dual tasking using additional simultaneous tasks while still performing the movement.	• Internal focus on body part, tactile sensations of friction, pressure, performance technique. • Tactile cues to bring attention to specific body part(s) • External focus on spatial direction of targets, timing of movement. Visual cues such as lines on the floor, targets on the wall. Verbal cues, tactile stimulation to help initiate movement or bring attention back to task. Auditory cues such as metronome/music to aid rhythmic patterns • Add an additional cognitive task - talking, cognitive challenge, or additional functional movements - carrying a drink or interacting with a smartphone
10. Beliefs & self-efficacy	Perceived self-efficacy is concerned with people's beliefs in their ability to influence events that affect their lives (Bandura, 2010). Does the person believe that the training is useful and beneficial? Do they believe the training/movement is in some way harmful or do they have concerns or reservations? Is there potential to become more confident in the movement? Does the training encourage confidence to self-monitor, initiate and continue their own training?	• Screen for preconceived negative beliefs about specific movements, impairments and treatments; listen to the person's opinion about the training ideas before, during and after sessions • Provide education in the context of an individualised rehabilitation plan and invite them and/or their carers to help in the design • Measure self-efficacy before, during and after a programme; discuss and map long-term strategies from the outset and encourage positive behaviour modification