Testing the efficacy of motor analogies for landing safely from falls

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Abstract

Fall-related injuries are a major concern in countries with an aging population. One approach for reducing the likelihood of fall injuries is to teach older adults how to land safely. However, different safe landing techniques are required for different types of fall and direction of fall. Additionally, after a fall is initiated there is insufficient time to choose and use an appropriate safe-landing technique—particularly for older adults, who frequently display age-related cognitive deficiencies. Literature suggests that motor analogies are easy to retrieve from memory, can rapidly deploy attention during movement, and may even speed up the motor learning process. This thesis explores whether motor analogies can be utilized as a rule-of-thumb to promote safer landing (i.e., reduced risk of injury). Two laboratory experiments were conducted to examine the effect of motor analogies on biomechanical factors associated with landing by young adults (Chapters 2 and 4). A series of three online experiments examined whether motor analogies invoke mental representations associated with characteristics of safe landing (Chapter 3). Finally, a clinically-registered randomised controlled protocol was designed to investigate motor analogies in older adults (Chapter 5) (due to Covid-19 restrictions, the trial has not yet been completed). The findings suggest that an appropriate motor analogy can invoke mental representations associated with safe landing, and that participants instructed to use a motor analogy land in ways that are likely to result in less severity of injury, regardless of the direction in which they fall. The research provides preliminary evidence for the potential of motor analogies to reduce fall-related injuries, paving the way for future clinical studies.

Dedication

To the people of Iran fighting for their freedom…

May we all sing ‘Jin, Jiyan, Azadî’ (Woman, Life, Freedom) in a free Iran!

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Wait a second, I can't forget my little buddy Zakros: We submitted this thesis together and shortly after you entered this world. Thank you for putting up with your stressed mama as I completed this chapter of my life.

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Publications arising from the work generated in this thesis

Manuscripts published

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Manuscripts under review

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Manuscripts in preparation

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Chapter 1. General introduction

Falls are a major concern in countries with an aging population and one of the leading causes of injury and death among older adults. Prevention of falls has been the most common strategy for combating this issue; however, fall prevention programmes often have low participation rates and the extent to which they moderate serious injury is unclear (Lamb et al., 2005). A meta-analysis of fall prevention programmes revealed that they may reduce the frequency of falls, but have minimal effect on fall-related injuries and their severity (Hopewell et al., 2020). A supplementary approach to prevention, which has been largely neglected by researchers, is to teach older adults how to land safely if an accidental fall occurs (Hsieh & Sosnoff, 2020; Moon & Sosnoff, 2016). Learning safe landing strategies can reduce the likelihood of injuries, but these strategies often involve difficult motor skills that are challenging to learn late in life. Nevertheless, research in motor learning has demonstrated that motor analogies can provide a powerful tool for guiding motor skill learning effectively and efficiently, particularly in older adults who often display age-related cognitive deficiencies (Masters et al., 2020). The main contribution of this research is to find a practical solution to promote safe landing among older adults, by means of motor analogies.

1.1 Falling by older adults

Aging is a complex process that is associated with a progressive loss of muscle mass, strength, power, endurance, bone density, and overall functional capacity (Conlon et al., 2016). Loss of strength, general neuromuscular deconditioning, and sensory impairments that stem from growing older increase the likelihood of falling (Lord, 2021). Falls can cause a variety of health problems among the older adult population, including frailty, immobility, and decline in functional ability (Berg & Cassells, 1992). Some other prominent complications linked to falling include: intracranial hematomas, injury of internal organs, and fractures of the humerus, wrist, pelvis, and femur (Pasquetti et al., 2014).

Every year, approximately 30-60% of older adults experience a fall (Rubenstein, 2006). Accidental falls account for 30-50% of injury-related hospitalisations among older adults (Scott et al., 2005; Scuffham et al., 2003) and duration of hospital stays following a fall injury is considerably longer than for other injuries, lasting up to 15 days (World Health Organization, 2008). Consequently, the prolonged hospitalisation experience can impose enforced immobilisation, accelerated bone loss, and sensory deficiencies, which can lead to irreversible functional decline (Creditor, 1993).

In addition to physical injuries, falls in the older adult community can lead to gradual loss of confidence and independence (Parry et al., 2001). These losses can cause self-imposed restrictions on the daily physical activities of the older adults (Katsumata et al., 2011; Tinetti et al., 1994). Individuals who experience falls often fear that they may fall again, which negatively impacts their quality of life. Fear of falling among the aging population can also become the root of more serious problems by causing inactivity and muscular deconditioning, subsequently increasing the risk of falls among this age group (Schoene et al., 2019). Falls have also been shown to be a driving force behind social withdrawal, depression, and confusion among older adults (Al Nahian et al., 2020; Nevitt et al., 1991).

Therefore, it should be no surprise that medical health professionals have become increasingly concerned about the hazards of falling among older adults. Worldwide, falls are considered the 3rd most important cause of injury and are associated with direct medical costs exceeding $34 billion in the USA in older adults (Keall et al., 2017). In Aotearoa New Zealand (NZ), 18% of the total cost of injury is due to falls (Deverall et al., 2019). The NZ government estimates that by the year 2025, fall-related injuries will cost the country around

$418 million dollars annually (Barry & Kaye, 2016). According to the NZ government's national population projections,[1] the country's older adult population is expected to double in size in the next 25 years (i.e., from 0.79 million in 2020 to 1.36–1.51 million in 2048); consequently, the costs associated with falling are also likely to increase. Extra expenses, such as post-discharge assistance from hospitals and rehabilitation costs for individuals who have experienced falls, will also increase. Falling not only burdens the healthcare system, but also causes many older adults to enter nursing homes when they otherwise are capable of enjoying an independent life. This need to rehome older adults raises other problems, including inadequate specialised facilities to deal with the growing older adult population, lack of professionals to care for the needs of older adult fallers, limited hospital space, and increasing need for long-term hospice care.

Various methods have been proposed to reduce fall-related injuries, ranging from identifying older adults who are at risk of falling (Maranesi et al., 2015; Patel et al., 2020; Pradhan et al., 2019) to fall prevention interventions (Sherrington et al., 2020). Fall prevention interventions have included martial arts (del-Pino-Casado et al., 2016; Mortazavi et al., 2018); dance (Coubard et al., 2011; Krampe et al., 2010; Merom et al., 2013); and resistance, balance, and functional training (Buchner et al., 1997; Granacher et al., 2013; Gschwind et al., 2013; Kyrdalen et al., 2014; Renfro et al., 2016). However, one of the many challenges faced is the existence of several risk factors associated with falling, such as impairment of balance, gait, cognitive status, and vision, as well as environmental hazards (Ambrose et al., 2013; Tinetti et al., 1988), which each require targeted interventions. Consequently, the complex nature of falls makes medical assessment of fall risks challenging

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[1] https://www.stats.govt.nz

and the establishment of truly effective interventions difficult (Rubenstein, 2006). Thus, due to the multifactorial nature of falls, many researchers encourage healthcare professionals to look beyond one-dimensional methods and use multi-disciplinary, complementary approaches to address falling in the older adult community (Chang et al., 2004; Gillespie et al., 2009; Kannus et al., 2005; Reed-Jones et al., 2013; Rubenstein, 2006). Consistent with this position, a small number of researchers have proposed an alternative method to reduce fall-related injury, which involves teaching older adults how to land safely when a fall occurs (Moon et al., 2019; Moon & Sosnoff, 2016).

1.2 Landing safely from accidental falls

Landing safely in the event of an accidental fall requires implementation of movement techniques to reduce the likelihood of fall-related injuries; however, there is a paucity of research on this topic (DeGoede et al., 2003; Hsiao & Robinovitch, 1997). According to a systematic review by Moon and Sosnoff (2016), very few studies (i.e., thirteen in total) have investigated safe landing techniques, of which only one study investigated safe landing in older adults.

One of the core challenges of safe landing is that multiple factors, such as the location of impact, fall direction, and magnitude of loads applied to the body at impact, play a role in choosing an appropriate safe landing strategy (Robinovitch et al., 2004). The direction of fall is particularly important; hence, landing techniques and instructions used to encourage safe landing vary as a consequence of the direction of fall. For instance, for forward falls, young participants were instructed to flex their elbows as they would during a push-up (Chou et al., 2001), or received a variety of instructions (e.g., “reduce your elbow extension speed prior to hand-ground impact”, “avoid accelerating your hand into the ground at impact – just hold it steady and wait for the ground to hit it", "land with a slightly flexed elbow angle, do not ever land with a straight elbow") (Lo et al., 2003). For backwards falls, young participants were instructed to fall with flexed knees and reduce impact to their hips (Tan et al., 2006), or to flex their knees and hips while contracting the muscles crossing over these joints, similar to when reducing the speed of descent during sitting (Robinovitch et al., 2004). For sideways falls, different instructions were used, including "fall with the body as relaxed as possible" (Sabick et al., 1999), "avoid impacting the hip during the fall" (Robinovitch et al., 2004), or to use the martial arts technique of roll and slap (Groen et al., 2010; Groen et al., 2007; Groen et al., 2008; Weerdesteyn et al., 2008).

Additionally, most safe landing techniques can only protect specific body parts. For instance, analysis of a cohort study revealed that in a forward fall, rotating sideways during descent reduced the risk of head impact, but increased the risk of hip impact (Komisar & Robinovitch, 2021). This observation brings about a compex conundrum: which body part should be protected? It is a conundrum that is particularly complicated for older adults, because both head and hip injuries can have serious consequences in this population. Head traumas are responsible for concussions and comas, and even minor head traumas from falls cause more than one-third of older adults to return to the emergency department in the following 90 days (Southerland et al., 2016). Older adults suffering from hip fractures tend to stay the longest in hospital and 20% are expected to die within a year of sustaining their injuries (Zuckermann, 1996). In view of the relatively high mortality rate associated with hip fractures, a comprehensive review of studies over a period of 10 years found that mortality one year after hip fracture is three to four times higher than expected in older adults (Roche et al., 2005).

Additionally, it takes approximately 0.3 seconds to recover balance when falling from a standing height, with impact occurring after approximately 0.7 seconds if recovery is not possible (Le Goic et al., 2018). This timeframe leaves inadequate time between the balance recovery phase and impact with the ground (i.e., 0.4 seconds) to choose and use an appropriate safe landing technique. The variety of landing techniques required to land safely when falling in different directions, combined with the complex dilemma of prioritising one body part over another and the minimal time one has before impact occurs, accentuates feasibility issues with respect to older adults adopting safe landing strategies, particularly given the impaired cognitive and motor learning responses associated with ageing (Harrington & Haaland, 1992; King et al., 2013; Nettelbeck & Burns, 2010).

1.3 Age-related cognitive deficiencies

Age-related changes in the brain contribute to motor impairments, slowing of movements and cognition in older adults (Camicioli et al., 1999). Magnetic resonance imaging studies report abnormalities, such as white matter lesions on the brain of older adults, which are associated with cognitive and neurologic decline (Prins et al., 2004; Silbert et al., 2008; Soumaré et al., 2009; van den Heuvel et al., 2006). Changes in older adults' brain structure are also thought to impose constraints on the performance of working memory and to reduce its capacity (Nettelbeck & Burns, 2010).

Working memory is considered to be the "blackboard" of the brain (Goldman-Rakic, 1992) and believed to underpin the dynamic relationship between passive storage and active modification of information by the brain (Baddeley & Hitch, 1974; Bopp & Verhaeghen, 2005; Kane et al., 2001; Oberauer et al., 2000). The widely acceptable model of working memory presented in Figure 1 consists of two core systems and two subsidiary systems. The main systems are a central controller, which is in charge of executive functions and regulating ongoing processes (e.g., directing attention), and an episodic buffer, which acts as an interface between long term memory and two subordinate systems. The two subordinate or subsidiary systems are a visuospatial sketchpad (for processing visual information) and a phonological loop (for processing speech-based information) (Eysenck et al., 2007).

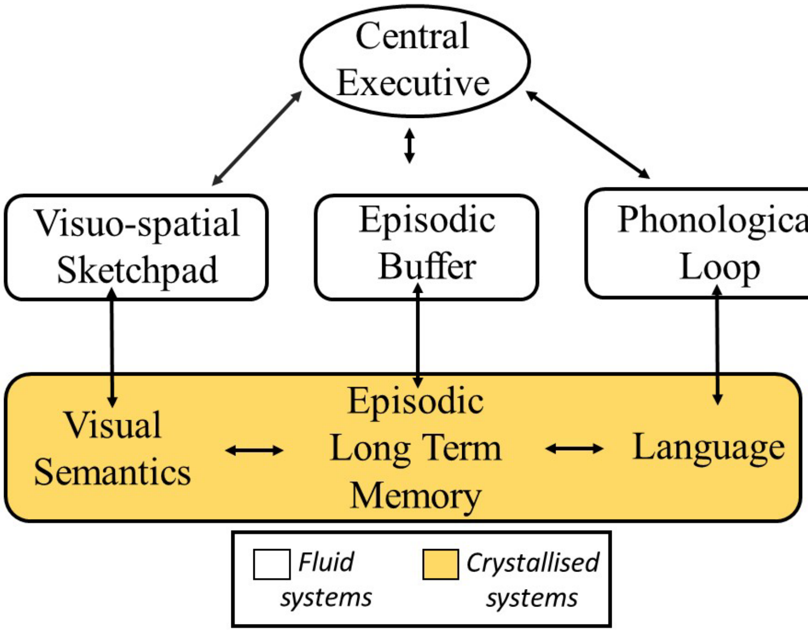

Figure 1: Subsystems of working memory (Baddeley, 2012).

A key feature of working memory is that, due to limited capacity, resources are required to be shared between storage and processing (Bopp & Verhaeghen, 2005). This limited capacity issue means that if one subsystem is burdened by the need to perform a cognitively challenging task, the execution of other tasks that rely on the same subsystem suffers; hence, the amount of cognitive resources available for storing information while simultaneously processing incoming or recently acquired information inhibits working memory performance (Borella et al., 2008).

On one hand, ageing is linked to a decrease in processing resources and processing speed, which is evident by inferior working memory performance in older as opposed to younger adults (Borella et al., 2008; De Beni & Palladino, 2004; Waters & Caplan, 2001, 2003; Wingfield et al., 1988). On the other hand, when learning a new motor skill, the processing of movement related information places a high load on working memory (Schlapkohl et al., 2012). Considering that motor learning relies on a continuous interaction between cognitive and motor processes (Mulder & Hochstenbach, 2003), it is not surprising that older adults learn motor skills more slowly than young adults and fail to reach similar levels of proficiency (McNay & Willingham, 1998; Serbruyns et al., 2015; Voelcker-Rehage, 2008). Hence, there are practicality issues surrounding teaching older adults various motor skills (i.e., different safe landing techniques based on fall direction) and expecting them to implement them in the very little time (i.e., 0.4 s) that they have before fall impact occurs. However, it is well established in the literature that ageing mainly affects effortful memory processes, whereas procedural (automatic) memory processes remain relatively intact (Hoyer & Verhaeghen, 2006). For instance, Chauvel et al. (2012) found that age related memory deficits disappeared when they promoted acquisition of a skill (golf putting) in which procedural (automatic) memory processes were predominant over declarative (effortful) memory processes, a technique known as implicit motor learning (Masters, 1992; Masters & Maxwell, 2004; Maxwell et al., 2001).

1.4 Implicit motor learning

Reber (1967) showed that information can be gained from the environment with little or no conscious insight about the governing rules (i.e., learning artificial grammars) and coined the term implicit learning. This phenomenon was later expanded into learning simple motor tasks, such as pressing buttons, tracking a moving target with a cursor, and tracking and catching a ball with a joystick (Green & Flowers, 1991; Nissen & Bullemer, 1987; Pew, 1974; Wulf & Schmidt, 1997). The findings of these studies implied that implicit learning can improve motor performance without the learner having conscious access to the information that is learned or the need to be aware of what is being learned (i.e., explicit knowledge). Masters (1992) argued in favour of the acquisition or improvement of complex movements implicitly and provided the first evidence for learning a complex motor skill (i.e., a golf putting task) with little to no explicit knowledge about how the movements are carried out.

Studying the neurophysiological mechanisms of adaptive implicit memory, which includes brain stem, limbic, and thalamic regulation of neocortical representations, could lead to a more comprehensive understanding of the neurophysiological process involved in explicit and implicit learning (Tucker et al., 2022). For instance, functional magnetic resonance imaging (fMRI) studies have provided neuroimaging evidence of cortical and subcortical activation during explicit and implicit learning processes (Yang & Li, 2012). Meanwhile, Aizenstein et al., (2004) observed differences in brain activity in the visual regions of the brain with respect to implicit and explicit learning. The researchers found a decrease in activity in the visual regions of the brain during implicit sequence learning but not during explicit learning. Additionally, the activation of a particular brain region (i.e., insula) during explicit learning processes but not during implicit learning processes, suggests that higher-order attentional/intentional processing is dedicated to explicit learning, as well as a possibly stronger engagement of articulatory planning and control processes that are involved (Yang & Li, 2012). It can, therefore, be inferred that the changes in brain activity during implicit and explicit learning can be because of these learning processes relying on different memory mechanisms. Thus, these observations provide a theoretical framework that could explain the benefits of implicit motor learning, which presumably requires fewer processing resources than explicit learning.

Implicit motor learning is thought to promote procedural (automatic) memory processes more than explicit motor learning, which is thought to rely more on effortful memory processes (Masters, 1992; Masters & Maxwell, 2004; Masters et al., 2020; Maxwell et al., 2001). This further reliance on procedural (automatic) memory processes can reduce the loads on the central control system of working memory (Hayes & Broadbent, 1988), which in turn can free up space for information processing (Berry & Broadbent, 1984) and can result in robust performance under conditions of psychological stress and physiological fatigue (Maxwell et al., 2003). Many experiments have provided evidence that implicitly acquired skills are less likely to fail under pressure compared to explicitly acquired skills (Hardy et al., 1996; Masters, 1992, 2000; Mullen et al., 2007; Poolton et al., 2007b). For example, Chauvel et al. (2012) asked younger and older novices to practice a golf-putting task by hitting towards targets positioned at different distances. For some of the participants, the targets were nearby and easy to hit at the start (infrequent errors), but became more distant as practice progressed. For other participants, the targets were more distant at the start (frequent errors), but became closer as practice progressed. The results of the study indicated that learning with frequent errors caused participants to rely on explicit (declarative) memory processes, but learning with infrequent errors caused participants to rely more on implicit (procedural) automatic memory processes (i.e., implicit motor learning). The results also showed that during a dual-task condition (i.e., tone counting and putting), the motor performance of participants who practiced with frequent error was impaired, whereas the motor performance of participants who practice with infrequent errors remained intact. Most importantly, the study demonstrated age-equivalent motor performance between younger and older adults who learned implicitly (infrequent errors), but not explicitly (frequent errors). These findings are consistent with work by Maxwell et al. (2001), which argued that reducing the number of errors that occur during practice causes implicit motor learning because participants are less likely to test hypotheses (and accumulate explicit knowledge) about their movements if they are making few errors; consequently, individuals rely more on implicit (non-declarative) automatic memory processes.

Various other methods have been proposed to cause implicit motor learning, with most of them focusing on impeding the learner's ability to use working memory for hypothesis testing. During motor learning, working memory is used to hold and manipulate information related to correcting errors or changing movements to avoid errors and/or improve performance (i.e., hypothesis testing) (Klayman & Ha, 1987; Ohlsson, 1996). An outcome of such hypothesis testing is the accrual of explicit (declarative) knowledge about the movements. Implicit motor learning paradigms seek to limit the accrual of explicit (declarative) knowledge. Other techniques that have been developed to encourage implicit motor learning include dual-task learning (using a concurrent irrelevant task to drain working memory resources), manipulating outcome feedback so that the learners are unable to test hypotheses about the outcome of their movements, and analogy learning during which information underlying the execution of the to-be-learned movement is presented in an encapsulated chunk rather than as individual bits of knowledge or rules (See Masters et al., 2020, p. 79).

As demonstrated by Chauvel et al. (2012), age-related deficits in motor learning are mitigated when the learning (or practice) environment favors the use of implicit (procedural) memory processes to guide motor skills (i.e., implicit motor learning). Hence, Masters et al. (2018) suggested that implicit motor learning techniques, such as analogy learning, may provide a viable method by which to teach older adults to achieve safe landing. To invoke implicit motor learning characteristics, this research explores the use of motor analogies to promote safe landing.

1.5 Analogy learning

Analogies are commonly used in everyday life. For instance, to enhance understanding of a new concept, we often compare the new concept to a similar, more familiar concept (e.g., the heart works like a pump, a hydrogen atom is like our solar system).

It has been argued that learning via analogies has played a pivotal role in our evolution when learning how to hunt, make tools, and tie knots (Brand et al., 2021). For instance, to tie a knot, many steps need to be followed. These steps are difficult to learn and recall, but they can be efficiently taught, learned, and transmitted when they are anchored to a familiar behaviour or concept (i.e., an analogy). A common analogy used in this case is a rabbit analogy: “here is the rabbit burrow; the rabbit comes out of the burrow; the rabbit goes around the tree; the rabbit goes back down the burrow”. The analogy then can be communicated to others in the community, facilitating the spread of new knowledge and eventually leading to cultural evolution (Brand et al., 2021).

1.5.1 Analogical reasoning

Analogies have been used as an effective educational tool for the explanation and conceptualisation of new science materials, such as mapping similarities between a factory and an animal cell (Glynn & Takahashi, 1998) or other subjects, such as language and grammar learning (Gentner et al., 2011; Goswami, 1986, 1988), physics (Podolefsky & Finkelstein, 2006), chemistry (Orvis et al., 2016), and mathematics (Alvarez et al., 2017). Analogies act as a mediator between the existing knowledge and the new knowledge by mapping a well-known concept (base) onto the new concept (target), such that the target becomes more understandable and memorable (Glynn & Takahashi, 1998). The mapping feature of analogies also assists with solving everyday problems, because using a familiar concept as a framework can give insight into new problems (Keefer & Landau, 2016). In cognitive psychology, analogies have been declared to be at the core of cognition (Hofstadter, 2001).

Analogical reasoning requires the recognition of associations between multiple objects or representations, which allows the learner to acquire and organise new knowledge by structuring it in terms of information or knowledge that is already known (Starr et al., 2018). Hence, two critical processes that are required for analogies to be successful include retrieval of information from memory and mapping the relationship between the base and target domains (Hummel & Holyoak, 1997). Analogy learning is thought to occur in the following manner (Gentner & Clement, 1988; Gentner & Landers, 1985): first, the learner accesses the base (familiar concept) in long term memory; second, the learner maps similarities between the base and target; third, new knowledge is created by storing reasoning regarding the familiar concept; fourth, the robustness of the match is determined by assessing and adapting the reasoning; finally, similarities are extracted and a new schema is created. Different criteria have been proposed for selecting the to-be-mapped items, such as importance-guided matching (i.e., selecting a predicate for matching, based on importance, (Winston, 1980), systematicity (i.e., a highly generalised form of transfer between frameworks, (Hofstadter, 1984), and goal attainment (Holyoak, 1985). The latter model identifies goal achievement as the main criterion for mapping between concepts, stating that the reasoning of cognitive systems is often relevant to the system's goals. This reasoning implies that an active goal triggers a subset of the system's knowledge-base that is relevant to the system's goals. The system then provides input to deductive processes that create plans/predictions regarding the environment, causing change in behaviour/actions (Holyoak, 1985).

1.5.2 Analogies in motor learning

Analogies are also commonly used by physical educators, coaches, occupational therapists, and physical therapists to teach movements. These analogies convey the complex structure of the to-be-learned movement using a familiar concept (Liao & Masters, 2001; Masters, 2000) and are often referred to as motor analogies. For instance, an analogy used in basketball for shooting the ball into the hoop is "throw the ball as if you are trying to put cookies into a cookie jar on a high shelf" (Lam et al., 2009b). For most people, this analogy captures the biomechanical technique typically used by experts when making a free throw in basketball. Using motor analogies as opposed to multiple explicit verbal instructions results in conveying the information necessary to perform the movement in a non-explicit form that reduces conscious knowledge about how to move. Other examples of learning a new motor skill via analogies include "…swing the rope as if you are drawing circles on the sides with arms" for rope skipping (Tse, Fong, et al., 2017) and "throw the dart as if you are throwing a crumpledup piece of paper into a wastebasket located slightly farther away from the dartboard" for dart throwing (Zeniya & Tanaka, 2021).

Zacks and Friedman (2020) investigated whether motor analogies can reduce the motor learning process and improve skill acquisition in a drawing test. Kinematic measures (i.e., smoothness, accuracy, and movement duration) were used to quantify performance. The authors found that the analogy group demonstrated increased mastery of the drawing task compared to a control group, and recommended using new and creative ways of communicating motor instructions to enhance the motor learning process.

Empirical evidence favours the efficacy of motor analogies with respect to learning a new movement skill, confirming that using motor analogies results in similar learning patterns and performance to traditional explicit instructions (Bobrownicki et al., 2015; Lam et al., 2009a, 2009b; Law et al., 2003; Liao & Masters, 2001; Poolton et al., 2006; Poolton et al., 2007b). For instance, Koedijker et al. (2011) investigated the effects of attention focus and time restraints on motor learning (i.e., table tennis). These authors found that novices receiving explicit instructions were less accurate in skill-focused and dual-task conditions compared to single-task conditions. However, novices receiving a motor analogy were only less accurate in the skill-focused condition, and maintained accuracy under dual-task conditions. Considering that analogy instructions are thought to rely less on declarative memory processes, the authors recommended the use of motor analogies for promoting mastery with respect to attention control structures.

Many researchers argue that motor analogies need fewer processing resources (Law et al., 2003; Liao & Masters, 2001; Masters & Liao, 2003; Poolton et al., 2006), which in turn frees up working memory for additional cognitive processes. However, not all researchers support this claim. Bobrownicki et al. (2015) argued that the benefits of analogy learning are a consequence of the volume of information presented to the learner. In other words, the volume of information that must be explicitly processed by analogy learners is lower than for learners in control conditions. Bobrownicki et al. (2015) therefore compared motor learning (i.e., high jump) by participants in an analogy condition and an explicit condition that were matched for volume of content and information.[2] These authors reported that performance was similar in both conditions (although, the analogy learners displayed slightly more efficient technique and recalled fewer technical rules). It can be argued that the findings of Bobrownicki et al. (2015) are not particularly informative. Analogy learning was devised to overcome issues associated with explicit learning in real life, during which learners typically receive many explicit rules about how to perform a movement. By reducing the amount of information that needs to be processed to a mere three rules in their explicit condition, Bobrownicki et al. (2015) dramatically reduced the demands typically associated with explicit learning. Consequently, the negative impact that processing many explicit instructions has on learning was reduced, which made analogy learning appear to be no more effective than explicit learning. In support of this argument, Schücker et al. (2013) found no learning differences between participants who received a whole set of analogy instructions (nine sets) or multiple explicit instructions (nine technical rules) about how to perform a full golf swing (i.e., grip position, pressure on the grip, and posture).[3] By increasing the volume of analogies, Schücker et al. (2010) increased the amount of information that needed to be

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[2] Analogy condition: “Keep your upper body tall like a pencil through take off. Alternate your legs like scissors to clear the bungee cord”.
Explicit condition: “Keep upper body tall through take off. Lift left leg up over the cord and bring down. Repeat action with right leg”.

[3] Analogy instruction for the correct grip: “Imagine you have an open tube of toothpaste between your hands and the contents must not be pushed out.”
Explicit instruction for the correct grip: “The pressure of both hands on the grip is equal. The wrists should move freely, hands should stay on the grip while swinging”.

processed, which, not surprisingly, yielded similar outcomes to using multiple explicit instructions. Nevertheless, when Tse, Fong, et al. (2017) investigated the performance of children in a rope skipping task, they found that children provided with two set of analogies (i.e., one for jumping and one for swinging the rope) demonstrated more efficient performance under dual-task conditions compared to a group receiving explicit instructions. Taken together, it seems that control of movement becomes more independent of working memory processes when learning by motor analogies (Maxwell et al., 2003). However, the point of analogy learning is to encapsulate the relevant information (i.e., instructions/rules) as a chunk within a single analogy, thus reducing the demands that are placed on working memory to consciously recall and process explicit instructions, rules, or information during motor performance.

Hence, many studies attest that compared to explicit instructions, skill acquisition via motor analogies results in more stable performance under cognitively demanding situations, such as dual task conditions (Bobrownicki et al., 2015; Jie et al., 2016; Lam et al., 2009a; Liao & Masters, 2001; Poolton et al., 2007b; Tse, Fong, et al., 2017; Tse, Wong, et al., 2017), psychological stress conditions (Lam et al., 2009b; Law et al., 2003; Liao & Masters, 2001; Vine et al., 2013), and concurrent decision making (Masters et al., 2008; Poolton et al., 2006; Schlapkohl et al., 2012). For instance, to teach novices how to hit a topspin forehand shot in table tennis, Liao and Masters (2001) tested a motor analogy that required participants to swing the bat up the hypotenuse of [a] right-angled triangle when striking the ball. When compared to participants who received explicit rules, participants provided with a motor analogy showed motor behaviors similar to implicit motor learning (i.e., more stable performance under stressful conditions and secondary task loading). Liao and Masters (2001) suggested that motor analogies may be processed in the visuospatial sketchpad system of working memory rather than in the phonological system, so participants were able to process the tasks in different parts of working memory, allowing more stable performance (Masters et al., 2008). In line with this view, electroencephalography studies suggest that motor analogies result in more efficient verbal cognitive processing (van Duijn et al., 2020; van Duijn, Hoskens, et al., 2019). Additionally, studies investigating the kinematics of movement assert that movement patterns resulting from motor analogies represent more “implicit movement control” compared to explicit instructions (Lam et al., 2009b) and that motor analogies enhance inter-joint coordination (Zeniya & Tanaka, 2021).

Considering the features associated with using motor analogies for skill acquisition, this technique may be beneficial for populations with constraints on their cognitive resources, such as older adults, patients with stroke, Parkinson’s disease, Alzheimer’s disease, etc. Hence, motor analogies might be a useful tool to promote safe landing during an unexpected fall in older adults.

1.5.3 Analogies in older adults

Motor learning is crucial in the development of humans in the early years of life, and continues to be important throughout the lifespan. Older adults often need to learn new motor skills (e.g., hobbies and activities of daily living) or relearn already known skills (e.g., in case of stroke or any other damage to the brain) to improve quality of life. The decline in learning complex motor skills that is associated with ageing is documented in the literature, with researchers showing that older adults improve less efficiently compared to young adults (Curran & Keele, 1993; Shea et al., 2006). The decline has been attributed to age-related impairments in sensorimotor and cognitive performance (i.e., working memory) (Tse, Wong, et al., 2017). However, according to a review by Hoyer and Verhaeghen (2006), age-related cognitive deficiencies affect effortful memory processes, which are mainly required for processing explicit information or instructions, while automatic memory processes remain more or less unaffected. Consistent with this claim, Chauvel et al. (2012) provided evidence of age-equivalent motor performance in young and older adults, when motor skills were predominantly controlled by procedural (automatic) memory processes (i.e., implicit motor learning), but distinct age differences when motor skills were predominantly controlled by declarative (effortful) memory processes (i.e., explicit motor learning). The authors suggested that implicit motor learning approaches should be used to promote procedural memory processes when older adults need to learn or relearn motor skills. Hence, it is not surprising that motor analogies have been shown to result in better learning by older adults (Tse, Wong, et al., 2017), to enhance dynamic balance training outcomes (Kim et al., 2021), and to benefit rehabilitation (Jie et al., 2016; Kleynen et al., 2014).

In one study, Jie et al. (2016) investigated the walking performance of individuals with Parkinson's disease using the following analogy instruction: "following footprints in the sand". Walking performance was measured under single- and dual-task (motor and cognitive) conditions. The authors concurred that analogy learning successfully reduced working memory demands and facilitated the walking performance of participants. When Jie et al. (2021) examined the effects of analogy instructions on walking parameters in a real-life setting, they found equivalent effects for participants who received analogy instructions and those who received explicit instructions. The study included nine intervention sessions over a period of three weeks. The therapists were provided with an intervention guideline on how to deliver explicit motor learning and analogy learning. The guidelines instructed the therapists to use analogy instructions that only contained information about the analogy (i.e., analogies should be based on past experiences and/or meaningful situations) with no information about joint angles and gait biomechanics. These analogies included examples, such as: “walk as if you are walking through a deep layer of snow”, “walk as if you follow the footprints in the sand”, and “try to cross a small bridge”. Nineteen participants completed the treatments. Considering the small sample size and the various analogy instructions, it is difficult to isolate the effect of the motor analogies used in this particular study. Additionally, the treatment effects in the study were likely influenced by “noise” accompanying the real-life setting in which the study was conducted. In contrast, Kleynen et al. (2014) observed significant improvement in gait characteristics of post-stroke individuals (i.e., speed, step height, and step width) when they were provided with analogy instructions. Additionally, Tse, Wong, et al. (2017) investigated the effect of a motor analogy (“move your racket such that it is traveling up the side of a mountain”) and multiple explicit instructions on motor performance of young and older adults novice to the table tennis task. The participants were asked to perform the motor task (i.e., forehand topspin stroke) in dual-task, immediate retention, and skill consolidation conditions. Their results showed that older adults acquired the new motor skill via the analogy instruction in a similar manner to the young participants, preserved their skill level over time, and displayed robust performance under dual-task conditions, compared to their explicitly instructed counterparts.

Motor analogies are simple to retrieve from memory (Donnelly & McDaniel, 1993), can rapidly deploy attention during movement (Koedijker et al., 2011), facilitate the development of mental representations in long term memory (Meier et al., 2020), and may even speed up the motor learning process (Zacks & Friedman, 2020). These qualities, combined with reducing demands on cognitive resources (i.e., working memory), suggest that motor analogies may offer a suitable method to teach safe landing to older adults.

1.5.4 Developing suitable motor analogies

For a motor analogy to be successful, it relies on the learner's knowledge about the base concept. The more familiar the concept, the more parallels can be drawn between the base (familiar concept) and the to-be-learned (target) domains (Duit, 1991; Ngu & Yeung, 2012; Paatz et al., 2004; Taber, 2001).

Additionally, it has been proposed that motor analogies should be presented in a manner that is easy to envision and can be implemented with minimal processing effort (Liao & Masters, 2001). Furthermore, when using a motor analogy to induce implicit motor learning, it is important for the participants to either have direct experience with the familiar domain or immediately recognize the implied characteristics (Zacks & Friedman, 2020). Consequently, a suitable motor analogy does not only need to guide the desired movement pattern, it should also be familiar/culturally relevant for the population in which it is being used.

This importance of familiarity and cultural relevance was demonstrated when a study endeavoured to translate an analogy used for English speaking participants for use by a Chinese-speaking population (Poolton et al., 2007a). The authors asserted that it is necessary to modify an analogy to become culturally suited for the population in which it is being used to avoid misunderstanding and to better communicate the underlying aspects of the analogy. Hence, a suitable motor analogy should not only be familiar to the learner, but it must also communicate all important characteristics of the to-be-learned movement and be culturally meaningful to the user.

In line with this view, Masters et al. (2018) proposed the use of motor analogies as a method of instruction to promote safer landing by people (especially older adults) when they fall.

Masters et al. (2018) used a focus group methodology to generate appropriate motor analogies for safe landing. A group of older adult fallers, physiotherapists, occupational therapists, martial artists, gymnasts, dancers, parkour enthusiasts, and health and safety experts were invited to join the focus groups and to participate in discussions to identify analogies that best described safe landing. Initially, numerous analogies were suggested, including: “fall like you are holding a baby”, “fall like a jellyfish”, “fall like an octopus”, and “tuck and roll”. It became clear from the focus groups that different motor analogies would be necessary for different fall directions (i.e., “fall like you’re holding a baby” may work for a backward fall or a sideways fall, but not for a forward fall). Nevertheless, when the focus group participants were asked to describe the characteristics associated with safe landing, three fundamental descriptors emerged from the focus group interviews: “soft”, “slow”, and “silent”. After identifying the three descriptors, Masters et al. (2018) proposed that motor analogies that have potential to embody these characteristics may be suitable for promoting safe landing. For instance, the landing of an object, such as a snowflake or feather, can be mapped to characteristics of movements that are soft, slow, and silent. Therefore, motor analogies, such as “land like a snowflake” or “land like a feather”, have the potential to guide movement patterns that encapsulate the descriptors associated with safe landing.

1.6 Summary and thesis outline

To reduce the severity of fall-related injuries in the older adult population, one complementary solution to fall prevention programmes is to promote safe landing in the event of an accidental fall (i.e., landing with reduced risk of injury). However, the necessity to use multiple safe landing techniques in response to different fall types, combined with age-related cognitive deficiencies and minimal time to process information before impact occurs, raises practicality issues with this approach. Implicit motor learning via motor analogies may provide a solution to these challenges, which in turn has the potential to not only reduce healthcare costs associated with falling; but most importantly, improve quality of life for older adults. The goal of this thesis is to investigate whether motor analogies can be used to promote safe landing in older adults with respect to biomechanical parameters associated with safe landing. The following experiments and chapters were designed to address this goal.

1) The first experiment (Chapter 2) investigated the efficacy of a motor analogy ("land like a snowflake") for promoting safe landing by young adults when self-initiating falls in a backward, forward, or sideways direction. To evaluate the quality of the landings, we extracted measures from three Inertial Measurement Units (IMUs) and calculated impact force normalised by mass (i.e., maximum acceleration), duration of fall, and duration of impact. It was predicted that participants in the analogy group would: (a) fall more slowly (i.e., longer freefall duration), (b) land with lower maximum acceleration, and (c) display longer impact duration.
2) The second experiment (Chapter 3) investigated whether a motor analogy ("land like a feather") evoked representations of safe landing. To confirm that the mental representation of a feather landing is associate with safe landing characteristics (i.e., soft, slow, silent), a series of online experiments were conducted using a priming paradigm. It was predicted that participants primed with a motor analogy ("land like a feather") would be faster than participants in a control condition to identify words relevant to the characteristics of safe landing (i.e., soft, slow, silent).
3) The third experiment (Chapter 4) investigated the efficacy of a motor analogy ("land like a feather") for promoting safe landing by young adults when falling unexpectedly

in a backward, forward, leftward, or rightward direction. To evaluate the quality of the landings, measures from 16 IMU sensors were extracted and used to calculate impact force normalised by mass (i.e., maximum acceleration), fracture risk ratio, duration of fall, and duration of impact. It was predicted that participants in the analogy group would: (a) fall more slowly (i.e., longer freefall duration), (b) land with lower maximum acceleration, (c) display longer impact duration, and (d) demonstrate lower wrist fracture risk ratios.

4) The fourth experiment (Chapter 5) presents a registered trial (Australian New Zealand Clinical Trials Registry ACTRN12621001189819), which is a randomised, controlled, single-blinded study to test the efficacy of the motor analogy "land like a feather" to promote safe landing by older adults. However, due to Covid-19 restrictions, data collection was not possible.

5) The final chapter in the thesis (Chapter 6) summarises and evaluates the findings and discusses the implications for safe landing by older adults who unexpectedly fall to the ground.

Chapter 2. Testing the efficacy of a motor analogy designed to promote safe landing: Kinematic measures associated with self-initiated falls.

2.1 Abstract

Introduction. A major concern in countries with an aging population is the increasing rate of injuries due to falling. Landing safely from a fall can reduce the likelihood of injuries, but is challenging to learn late in life. However, implicit motor learning approaches, such as analogy instructions, can potentially be used to acquire motor skills for safe landing in the older adult population. We investigated whether a motor analogy could be used to promote safe landing from falls in a low-risk young adult population. **Method and Analysis**. Ninety young adults were randomly allocated to an analogy or control group. After the attachment of inertial measurement units to the lower back and wrists, participants self-initiated 3 three falls (backward, forward, sideways) onto a soft mattress. Participants in the analogy group were instructed to "land like a snowflake: soft, silent, slow", whereas participants in the control group were instructed to "fall on the ground". A single magnitude vector was calculated from the tri-axial accelerometer data that was recorded and biomechanical variables relevant to safe landing were extracted. **Results.** Participants in the analogy group had a safer landing compared to participants in the control group (significantly higher free-fall duration (s), impact duration (s), and lower maximum acceleration (g) in all sensors). No significant interactions were evident between group and fall direction. **Discussion**. These findings suggest that a motor analogy can positively affect biomechanical variables

associated with landing, regardless of the fall direction. Hence, using motor analogies may be useful as a landing strategy to reduce the severity of fall-related injuries.

2.2 Introduction

Falls are one of the leading causes of injury and death among older adults. Despite the attempts of researchers and healthcare professionals to prevent falls, 30-60% of older adults fall each year (Rubenstein, 2006) and approximately 68% of falls cause physical injuries, alongside several other adverse effects (Stel et al., 2004). The complex nature of falls and the existence of many risk factors make establishing effective fall prevention interventions challenging (Rubenstein, 2006). Even when fall prevention programmes are successful in reducing the overall frequency of falls, they still only have minimal effect on reducing fall-related injuries, hospitalisations, and quality of life (Hopewell et al., 2020). Therefore, it is important to consider approaches that have potential to complement fall prevention. One such approach, which has received minimal attention in the literature, is to teach older adults how to land safely if a fall occurs. In fact, a review of 13 studies into safe landing techniques (Moon & Sosnoff, 2016), revealed that only one had assessed safe landing in older adults (Groen et al., 2010). It is important to address this gap in the literature and to explore innovative and practical strategies to effectively teach safe landing to older adults.

Achieving safe landing is not without its challenges for older adults. Factors, such as location of impact, fall direction, and the magnitude of loads applied to the body at impact, all play a role in the strategies required to reduce fall-related injuries (Robinovitch et al., 2004). The direction of a fall is particularly important; for instance, the hips are at a higher risk of injury when falling sideways compared to falling forward or backward. Hence, a sideways fall requires a different safe landing technique than a forward or backward fall.

Consequently, the handful of studies focused on safe landing recommend different safe landing strategies based on fall direction (e.g., squat for a backward fall, slightly flexed elbows for a forward fall, and the martial art technique of roll and slap for a sideways fall) (Moon & Sosnoff, 2016). Furthermore, most safe landing techniques focus on protecting specific body parts. For instance, rotating sideways during a forward fall reduces the risk of head impact, but increases the risk of hip impact (Komisar & Robinovitch, 2021), creating a dilemma for older adults, given the severe consequences associated with both head and hip injuries. The variety of landing techniques required to land safely when falling in different directions poses a dilemma for older adults and challenges the feasibility of older people using safe landing strategies across a range of circumstances.

Additionally, older adults generally display age-related cognitive deficiencies, such as slowed reaction times, declining attention resources, and reduced working memory capacity (Cabeza, 2002; Thomas et al., 2019; Westlake et al., 2016). Working memory is responsible for storing and managing information (Baddeley & Hitch, 1974), so comprehension of instructions is more challenging for older adults. Not surprisingly, research shows that older adults learn motor skills more slowly and fail to reach similar levels of expertise compared to younger adults (McNay & Willingham, 1998; Serbruyns et al., 2015; Voelcker-Rehage, 2008). It is noteworthy, however, that memory degradation in the older adult population mainly affects effortful memory processes, while procedural automatic memory processes show little to no age deficits (Chauvel et al., 2012; Hoyer & Verhaeghen, 2006). In the early stages of motor learning, it is possible to promote development of procedural (automatic) memory processes to a greater extent than explicit (effortful) memory processes, using an implicit motor learning approach (Masters, 1992; Masters & Maxwell, 2004; Masters et al., 2020; Maxwell et al., 2001). Considering that age affects effortful memory processes (e.g., explicit instructions), but automatic memory processes minimally (Chauvel et al., 2012), instructions that impose fewer demands on cognitive resources are preferable for leaning new motor skills in older populations (Tse, Wong, et al., 2017). Consequently, an implicit motor learning approach to landing safely may be feasible for older adults.

A practical way to achieve implicit motor learning is through motor analogies (Liao & Masters, 2001; Masters, 2000). Analogy learning uses an appropriate familiar concept to assist learning of new tasks and has historically been used for learning complex ordered sequences, such as hunting, tool making, tying a bowline knot, etc. (Brand et al., 2021). Similarly, in the context of motor learning, analogies contain information about the "to-be learned" movement in reference to a well-known concept (Koedijker et al., 2011; Liao & Masters, 2001; Masters, 2000). For instance, in two experiments, Liao and Masters (2001) instructed novices to "strike the ball while bringing the bat up the hypotenuse of [a] triangle" to learn a topspin forehand in table tennis. The novices reported minimal explicit knowledge of how they completed the topspin shot, yet performed equally to participants who were provided explicit instructions and performed more stably under a secondary task load (Experiment 1) and in stressful conditions (Experiment 2). Motor analogies free up working memory for additional cognitive processes (Maxwell et al., 2003), which is why many studies attest that, compared to explicit instructions, skill acquisition via motor analogies results in more stable performance under cognitively demanding situations, such as performance of a concurrent task or decision making (Koedijker et al., 2011; Masters et al., 2008; Tse, Wong, et al., 2017; Zeniya & Tanaka, 2021). Additionally, motor analogies have been used to promote the acquisition of both ontogenetic (i.e., learned) and phylogenetic (i.e., inborn) skills (e.g., table tennis, dynamic balance) by healthy older people (Tse, Wong, et al., 2017) and the rehabilitation of movements (e.g., walking) by older people with Parkinson's disease (Jie et al., 2016) and stroke (Kleynen et al., 2014; Orrell et al., 2006).

When a fall occurs, there is a brief duration (approximately 0.4 seconds) before impact (Le Goic et al., 2018), during which a significant amount of information must be processed if the faller is to have any chance of landing safely. Among other things, a faller must process the fall direction, prioritise the safety of specific body parts, and then decide upon and use an appropriate landing strategy. Consequently, there is very little time to process explicit instructions about how to land safely. Motor analogies may provide a solution to these challenges, especially for older adults who process information more slowly, and are more vulnerable to injury.

To develop a motor analogy that encapsulates the characteristics associated with landing safely, Masters et al. (2018) conducted focus group interviews with fall experts (i.e., parkour enthusiasts, martial artists, gymnasts, etc.), healthcare professionals (i.e., physiotherapist, occupational therapists, health and safety expert, etc.) and older adults. Three fundamental descriptors of the characteristics of a safe fall emerged from the focus group interviews: soft, slow, silent. Masters et al (2018) proposed that motor analogies, such as "land like a snowflake", have potential to embody these characteristics because snowflakes land on the ground in a way that is soft, slow, and silent.

The goal of this experiment was to test the efficacy of the analogy "land like a snowflake" for promoting safe landing from self-initiated falls in a backward, forward, or sideways direction. To evaluate the quality of the landings, we attached three Inertial Measurement Units (IMUs) to different body segments of participants to extract impact force normalised to body mass (i.e., maximum acceleration), duration of fall, and duration of impact measures. The present study is the first to investigate the effect of a motor analogy on fall landing characteristics. We compared landing measures between participants instructed to "land like a snowflake" (the analogy group) and participants instructed to "land safely" (the control group). We sampled from a young adult population in the first instance, because they were at low-risk of fall-related injury. We hypothesized that participants in the analogy group would: (1) fall more slowly (i.e., longer freefall duration), (2) land with lower maximum acceleration, and (3) display longer impact duration.

2.3 Method

2.3.1 Participants

Ninety young adults were recruited from the university campus. After providing informed consent and completing demographic information, participants were randomly allocated to an analogy (n = 47) or a control (n = 43) group using a random generator computer programme. Independent-samples t-tests showed no significant between-group differences (all $p > 0.05$) in terms of age, height, or mass (see Table 1, Demographic characteristics), and a Chi-squared test indicated a similar proportion of males and females between groups ($p >$ 0.05). The Human Research Ethics Committee (Health) of the institution approved the project prior to participant recruitment.

Table 1. Demographic characteristics of participants (mean ± standard deviation).

	Analogy (n= 47)	Control (n = 43)	All (n = 90)	Between-group difference p value (2-tailed)
Age (years)	18.5 ± 1.2	18.7 ± 1.9	18.6 ± 1.6	0.49
Height (cm)	176.0 ± 9.7	175.4 ± 9.8	175.7 ± 9.7	0.79
Mass (kg)	73.9 ± 14.6	79.8 ± 15.8	77.0 ± 15.4	0.08
Gender	23 females 24 males	18 females 25 males	41 females 49 males	

2.3.2 Measurements and instrumentation

A two-dimensional video camera (Canyon, 25 frames per second) and three Delsys Trigno^{TM} (Delsys Inc., Natrick, MA) inertial measurement units (IMUs) were used to assess kinematics of each fall. The video camera was positioned 3 meters from the side of the participants on a tripod (height 1.3 meters). Acceleration data from the IMUs were recorded at a frequency of 148.15 Hz using EMGworks Acquisition software (Version 4.5.4). One sensor was positioned on the lower back (via a belt), level with the L3 vertebra (Greene et al., 2012) to estimate center of mass (COM) acceleration (Howcroft et al., 2013). The two remaining sensors were positioned on the dorsal part of the left and right wrist (Mannini et al., 2013b; Ozemek et al., 2014; Zhang et al., 2012) secured via wrist bands to approximate wrist impacts when landing.

2.3.3 Procedure

Participants allocated to the analogy group were required to complete a three-word crossword puzzle designed to prime them about how snowflakes land on the ground: soft, slow, and silent (see Figure 2, Panel A). Participants allocated to the control group completed a similar crossword puzzle that used names of birds as neutral primes: swallow, shag, and swan (see Figure 2, Panel B). Hints were provided if participants had difficulty completing the crossword.

The IMUs were then secured in position and participants were asked to self-initiate a fall. Participants completed 3 falls, one backward, one forward and one sideways (leftward). Video and IMU data were recorded during each fall. Order of fall direction was randomised, using a random order generator. In all instances, the fall was self-initiated from a standing position, with participants falling onto a padded surface. Participants in the analogy group were instructed to “land like a snowflake”, whereas participants in the control group were instructed to “land on the ground”. No other guidance on how to fall was provided.

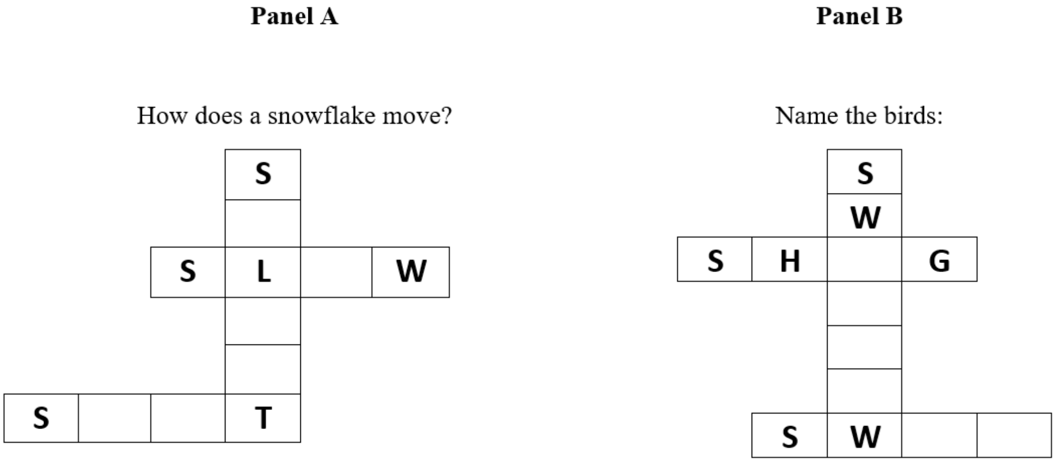

Figure 2. Crosswords for priming participants in the analogy (Panel A) and control (Panel B) groups. Panel A: soft, slow, silent. Panel B: swallow, shag, swan.

2.3.4 Data analysis

The acceleration data from the IMUs were exported in an excel format and processed using Matlab (R2017b, MathWorks Inc., Natic, USA). The data were low-pass filtered at 4 Hz using a 2nd order Butterworth filter (Bourke et al., 2010; Karantonis et al., 2006; Mathie et al., 2004). A median filter with $n = 3$ was subsequently applied to the accelerometer data to remove any abnormal noise spikes (Karantonis et al., 2006).

A one-dimensional signal magnitude vector (SMV), or resultant acceleration, was calculated from the tri-axial accelerometer data using the following standard equation (Mannini et al., 2013b; Ozemek et al., 2014; Zhang et al., 2012):

$$SMV\ (g) = \sqrt{{a_x}^2 + {a_y}^2 + {a_z}^2}$$

Start of fall ($\text{Start}_{\text{Fall}}$), initial body contact with the ground ($\text{Contact}_{\text{First}}$), and end of fall ($\text{End}_{\text{Fall}}$) were extracted from the SMV of the lower back sensor. Subsequently, these events were used to compute free-fall duration and impact duration in seconds (s). Free-fall duration was defined as the time period between $\text{Start}_{\text{Fall}}$ to $\text{Contact}_{\text{First}}$, whereas impact duration was defined as the the time period between $\text{Contact}_{\text{First}}$ to End_{Fall}. Figure 3 displays $\text{Start}_{\text{Fall}}$, $\text{Contact}_{\text{First}}$, and End_{Fall} extracted from the lower back IMU of a participant perfermong a backward fall.

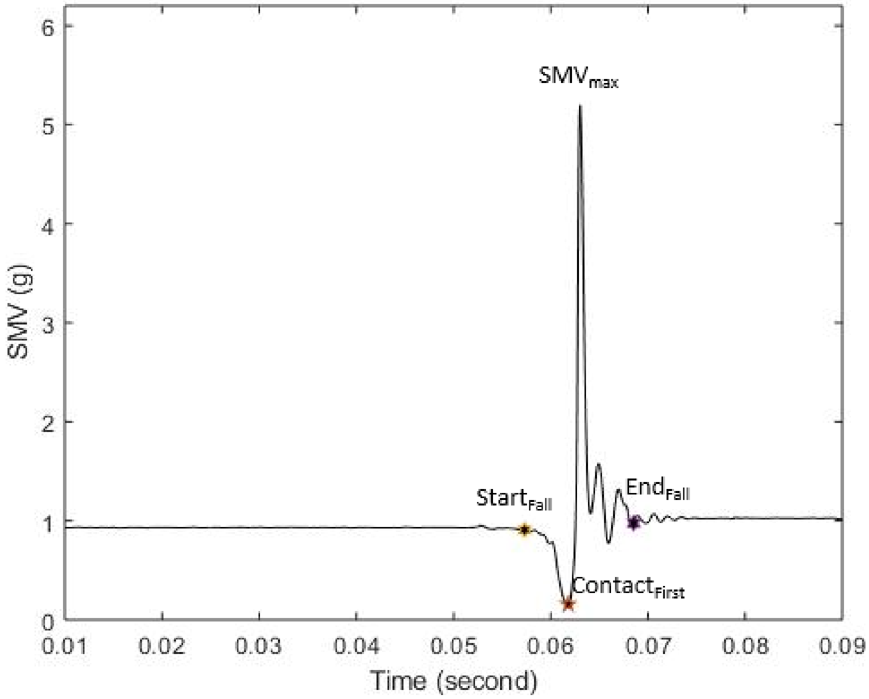

Figure 3. Signal magnitude vector (SMV) extracted from the lower back inertial measurement unit during a self-initiated backward fall. SMV_{max}, signal magnitude vector maximum, $\text{Start}_{\text{Fall}}$: start of fall, $\text{Contact}_{\text{First}}$: initial body contact with the ground, End_{Fall}: end of fall.

To determine the beginning and end of a fall, a threshold was calculated using 100 ms moving windows applied to the SMV data. Subsequently, the relative standard deviation (RSD) of these windows was calculated. The generated RSDs were averaged and used as a thereshold for identifying the start and the end of the fall for each file. RSD has previously been used to compute thresholds for identifying cancer cells (Ericson et al., 2003), optic-nerve signals (Hay & Chesters, 1972), and in various human motion dynamics studies

(Venture et al., 2009), and found to appropriately delineate the start and end of falls within our study. More specifically, the start of the fall was defined by the SMV crossing the threshold into the trench preceding its maximum value (SMV_{max}) (Degen et al., 2003; Kangas et al., 2007; Kangas et al., 2011). The end of the fall was defined by SMV crossing the threshold after it reached its maximum value (SMV_{max}). The start and end of fall identification method was verified using the video recordings. In addition to free-fall duration and impact duration, maximum acceleration (SMV_{max}, g) was extracted from the three sensors.

2.3.5 Statistical analysis

Mean and standard deviation (SD) values were calculated for each variable and differences between groups were examined using IBM SPSS Statistics 25 (IBM® SPSS Statistics Software). To mitigate the risk of Type 1 error from multiple statistical tests, a 2x3 mixed model multivariate analysis of variance (MANOVA) was conducted as an omnibus test (Huberty & Petoskey, 2000) of the impact of group (analogy, control) and fall direction (forward, backward, sideways) on all of the variables of interest (free-fall duration, impact duration, and SMV_{max} of lower back, left wrist, and right wrist). In the event of a statistically significant MANOVA effect, further examination of the variables was conducted separately using ANOVAs, followed by Tukey's honestly significant difference tests where appropriate. We adopted an alpha level of 0.01 to reduce the probability of accepting false hypotheses (Pollok et al., 2014; Sture, 1979). The strength of the partial eta squared values (effect size) was interpreted using the following thresholds: small=0.01, medium=0.06, and large=0.14 (Olejnik & Algina, 2000).

2.4 Results

Descriptive data of the IMU-derived measures for each group and fall direction are presented in Table 2. MANOVA revealed main effects of group [F(5, 254) = 5.02, $p < 0.001$; Wilks' Lambda = 0.91; $\eta_p^2 = 0.09$] and fall direction [F(10, 508) = 11.69, $p < 0.001$; Wilks' Lambda = 0.66; $\eta_p^2 = 0.18$]. A significant interaction was not evident between group and fall direction [F(10, 508) = 0.60, $p = 0.80$; Wilks' Lambda = 0.97; $\eta_p^2 = 0.01$]. Two-way ANOVAs were therefore used to examine the main effects of group and fall direction, but not the interactions, for each variable separately.

Table 2. Means ±SD free-fall duration, impact duration, and SMV_{max} of lower back (Lb), left wrist (Lw), and right wrist (Rw) sensors in the control group (Cn) and analogy (An) group as a function of fall direction (backward, forward, sideways).

Measured Variables	Backward		Forward		Sideways	
	Cn	An	Cn	An	Cn	An
Free-fall duration (s)	0.61 ± 0.16	0.68 ± 0.23	0.66 ± 0.23	0.76 ± 0.35	0.60 ± 0.18	0.66 ± 0.17
Impact duration (s)	0.83 ± 0.20	0.95 ± 0.22	0.83 ± 0.20	0.82 ± 0.20	0.76 ± 0.20	0.88 ± 0.29
Lb-SMV_{max} (g)	4.97 ± 1.78	4.35 ± 1.75	3.77 ± 1.12	3.40 ± 1.21	4.48 ± 1.46	3.87 ± 1.18
Lw-SMV_{max} (g)	6.12 ± 2.59	5.33 ± 2.72	7.11 ± 1.21	6.19 ± 1.48	6.33 ± 1.59	5.53 ± 1.72
Rw-SMV_{max} (g)	5.92 ± 2.38	5.07 ± 2.34	7.03 ± 1.32	5.97 ± 1.31	5.68 ± 1.97	4.62 ± 1.80

2.4.1 Free-fall duration and impact duration

Two-way ANOVAs (group x fall direction) revealed a statistically significant main effect of group for both free-fall duration [F(1, 258) = 7.48, $p = 0.007$; $\eta_p^2 = 0.03$] and impact duration [F(1, 258) = 7.09, $p = 0.008$; $\eta_p^2 = 0.03$]. Participants in the analogy group displayed longer free fall duration and impact duration (see Figure 4). There was no statistically significant main effect of fall direction on free-fall duration or impact duration [F(2, 258) = 3.28, $p = 0.04$; $\eta_p^2 = 0.02$, F(2, 258) = 2.68, $p = 0.07$; $\eta_p^2 = 0.02$, respectively].

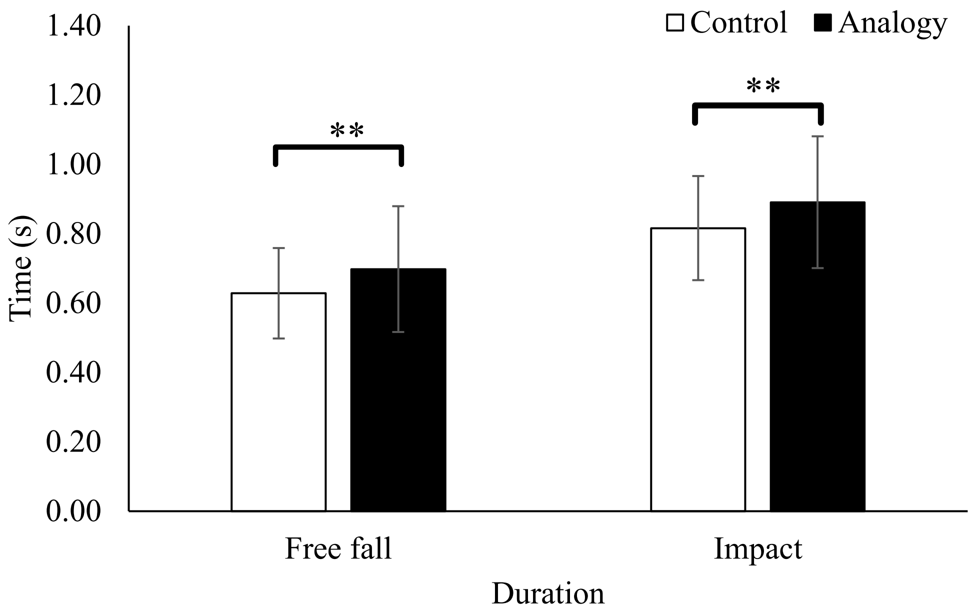

Figure 4. Mean free-fall duration (s) and impact duration (s) for the analogy group and the control group. ** indicates significant difference ($p < 0.01$). Error bars represent standard deviations.

2.4.2 Maximum acceleration (SMVmax)

Two-way ANOVAs (group x fall direction) revealed a statistically significant main effect of group for SMV_{max} of the lower back [F(1, 258 = 8.88, $p = 0.003$; $\eta_p^2 = 0.03$], left wrist [F(1, 258) = 17.76, $p < 0.001$; $\eta_p^2 = 0.04$, small effect size], and right wrist [F(1, 258) = 17.76, $p < 0.001$; $\eta_p^2 = 0.06$]. In all cases, mean SMV_{max} was lower for the analogy group compared to the control group (see Figure 5).

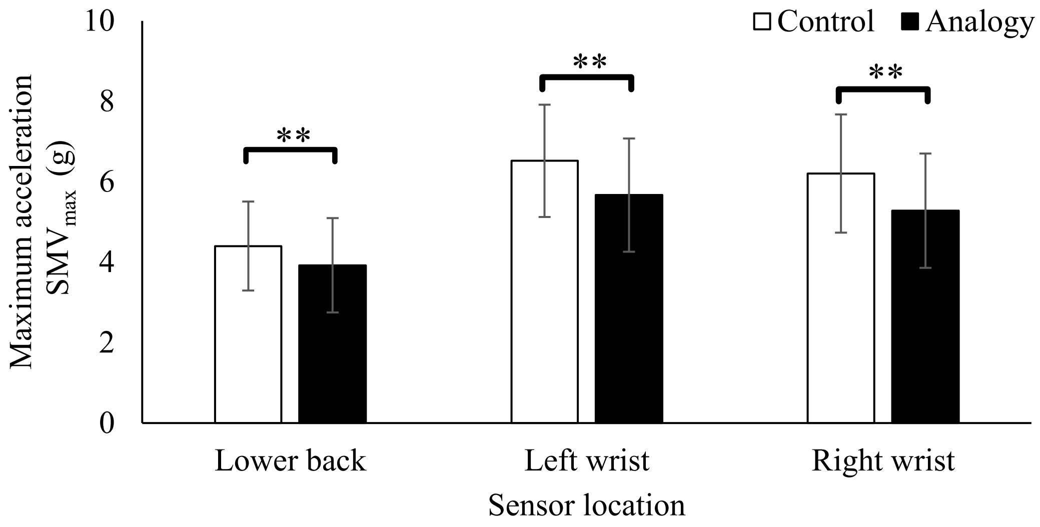

Figure 5. Mean maximum acceleration (SMV$_{max}$) of the lower back, left wrist, and right wrist as a function of group (analogy, control). ** indicates significant difference ($p < 0.01$). Error bars represent standard deviations.

For fall direction, a statistically significant main effect was evident for SMV$_{max}$ of the lower back [F(2, 258) = 12.19, $p < 0.001$, $\eta_p^2 = 0.08$], left wrist [F(2, 258) = 5.30, $p = 0.006$, $\eta_p^2 = 0.03$], and right wrist [F(2, 258) = 11.9, $p < 0.001$, $\eta_p^2 = 0.08$]. Tukey's honestly significant difference post-hoc tests showed that for the lower back, SMV$_{max}$ was higher during backward compared to forward falls ($p < 0.001$). For the left wrist, SMV$_{max}$ was higher during forward falls compared to backward falls ($p = 0.005$). For the right wrist, SMV$_{max}$ was higher during forward falls compared to backward falls ($p = 0.001$) and during backward compared to sideways (leftward) falls ($p < 0.001$). No other differences were significant (all $p > 0.01$) (see Figure 6).

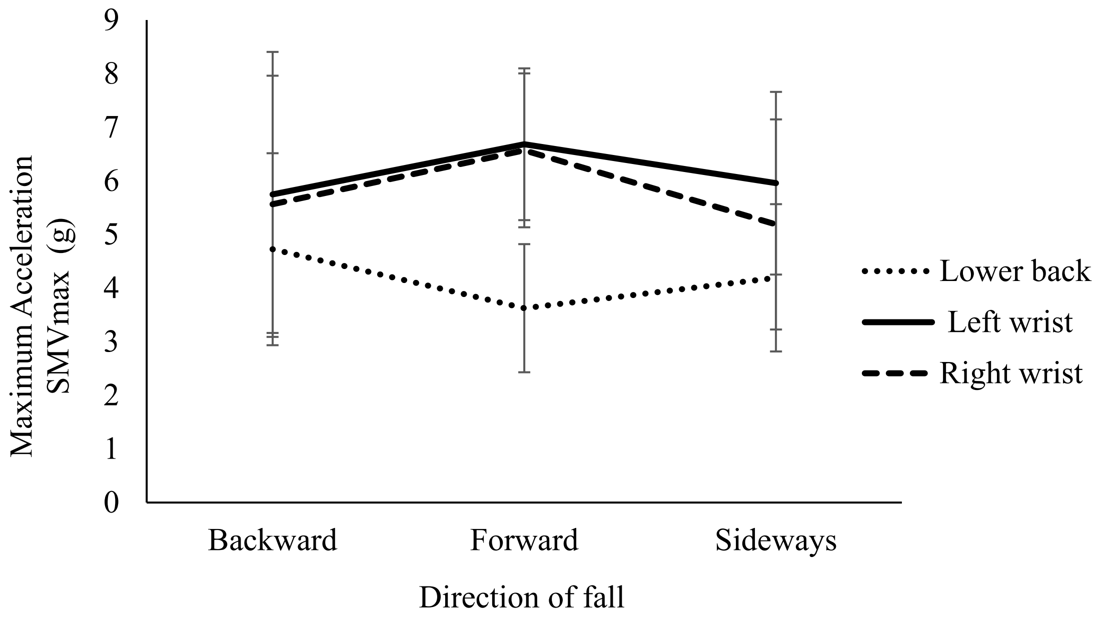

Figure 6. Mean maximum acceleration (SMV_{max}) of the lower back, left wrist, and right wrist as a function of fall direction (backward, forward, sideways). Error bars represent standard deviations.

2.5 Discussion

This study investigated the efficacy of motor analogy designed to promote safe landing following self-initiated falls by young physically active adults. Relevant biomechanical measures were extracted from forward, backward, and sideways (leftward) falls and compared between an analogy (land like a snowflake) and a control (land on the ground) group. Significant group differences were evident in free-fall duration, impact duration, and SMV_{max} of the lower back, left wrist, and right wrist sensors, with small to medium effect sizes. Participants in the analogy group displayed significantly longer free-fall duration, suggesting that instructions to "land like a snowflake" caused them to fall more slowly than participants in the control group who were instructed to "land on the ground". It is not unreasonable to assume that falling more slowly is beneficial for safe landing. Previous research, for instance, has demonstrated that during self-initiated backward falls a longer duration descent phase allows greater flexion and rotation angles whilst falling and better energy absorption by the knees and hips, which results in safer falls (Robinovitch et al., 2004). Participants in the analogy group also displayed significantly longer impact durations than participants in the control group. Impact force applied to the body over a longer duration is likely to result in a less severe fall than impact force applied over a lesser duration (Habtour et al., 2013). Consequently, the longer impact duration observed in the analogy group may be associated with reduced likelihood of injury when landing. However, we are cognisant of the fact that small to medium effect sizes were evident between the analogy and control groups. Further work is therefore needed to establish whether our motor analogy causes meaningful differences in impact force that will result in less severe injury in the event of a fall. It is conceivable, for instance, that the effect of the motor analogy on impact force when landing is accentuated in older adults.

The magnitude of impact force is proportional to body mass and acceleration. Greater SMV_{max} values reflect greater impact force magnitude, which is associated with fall severity (Wu & Xue, 2008). Therefore, significantly lower SMV_{max} in the analogy group provides evidence of lower impact force at the lower back and wrists compared to the control group. The observed reduction in SMV_{max} values for the analogy group in all fall directions is consistent with impact force reductions reported by other studies that have examined safe landing strategies in sideways (van der Zijden et al., 2012), backwards (Robinovitch et al. (2004), and forward (Chou et al., 2001; Lo et al., 2003) falls.

Our results also indicate significant main effects of fall direction on SMV_{max} for all three sensors. The relationship between the location of the sensors and the direction of the falls explains these effects. For instance, measurements were highest for the lower back sensor during backward falls because participants tended to land on their buttocks, whereas measurements were highest for the wrist sensors during forward falls because participants tended to land on their hands to break their fall (as confirmed by video analysis). In conflict with our results, Tan et al. (2006) reported lower wrist impact velocities following unexpected forward falls compared to backward falls. However, in the latter study, participants were released from an angle of 15° from vertical during the forward falls and 5° from vertical during the backward falls; closer proximity to the landing surface during the forward falls may explain their findings. In the present study, participants self-initiated their falls from a vertical position (0°), regardless of fall direction.

A core challenge for safe landing strategies is to deploy a landing technique that is appropriate for the direction in which the fall occurs. We did not find a significant interaction between fall direction (forward, backward, sideways) and group (analogy, control) in any of the measured variables. The lack of interaction suggests that regardless of fall direction, the motor analogy promoted a safer landing compared to the control instruction. During a fall, the central nervous system controls the expected collision by modifying movement patterns (Santello, 2005). Our findings suggest that the motor analogy may have encouraged more adaptive functional movement patterns (Chow et al., 2006; Tse, Fong, et al., 2017), allowing participants to better adjust their movements to the direction of fall.

It is noteworthy that practice improves the skill and knowledge of a learner; hence, participants in motor analogy studies often practice during multiple trials (e.g., six blocks of 50 trials–Liao & Masters, 2001). However, in our study, little or no practice occurred (i.e., participants were exposed to the motor analogy immediately before falling onto the mattress and only fell once in each direction). Nonetheless, participants in the analogy group outperformed those in the control group in terms of landing more safely. This finding is in line with Zacks and Friedman (2020), who found that a group receiving an analogy for performing a fine motor task (drawing) displayed mastery gains and improvement in co-articulation, a feature associated with hours of practice. Perhaps if participants in the analogy group had more practice with the analogy during falling, their performance would have improved to a greater extent (i.e., landing more safely). Nevertheless, due to the risk of injury associated with falling, practicing multiple falls does not seem to be a viable option for older adults; hence, our findings overall suggest that using motor analogies may be a practical method to promote safe landing for the older adult population without requiring multiple practice trials.

This study was not without limitations. Although participants were instructed to immediately initiate a fall in the direction indicated by the experimenter, it is possible that they were able to programme a landing strategy in response to the instruction. In an accidental fall, there is seldom enough time to plan a response. Future studies develop more ecologically valid methods to cause unexpected falls to address these limitations. Additionally, recruiting young university-aged participants makes it difficult to generalise the findings of this study to older participants, particularly given that older adults motor learning responses differ from younger adults (Harrington & Haaland, 1992; King et al., 2013). The recruitment of younger individuals was necessary in this first-of-a-kind study, however, in order to first establish whether the motor analogy effectively promotes safer landing strategies in a cohort of participants who were at low-risk of fall-related injury. Future studies need to target older adults now that the analogy has been shown to be effective for this purpose.

Another limitation of this study relates to the participants' familiarity with the landing of a snowflake. According to structure-mapping theory*,* analogies rely on mapping between the familiar and to-be learned (target) domains, so systematic relationships between the two domains can be identified (e.g., causal, mathematical, or functional relations) (Gentner & Holyoak, 1997). Hence, it is important for participants to either have direct experience with the familiar domain or immediately recognise the implied characteristics (Zacks & Friedman, 2020). Consequently, a suitable motor analogy does not only need to guide the desired movement pattern, it should also be familiar/culturally relevant for the population in which it is being used. For instance, a study by Poolton et al. (2007a), revealed that an analogy that improved performance in English-speaking learners did not work adequately for Cantonese-speaking learners, requiring the researchers to create a different motor analogy that was culturally familiar to their Chinese audience. In the current study, we noticed that many of our participants were not familiar with the landing of a snowflake. This lack of familiarity is due to the limited amount of snow fall in the upper portion of New Zealand. Thus, participants may not have made the connection between the snowflake analogy and the soft, slow, silent descriptors that were used. using a more relatable/meaningful analogy that captures the essence of the descriptors in future studies would address this limitation. A further limitation of this study was that the use of only three sensors limited our understanding of the landings to the wrists and lower back, omitting other body segments that may be helpful for quantifying falls. Nevertheless, our findings provide the first evidence that motor analogies may provide a useful method by which to promote safe landing.

In conclusion, the current study investigated the effect of a motor analogy on landing from self-initiated backward, forward and sideways falls. Regardless of fall direction, participants in the analogy group displayed significantly lower maximum acceleration at the wrists and lower back and longer free-fall and impact durations. These findings provide preliminary evidence that motor analogies may be useful for reducing the risk of injury when people fall, but further research is needed to establish the efficacy of safe landing analogies when falls are unexpected and the population is older.

Chapter 3. Using the Lexical Decision Test to validate whether "land like a feather" evokes representations of safe landing

3.1 Abstract

Introduction. Movements that are soft, slow, and silent are likely to result in safer landing when an unexpected fall occurs. We identified a motor analogy ("land like a feather") that was designed to elicit landing behaviours that are soft, slow, and silent. We used the Lexical Decision Task to validate whether "land like a feather" activates mental representations associated with characteristics of softness, slowness and silence. **Method**. Three online experiments were conducted using OpenSesame 3.3.5 software. In Experiment 1, participants (*n*= 47) viewed an image of a feather, a brick or a blank screen (counterbalanced) followed by words related to safe landing (e.g., soft/slow/silent), antonyms of words related to safe landing (e.g., hard, fast, loud, etc.) or words unrelated to landing (e.g., lemon, sell, oysters, etc.). In Experiments 2 and 3, participants (*n*=88 and *n*=100 respectively) viewed the phrase "land like a feather" or a neutral prime (counterbalanced) followed by words related to safe landing (e.g., soft/slow/silent) or words unrelated to landing (e.g., bike/hair/galaxy). Participants were required to identify the valid English words as rapidly as possible. **Results**. Participants were significantly faster when discriminating words related to safe landing (all $p < 0.05$), but not words unrelated to landing (all $p > 0.05$); however, this was only the case when the words were preceded by the primes rather than no prime or a neutral prime. **Discussion**. Faster discrimination of words related to safe landing suggests that the motor analogy, land like a feather, activated mental representations associated with words such as and soft, slow, silent. **Conclusion**. A motor analogy that encourages people to "land like a

feather" may trigger falling behaviours that are soft, slow, and silent, which is likely to result in lower impact when arriving on the ground.

3.2 Introduction

Analogy instructions have been shown to be an effective way to teach movements and improve performance. In comparison to classical methods, which often involve many verbal instructions, an analogy instruction uses a familiar, related concept to convey information about how to execute the to-be-learned motor skill (Liao & Masters, 2001). For instance, when teaching a novice table tennis player how to hit a topspin forehand, Liao and Masters (2001, p. 310) instructed participants to "strike the ball while bringing the bat up the hypotenuse of [a] triangle". Research evidence suggests that this approach results in stable performance under pressure or when multitasking (Bobrownicki et al., 2015; Jie et al., 2016; Lam et al., 2009a; Liao & Masters, 2001; Poolton et al., 2007b; Tse, Fong, et al., 2017; Tse, Wong, et al., 2017).

If chosen well, one motor analogy combines most of the technical rules required to perform the to-be-learned skill, thus reducing the demands on cognitive resources needed to process the task related information (Law et al., 2003; Liao & Masters, 2001; Masters & Liao, 2003; Poolton et al., 2006). It is therefore no surprise that analogy instructions have been found to be suitable for teaching new motor skills to older adults who show age-related cognitive deficits (Cabeza, 2002; Thomas et al., 2019; Westlake et al., 2016). For instance, Tse, Wong, et al. (2017) demonstrated the efficacy of an analogy instruction for teaching healthy older adults a new motor skill (i.e., topspin forehand stroke). Not only did the older adults display preserved skill level over time, but they were also able to perform the skill equally well under dual-task conditions. Furthermore, analogy instructions have been successfully used in rehabilitation therapy to improve dynamic balance and gait in stroke patients and individuals with Parkinson’s disease (Jie et al., 2016; Kim et al., 2021; Kleynen et al., 2014; Orrell et al., 2006).

Masters et al. (2018) proposed that analogy instructions may be a viable method by which to promote safer landing by older adults if they fall. After a fall is initiated there are approximately 0.4 seconds before impact occurs (Le Goic et al., 2018), leaving minimal time for the faller to select an appropriate landing technique (e.g., squat-like motion, semi flexion of elbows, tuck and roll). Considering the rapid processing time associated with motor analogies (Koedijker et al., 2011; Maxwell et al., 2003) and the reduced demands on cognitive processes, Masters et al. (2018) argued that a suitable motor analogy for landing safely is more likely to result in the desired outcome than when using traditional learning styles (i.e., explicit rules). Thus, Masters et al. (2018) proposed an analogy instruction (“land like a snowflake”) that was designed to encapsulate the essence of safe landing (i.e., soft, silent, slow). Subsequently, Oladi, Uiga, Hebert-Losier, and Masters (under review/Chapter 2) tested the efficacy of this analogy instruction in young adults. The results suggested that when provided with the analogy young adults who self-initiated falls landed with less impact force and longer fall duration, which potentially is associated with safer landing. However, Oladi et al. (under review/Chapter 2) noted that many participants in the study were not well acquainted with snowflakes, presumably due to the relative lack of snow precipitation in New Zealand. Analogies rely on mapping between the familiar and to-be learned (target) domains, so that systematic relationships between the two domains can be identified (e.g., causal, mathematical, or functional relations) (Gentner & Holyoak, 1997). Therefore, to be maximally effective a safe landing analogy should generate mental representations that are associated with the verbal descriptors (e.g., soft, slow, silent). It is possible, therefore, that many of the participants in the Oladi et al. (under review/Chapter 2) study did not generate a mental image of a snowflake landing softly, slowly, and silently. To rectify this issue, we developed a motor analogy that was based on a different concept. We expected that the concept underpinning the new motor analogy ("land like a feather") would be more familiar to our population sample. To confirm that the mental representation of a feather landing is associate with safe landing characteristics (i.e., soft, slow silent), this chapter describes a series of online experiments using a priming paradigm.

One of the goals of using a priming paradigm is to study the pre-activation of concepts and motor reactions by related stimuli. Priming occurs when exposure to a stimulus influences responses to a subsequent stimulus without conscious intention (Weingarten et al., 2016). A priming stimulus activates parts of a particular representation or association in memory just before an action or task is initiated. This effect has been well established in the literature (Noguera et al., 2007). Researchers often use the priming paradigm in conjunction with the Lexical Decision Task (LDT) (Fernández-López et al., 2019). In one version of the LDT, participants observe a priming stimulus (e.g., word or picture) and then decide whether strings of letters are valid English words or non-words. The presence of an association between the priming stimulus and specific target words (i.e., words associated with the prime) should facilitate a positive lexical decision (identifying the valid word) and cause a faster response time when compared to words that are not associated with the prime (Noguera et al., 2007).

Researchers have demonstrated that images (Leech et al., 2008; Margolin et al., 1996; Vanderwart, 1984) and analogical primes (Spellman et al., 2001) influence lexical decisions and function as strong cues because they receive superior sensory encoding (Nelson et al., 1976) or more extensive processing (Smith & Magee, 1980). Consequently, the priming paradigm provides a method by which to determine whether the concept underpinning “land like a feather” evokes mental representations that are associated with characteristics of softness, slowness, and silence. We therefore designed three online experiments in which we tested whether an image of a feather (Experiment 1: young adults) or the “land like a feather” analogy (Experiment 2: young adults; Experiment 3: older adults) primed faster responses on the LDT when discriminating safe landing words (e.g., soft, slow, silent) from matched non-words.

3.3 Experiment 1

In the first experiment, we used an image of a feather as a prime and compared it with an image of a brick as a prime or no prime (control). Young adult participants were asked to discriminate the valid English word as quickly as possible from word/non-word pairs that were divided into 3 semantic categories: words related to safe landing (e.g., soft/moft, slow/peow, silent/pilent etc.), antonyms of words related to safe landing (e.g., hard/hars, fast/dast, loud/moul etc.), and words unrelated to landing (e.g., sell/lell, oysters/wosters, lemon/temon etc.).We hypothesised that when discriminating words related to safe landing, lexical decisions would be faster after priming with an image of a feather compared to priming with an image of a brick or no prime. Additionally, we hypothesised that when discriminating antonyms of words related to safe landing, lexical decisions would be faster after priming with an image of a brick compared to priming with an image of a feather or no prime. We expected no differences in response times as a function of prime condition (Fp, Bp, Cn) when participants were discriminating words unrelated to landing.

3.3.1 Participants and design

Sample size estimation was conducted using a customisable statistical spreadsheet (xSampleSize.xlsx, www.sportsci.org). Response time data from the English Lexicon Project (ELP) database was used for the calculations. The ELP response time data refers to trial response times (ms) when discriminating words from non-words (see Balota et al., 2007). Response time (ms) was our primary outcome. For the eighteen words that we selected from the ELP we used the smallest difference in the response times for any two words= 100 ms; between subject SD=83.86 ms for sample size calculation. Sample size requirements were calculated using 80% power ($\beta = 0.20$) and a 5% significance level ($\alpha = 0.05$). The calculations resulted in a total sample size of minimum of 24 participants.

Forty-seven participants (23 female, 24 male; Mean age ± SD: 19.81 ± 1.41 years) took part in an online LDT experiment using OpenSesame 3.3.5 software. Each trial was initiated by a black central fixation cross on a white background. After 500 ms the fixation cross was replaced by a silhouette image of a feather (Feather prime, Fp), a brick (Brick prime, Bp), or no prime (Control, Cn). The image was presented for 750 ms and then was followed by a blank screen for 600 ms. Evidence suggests that these durations cause a reliable prime–target stimulus onset asynchrony (Abad et al., 2003; Gilligan & Rafal, 2018; Noguera et al., 2007). Participants were then presented with a valid (English) word and non-word on either side of the screen (counterbalanced). The words/non-words were matched for string length (range 4-7 letters). Eighteen word/non-word pairs were identified. Each pair was presented twice, such that the correct response occurred once on the left and once on the right side of the screen for each condition (Fp, Bp, Cn). Order of condition was randomised using a random generator programme. In total, 108 trials were completed by each participant, which took approximately 12 minutes.

Participants were instructed to indicate which string of letters was a valid English word by pressing the "a" key on the left-hand side of the keyboard if the letters on the left-hand side of the screen formed a valid English word or the "l" key on the right-hand side of the keyboard if the letters on the right side of the screen formed a valid English word. The word/non-word pair remained on the screen until a response was made or until 10,000 ms had elapsed. Response accuracy was indicated to the participant during each inter-trial interval (1,500 ms) via a green checkmark (correct) or a red cross (incorrect). Figure 7 displays an example of the sequence of events during a trial in each condition (Fp, Bp, Cn).

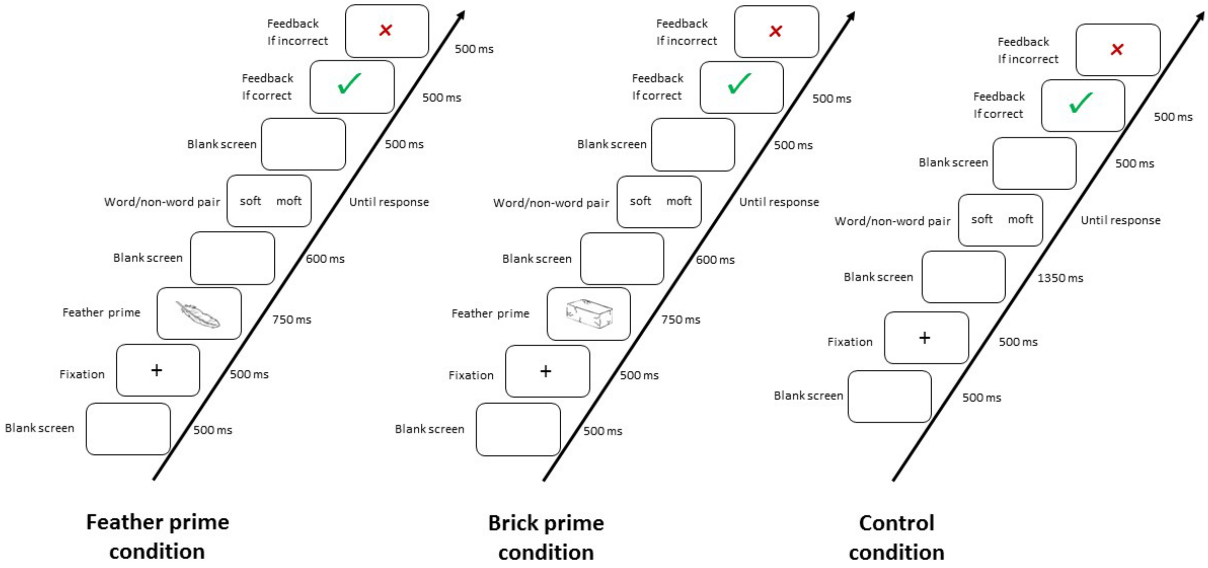

Figure 7. Sequence of events within a trial during the feather prime (Fp), brick prime (Bp), and control (Cn) conditions.

3.3.2 Word/non-word selection

Eighteen English words with similar length, log-frequency-Hal (LF-H), and mean accuracy (i.e., trial accuracy when discriminating words from non-words) were mined from the English Lexicon Project (ELP) database (Balota et al., 2007). The words were divided into 3 categories: words related to safe landing (n=6), antonyms of words related to safe landing (n=6), words unrelated to landing (n=6). Considering that frequency of word use plays a major role in lexical processing, with high frequency words processed more quickly than low frequency words (Chen et al., 2018), we selected words with similar frequencies of use in reading. To create matching non-words in each category, we used the ELP database for non-words. For each word, we chose a corresponding non-word with the same letter length, similar mean accuracy value (proportion of accurate responses when discriminating a particular word from a non-word), and with at least three common letters. Table 3 shows each category of word/non-word pairs and their respective length, log frequency-Hal (LF-H), Z- score, and mean accuracy.

Table 3. Word/non-word pairs related to safe landing, antonyms of words related to safe landing, and words unrelated to landing.

Word/non-word pairs related to safe landing				Antonyms of word/non-word pairs related to safe landing				Word/non-word pairs unrelated to landing			
	Length	**LF-H**	**MA**		**Length**	**LF-H**	**MA**		**Length**	**LF-H**	**MA**
soft	4	10	0.97	hard	4	12.08	1	grocer	6	5.29	0.91
moft	4		0.93	hars	4		0.94	groosy	6		0.9
gentle	6	8.81	1	rough	5	9.22	1	sell	4	11.25	0.97
kentor	6		1	routh	5		0.82	lell	4		0.97
slow	4	10.68	1	fast	4	11.25	0.97	oysters	7	5.72	0.91
peow	4		1	dast	4		0.82	wosters	7		0.94
gradual	7	7.44	0.91	noisy	5	7.91	0.97	lemon	5	8.29	1
ulgrade	7		0.94	roisy	5		0.91	temon	5		0.94
silent	6	9.13	1	loud	4	9.38	1	fusion	6	9.07	0.97
pilent	6		0.88	moul	4		0.91	susion	6		0.97
quiet	5	9.47	0.97	sudden	6	9.07	1	memo	4	8.1	0.97
quein	5		0.94	fudden	6		0.97	femo	4		0.94
Avg	5.33	9.25	0.96	Avg	4.67	9.82	0.94	Avg	5.33	7.95	0.95
SD	1.15	1.11	0.04	SD	0.78	1.54	0.07	SD	1.15	2.21	0.03

Length: is the number of letters in the word

Log Frequency-Hal (LF-H): refers to log-transformed HAL[4] frequency norms (Lund & Burgess, 1996), based on the HAL corpus.

Mean Accuracy (MA): proportion of accurate responses for a particular word, excluding errors and outliers.

3.3.3 Data analysis

All response time (RT) data were stored and analysed in Microsoft Excel 16.0. First, the mean RT of the correct responses was calculated. Responses that were two standard deviations above or below the mean RT were excluded from analysis (5.7% of the entire data set). This exclusion criterion was determined beforehand based on other research (Martens et al., 2011). Two word/non-word pairs (i.e., fusion/susion and grocer/groosy) were excluded from analysis because they exceeded the mean error rate (i.e., rate of

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[4] The Hyperspace Analogue to Language (HAL) is a cognitively motivated and validated semantic space model that captures statistical dependencies between words by considering their co-occurrences in a surrounding window of text (Yan et al., 2010).

incorrect answers) of the other word/non-word pairs by two standard deviations (Tainturier et al., 1989; von Studnitz & Green, 1997).

To test our specific hypotheses, we used *a priori* planned orthogonal contrasts. First, we tested our hypothesis that for words related to safe landing, priming with an image of a feather (Fp) would result in lower RTs (i.e., faster responses) than priming with an image of a brick (Bp) and no prime (Cn) combined (see Figure 8: Panel 1, Contrast 1). We also predicted that RTs would not differ between the Bp and Cn conditions when discriminating words related to safe landing (see Figure 8: Panel 1, Contrast 2). Second, we tested our hypothesis that for antonyms of words related to safe landing, priming with an image of a brick (Bp) would result in lower RTs than priming with an image of a feather (Fp) and no prime (Cn) combined. We also predicted that RTs would not differ between the Fp and Cn conditions when discriminating antonyms of words related to safe landing (see Figure 8: Panel 2, Contrast 2). Finally, for words unrelated to landing we expected that RTs in the no prime (Cn) condition would not be significantly different from the Fp and Bp conditions combined (see Figure 8: Panel 3, Contrast 1) and that RTs in the Fp and Bp conditions would not differ (see Figure 8: Panel 3, Contrast 2).

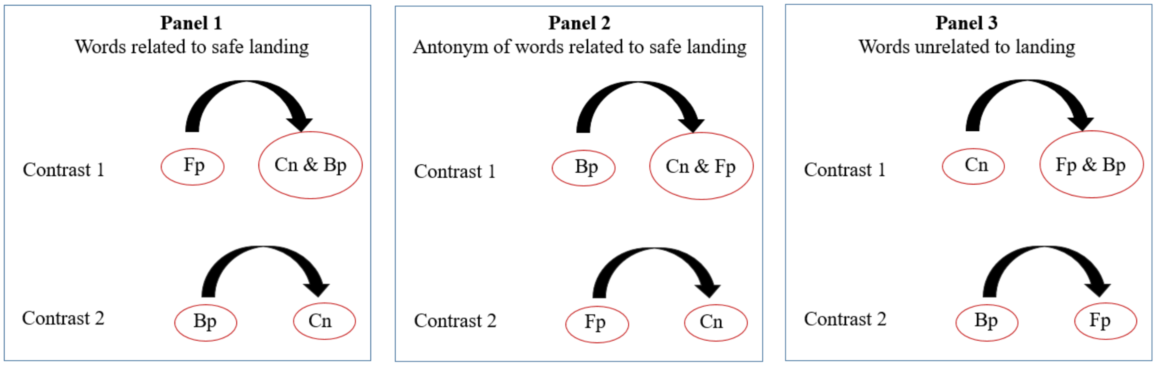

Figure 8. Planned contrasts for different word types (Panel 1: words related to safe landing; Panel 2: antonyms of words related to safe landing: Panel 3: words unrelated to landing). Fp: Feather prime condition; Bp: Brick prime condition; Cn: Control condition.

3.3.4 Results

The orthogonal contrasts revealed that when identifying words related to safe landing (e.g., soft, slow, silent, etc.), RTs were significantly lower in the Fp condition compared to the Bp and Cn conditions combined (Contrast 1), t(1621) = -1.96, *p* = 0.04 (one-tailed). There was no significant difference in RTs between the Bp and Cn condition (Contrast 2), t(1621) = 0.46, *p* = 0.64 (two-tailed).

When identifying antonyms of words related to safe landing (e.g., hard, fast, loud, etc.), the orthogonal contrast revealed that RTs were not significantly different between the Bp condition and the Fp and Cn conditions combined (Contrast 1), t(1611) = -0.94, *p* = 0.34 (one-tailed). Additionally, there was no significant difference in RTs between the Fp and Cn conditions (Contrast 2), t(1611) = -1.73, *p* = 0.08 (two-tailed).

When identifying words unrelated to landing (e.g., lemon, sell, oysters, etc.), RTs were not significantly different between the Cn condition and the Fp and Bp conditions combined (Contrast 1), t(1053) =1.38, *p* = 0.16 (two-tailed), or between the Fp and Bp conditions (Contrast 2), t(1053) = -0.60, *p* = 0.54 (two-tailed). Figure 9 shows the average RT for each word type (words related to safe landing, antonyms of words related to safe landing, words unrelated to landing) in the different conditions (Fp, Bp, Cn).

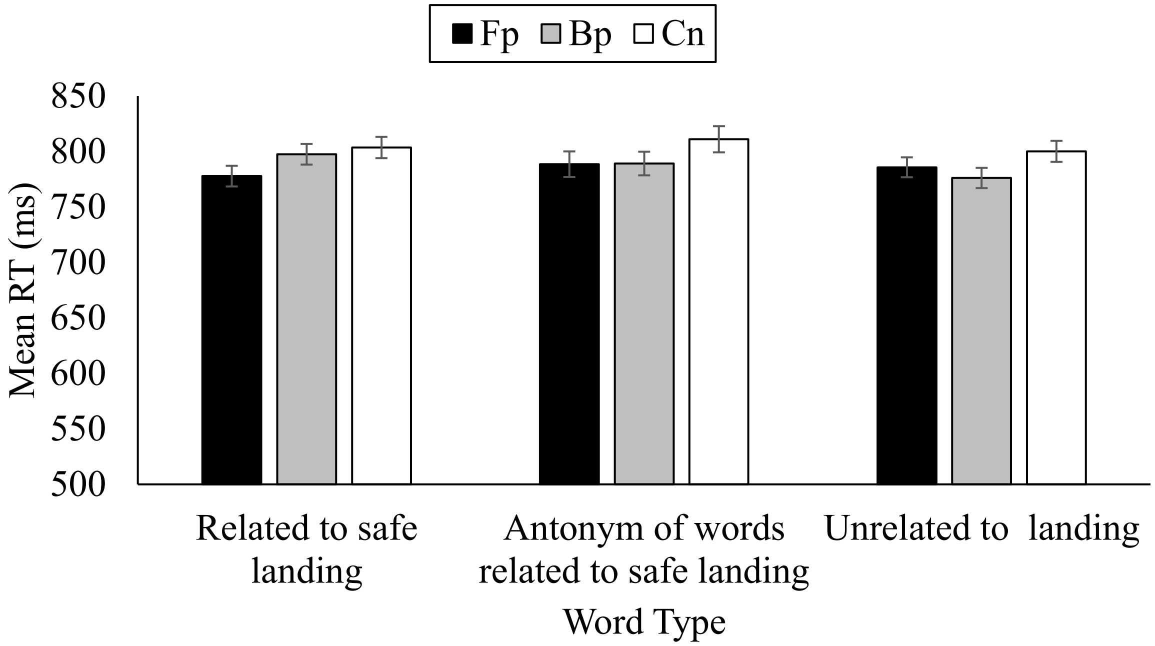

Figure 9. Average RT (ms) for words related to safe landing, antonyms of words related to safe landing, and words unrelated to landing, during the feather prime (Fp), brick prime (Bp) and control (Cn) conditions.

3.3.5 Discussion

In Experiment 1, we investigated whether priming participants with an image of a feather triggers faster identification of words related to safe landing than priming with an image of a brick or no image. Our findings confirmed that an image of a feather primes more rapid identification of words that represent safe landing characteristics than an image of a brick or no image. This finding implies that perceiving a feather awakens mental representations of characteristics (e.g., softness, slowness, silence etc) that are likely to facilitate landings in which ground impacts are reduced.

Interestingly, contrary to our prediction we found that an image of a brick did not trigger more rapid identification for antonyms of words related to safe landing. This may have been due to a weak association between an image of a brick and its landing characteristics (e.g., hard, fast, loud etc), although another explanation is that a list context effect occurred. That is, the context created by the types of semantic relatedness (antonyms & synonyms) diminished the priming effect (McNamara, 2005). For instance, including words that are antonyms (close-far) in a list of words that are synonyms (e.g., close-near), can eliminate semantic priming effects for the words that are antonyms (McKoon & Ratcliff, 1995). The design of the current experiment included words with synonyms (e.g., silent/quiet) and words with antonyms (e.g., silent/loud), which might have eliminated the effect of the brick prime. Another reason for this finding could be that in order to present the valid English word on both sides of the screen in each condition (Fp, Bp, Cn), we presented each word pair six times (108 trials in total). According to McNamara (2005), repetition can have unpredictable effects on semantic relatedness. For instance, semantic relatedness and target repetition can interact with word frequency characteristics to increase the likelihood that decisions about repeated items are influenced by episodic memory rather than semantic memory (McNamara, 2005). That is, responses to repeated items are made using memories of previous responses, which in turn can weaken or eliminate semantic priming effects.

It is noteworthy to mention that in this experiment we primed our participants with an image of a feather instead of the motor analogy “land like a feather”. This makes it difficult to establish whether the association that we found between the feather prime and safe landing words was due to their proximity in the semantic network or to the fact that feathers really do land in a manner that represents safe landing characteristics. Furthermore, during post-experiment debriefings with participants it was noted that the duration available to make a choice about the status of the word/non-word pairs (i.e., 10,000 ms) may have reduced the participants’ engagement with the experiment (i.e., hence, they lacked motivation to respond quickly). To resolve these limitations, we designed a second experiment in which we presented participants with the motor analogy “land like a feather”, reduced the amount of word/non-word pair repetition by excluding the Bp condition, and reduced the duration for making a choice from 10,000 ms to 3,000 ms).

3.4 Experiment 2

In Experiment 2, we extended our findings by investigating whether priming with a motor analogy, “land like a feather”, triggered faster RTs when identifying words related to safe landing (e.g., soft, slow, silent, etc.). We therefore changed our prime from an image of a feather to an image of a stick figure falling and included the words “land like a feather” beneath the figure. We chose to exclude antonyms of words related to safe landing and we did not use a brick-related prime. Participants completed 40 trials during which they were primed with the motor analogy (An) or a large cross (i.e., Control, Cn). We hypothesized that RT for words related to safe landing (e.g., soft, slow, silent, etc.) would be significantly faster in the An condition compared to the Cn condition. We did not expect RTs to be significantly different in the An condition compared to the Cn for words unrelated to landing (e.g., bike, hair, infant, etc.)

3.4.1 Participants and design

Sample size estimation was conducted using a customisable statistical spreadsheet (xSampleSize.xlsx, www.sportsci.org). We used RT data from Experiment 1 (smallest difference=125 ms; between subject SD=197 ms) for the calculations, with RT (ms) as our primary outcome. Sample size requirements were calculated using an 80% power ($\beta = 0.20$), and 5% significance level ($\alpha = 0.05$). The calculations resulted in a total sample size of minimum of 80 participants.

Eighty-eight participants (21 females, 61 males, 6 unknown; mean age ± SD: 33.63 ± 8.78 years) took part in an online LDT experiment using OpenSesame 3.3.5 software. To match the Cn condition with the An condition, we replaced the blank screen with a large cross (neutral image). Additionally, to ensure that the participants read letter strings on both sides we added two pairs of "catch trials" in which letter stings on both sides of the screen were valid English words. Participants were instructed that they should not press any key when the letter strings on both sides formed a valid English word. The catch trials were not included in our analysis.

Each trial was initiated by a black central fixation cross on a white background. After 500 ms the fixation cross was replaced by the motor analogy "land like a feather" displayed underneath an image of a stick figure falling (Analogy condition, An), or a silhouette image of a large cross serving as neutral prime (Control condition, Cn). The image was presented for 1000 ms and then was followed by a blank screen for 600 ms. Evidence suggests that these durations cause a reliable prime–target stimulus onset asynchrony (Abad et al., 2003; Gilligan & Rafal, 2018; Noguera et al., 2007). Participants were then presented with a valid (English) word and non-word on either side of the screen (counterbalanced). The words/non-words were matched for string length (range 4-7 letters). Eight word/non-word pairs and two word/word pairs (catch trials) were identified. The order of the conditions (An, Cn) and the appearance of the correct response on the left and right side of the screen were counterbalanced using a random generator programme. In total, 40 trials were completed by each participant, which took approximately 5 minutes.

Participants were instructed to indicate which string of letters was a valid English word by pressing the "a" key on the left-hand side of the keyboard if the letters on the left-hand side of the screen formed a valid English word or the "l" key on the right-hand side of the keyboard if the letters on the right side of the screen formed a valid English word. No key was to be pressed when letters on both sides of the screen formed valid English words. The word/non-word pair and word/word pair catch trials remained on the screen until a response was made or until 3,000 ms had elapsed. Response accuracy was indicated to the participant during each inter-trial interval (1,500 ms) via a green checkmark (correct) or a red cross (incorrect). Figure 10 displays the sequence of trials for each condition (An, Cn).

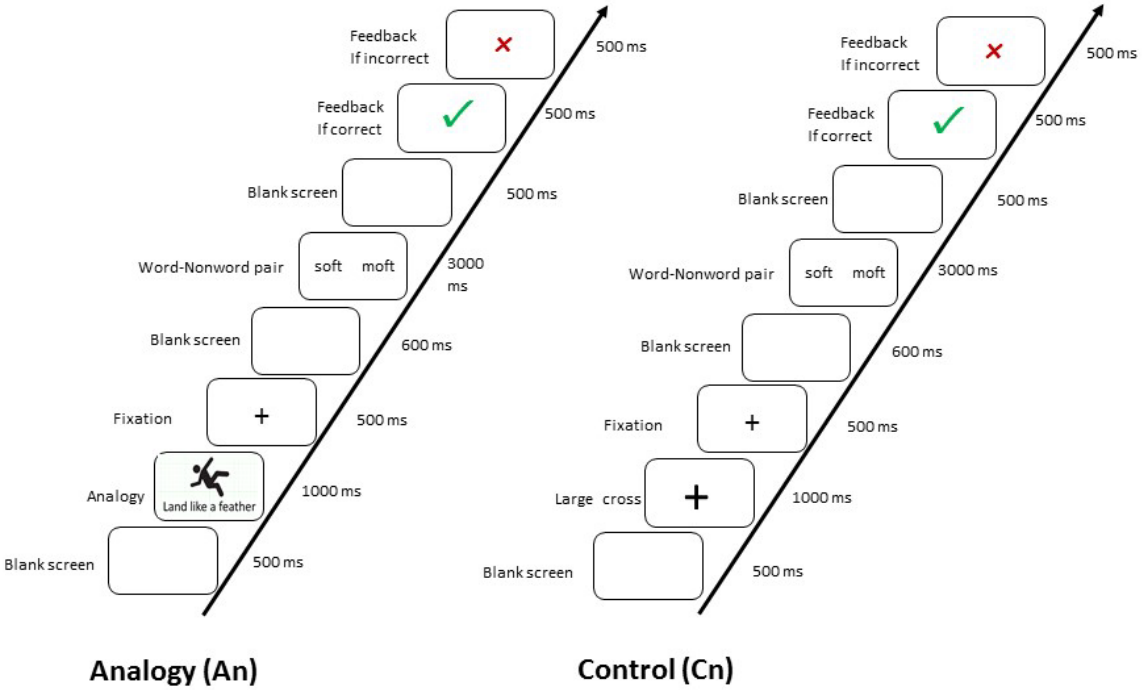

Figure 10. Sequence of events within a trial during the analogy (An) and control (Cn) conditions.

3.4.2 Word/non-word selection

Antonyms of words related to safe landing were excluded so word/non-word pairs related to safe landing were coupled with a word/non-word pair unrelated to landing and matched for length, frequency, mean accuracy and z-score[5] (Faust et al., 1999). Table 4 shows the word/non-word pairs and their respective length, log-frequency-Hal (L-F-H), z- score, and mean accuracy (MA).

Table 4. Word/non-word pairs related to safe landing and unrelated to landing, with their respective length, log-frequency-Hal (L-F-H), z- score, and mean accuracy (MA).

Word/non-word pairs related to safe landing					**Word/non-word pairs unrelated to landing**				
	length	**L-FH**	**Z-score**	**MA**		**length**	**L-FH**	**Z-score**	**MA**
soft	4	10.00	-0.81	0.97	bike	4	10.02	-0.62	1.00
moft	4			0.93	fike	4			0.85
slow	4	10.68	-0.84	1.00	hair	4	10.66	-0.86	1.00
peow	4			1.00	haip	4			1.00
silent	6	9.13	-0.52	1.00	infant	6	9.13	-0.51	0.97
pilent	6			0.88	influd	6			0.97
quiet	5	9.47	-0.58	0.97	crowd	5	9.47	-0.54	0.97
quein	5			0.94	gowed	5			0.91
Avg	4.75	9.82	-0.69	0.96	Avg	4.75	9.82	-0.63	0.97
SD	0.89	0.68	0.16	0.04	SD	0.89	0.67	0.16	0.05

3.4.3 Data analysis

All response time (RT) data was stored and analysed in Microsoft Excel 16.0. Initially, the mean RT of the correct responses was calculated. Similar to Experiment 1, the mean RT ± 2SD was determined as our exclusion criterion for outliers (Martens et al., 2011), which did not result in any exclusions from the data set. One word/non-word pair (i.e., infant/influd) was excluded from analysis because it exceeded the mean error rate (i.e., rate of incorrect answers) of the other word/non-word pairs by two standard deviations (Tainturier et al., 1989; von Studnitz & Green, 1997). We conducted paired-samples t-tests to compare the

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[5] Z-score provides the standardized mean lexical decision latency for each word. Each participant's raw lexical decision latencies were standardized using a z-score transformation, and the mean z-score for all participants presented with a particular word was then computed. This metric allows the lexical decision performance for different words to be directly compared, with more negative z-scores denoting shorter latencies. Because there was considerable variability across participants in overall response latency and each participant only received a subset of the stimuli, the standardized item score is the most reliable measure, minimizing the influence of a participant's processing speed and variability.

participants' average response times (RT) in the analogy and control conditions when discriminating word/non-word pairs related to safe landing and when discriminating word/non-word pairs unrelated to landing.

3.4.4 Results

The results of the paired-samples t-tests revealed that RTs when discriminating words related to safe landing were significantly faster in the An condition compared to the Cn condition, t(87) = 2.66, *p* = 0.006 (one-tailed). However, RTs when discriminating words unrelated to landing were not significantly different between the An and Cn conditions, t(87) = 1.10, *p* = 0.27 (two-tailed). Figure 11 shows the average RT for discrimination of word/non-words related to safe landing and for word/non-word pairs unrelated to landing, in the An and Cn conditions.

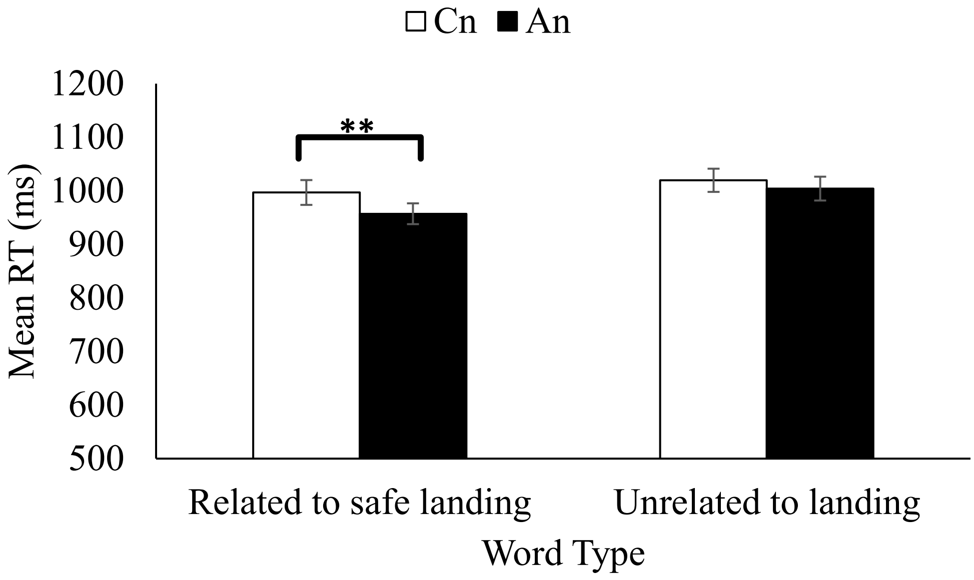

Figure 11. Average response time (RT) in milliseconds (ms) when identifying words related to safe landing or words unrelated to landing in the analogy (An) and control (Cn) conditions.

3.4.5 Discussion

In Experiment 2, we investigated whether priming participants with the words “land like a feather” combined with an image of a person falling triggered faster responses when identifying words associated with safe landing. The results confirmed our hypothesis. Participants in the priming condition (An) displayed significantly faster RTs than participants in a control condition (Cn), when discriminating words related to safe landing but not when discriminating words unrelated to landing. This suggests that even when the concept of a feather was presented in the context of an analogy instruction, mental associations with softness, slowness, and silence remained. This finding implies that perceiving the motor analogy “land like a feather” awakens mental representations of characteristics (e.g., softness, slowness, silence etc.) that are likely to facilitate landings in which ground impacts are reduced. Considering that our safe fall analogy is intended for use by people who are at higher risk of falling, Experiment 3 replicated Experiment 2 using older adults.

3.5 Experiment 3

Experiment 3 was identical to Experiment 2, save that we tested older adults. We hypothesised that older adults would more rapidly discriminate word/non-word pairs that were related to safe landing when they were primed with the same analogy instruction (“land like a feather”) compared to no priming (control). Responses for word/non-word pairs unrelated to landing were not expected to be significantly different between the analogy and control conditions.

3.5.1 Participants and design

Sample size estimation was conducted using a customisable statistical spreadsheet (xSampleSize.xlsx, www.sportsci.org). We used the young adult data from Experiment 2 (smallest difference=150 ms; between subject SD=243 ms) for the calculations, with RT (ms) as our primary outcome. Sample size requirements were calculated using an 80% power ($\beta = 0.20$), and 5% significance level ($\alpha = 0.05$). The calculations resulted in a total sample size of minimum of 84 participants.

We therefore recruited 100 cognitively healthy older adult participants (77 female, 23 male; mean age ± SD: 75.85 ± 7.53 years) to complete the online LDT experiment. Save for minor details (see below), the experimental methodology was identical to Experiment 2. A score above 3 on the mini cognition test (Mini-Cog) was required for participation. The test is used to assess likelihood of dementia, with a score ranging between 1 to 3 indicating that a person is "possibly impaired", and a score above 3 indicating that a person is "probably normal" (Borson et al., 2003).

3.5.2 Word/non-word selection

One word/non-word pair (infant/influd) was excluded from analysis in Experiment 2, so we replaced it with an alternative pair with similar features (galaxy, galaxo). Table 5 shows the word/non-word pairs and their respective length, log-frequency-Hal (L-F-H), Z- score, and mean accuracy.

Table 5. Word/non-word pairs related to safe landing and unrelated to landing, with their respective length, log-frequency-Hal (L-F-H), z- score, and mean accuracy (MA).

Word/non-word pairs related to safe landing					**Word/non-word pairs unrelated to landing**				
	length	**L_FH**	**Z_score**	**MA**		**length**	**L_FH**	**Z_score**	**MA**
soft	4	10.00	-0.81	0.97	bike	4	10.022	-0.62	1.00
moft	4			0.93	fike	4			0.85
slow	4	10.68	-0.84	1.00	hair	4	10.66	-0.86	1.00
peow	4			1.00	haip	4			1.00
silent	6	9.13	-0.52	1.00	galaxy	6	9.14	-0.56	0.97
pilent	6			0.88	galaxo	6			0.97
quiet	5	9.47	-0.58	0.97	crowd	5	9.472	-0.54	0.97
quein	5			0.94	gowed	5			0.91
Avg	4.75	9.82	-0.69	0.96	Avg	4.75	9.82	-0.65	0.96
SD	0.89	0.68	0.16	0.04	SD	0.89	0.67	0.15	0.05

3.5.3 Data analysis

All response time (RT) data were stored and analysed in Microsoft Excel 16.0. Initially, the mean RT of the correct responses was calculated. Similar to Experiments 1 and 2, the mean RT ± 2SD was used as the exclusion criterion (Martens et al., 2011). No RTs breached the criterion; however, it was necessary to exclude 1 word/non-word pair (i.e., galaxy/galaxo[6]) from the analysis, as the rate of incorrect responses for galaxy/galaxo was more than two standard deviations above the mean rate (Tainturier et al., 1989; von Studnitz & Green, 1997). We conducted paired-samples t-tests to compare the older adult participants' average response times (RT) in the analogy and control conditions when discriminating word/non-word pairs related to safe landing and when discriminating word/non-word pairs unrelated to landing.

3.5.4 Results

The results of the paired-samples t-tests revealed that RTs for words related to safe landing were significantly faster in the analogy condition (An) compared to the control (Cn) condition, $t(99) = 2.85$, $p = 0.003$ (one-tailed). However, RTs for words unrelated to landing were not significantly different between the An and Cn conditions, $t(99) = 1.04$, $p = 0.29$ (two-tailed). Figure 12 shows the average RT for words related to safe landing and for words unrelated to landing in the analogy (An) and control (Cn) conditions.

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[6] We were unaware that galaxo (the non-word that we matched to galaxy) was previously the name of a company in New Zealand, which is now known as GSK (https://www.gsk.com/en-gb/contact-us/worldwide/new-zealand/). Many older adults in New Zealand therefore consider galaxo to be a valid English word.

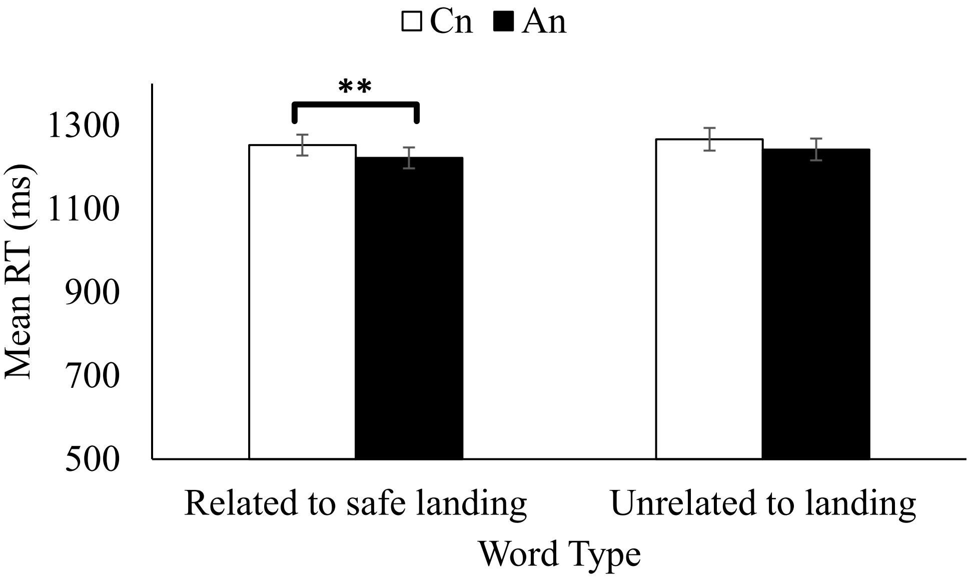

Figure 12. Average response time (RT) in milliseconds (ms) when identifying words related to safe landing or words unrelated to landing in the analogy (An) and control (Cn) conditions.

3.5.5 Discussion

In Experiment 3, we investigated whether priming older adults with the motor analogy "land like a feather" triggered faster responses when identifying words related to safe landing. The results confirmed our hypothesis–when older adults were primed with the motor analogy (An condition) they showed significantly faster RTs for words related to safe landing but not for words unrelated to landing, whereas when they were not primed there were no differences. These findings suggest that our proposed analogy may well invoke characteristics of softness, slowness and silence during landing.

3.6 General Discussion

A major concern in countries with an aging population is the increasing rate of injuries due to falling. One way to reduce the likelihood of injuries is to learn how to land safely from a fall. However, due to age-related cognitive deficiencies, multiple techniques required for landing safely and the short amount of time to process information before impact occurs, landing safely is a challenging task. One practical approach to implementing safe-landing in the older adult population is to use motor analogies. An effective motor analogy can reduce reliance on cognitive resources and is processed quickly; hence, it may be a useful method by which to promote safe landing safely by older adults. A suitable motor analogy is simple to retrieve from memory (Donnelly & McDaniel, 1993), invokes a prominent mental image (van Duijn, Thomas, et al., 2019), and facilitates the development of mental representations in long term memory (Meier et al., 2020) Therefore, when creating an analogy instruction it is important to use familiar concepts so that participants can make the association between the analogy and the implied characteristics (Zacks & Friedman, 2020). In order to investigate whether the concept of a feather evokes mental representations associated with softness, slowness, and silence, which are characteristics of safe landing, we conducted 3 online experiments.

In Experiment 1, we sought to verify that the mental image created by the object being used for the analogy (i.e., a feather) is associated with safe landing characteristics. Our results showed that priming participants with an image of a feather resulted in faster responses when they were asked to discriminate word/non-word pairs in which the word was related to safe-landing characteristics (e.g., soft, slow, silent). According to the Spreading Activation Model (Anderson & Pirolli, 1984; Collins & Loftus, 1975), priming effects are a function of activation spreading across a network of nodes (symbolizing concepts) and links (symbolizing associations or semantic relations). Thus, presentation of the image of a feather is likely to have activated linked nodes (e.g., soft), which made the information related to safe landing characteristics (i.e., soft, slow, silent) more accessible for further processing (Wentura, 2000). This implies that an image of a feather is associated with the descriptors related to safe landing and points to the potential for a feather to be incorporated into our motor analogy. We used a static image of a feather as the prime in Experiment 1, which makes it difficult to confirm whether the association that we found between the feather prime and safe landing words was because of their closeness in the semantic network or the association between the landing of feathers and characteristics of softness, slowness and silence. Therefore, in Experiments 2 and 3 we primed young adults and older adults, respectively, with our proposed motor analogy and investigated whether responses were faster for word/non-word pairs related to safe landing.

Employing a motor analogy as a prime utilizes the relational priming paradigm. This robust psychological phenomenon occurs when prior familiarity with a relationship facilitates subsequent judgments involving that relationship. The phenomenon has been repeatedly demonstrated in different studies (Green et al., 2006; Leech et al., 2008; Spellman et al., 2001). According to Leech et al. (2008), using analogies as primes relies on internal representations of the analogy, which in turn causes a bias towards words/concepts related to the analogy. This bias means that if the landing of a feather is internally represented by characteristics, such as softness, slowness and silence we should observe a bias (faster RTs) for these words compared to words unrelated to these features. In Experiments 2 and 3, we found that both young and older adults primed with the analogy showed significantly faster RTs when identifying words related to safe landing characteristics compared to when there was no prime. Since responses were faster when participants were primed with the analogy instruction, it is safe to assume that there was already an established relationship between the landing of a feather and safe-landing characteristics. This suggests that using the analogy of a feather landing has the potential to create a mental image that can guide movement patterns, such that safe landing is achieved. Perhaps the functional relationship between the landing of a feather and characteristics, such as “soft, slow, silent” can result in movement sequences that ultimately change the geometry of the body so that impact force is reduced and kinetic energy is spread across a wider contact area (i.e., safer landing).

The findings of our experiments shed light on the mental representations evoked by our motor analogy for both younger and older adults, which is the critical function of motor analogies. Motor analogies draw on familiar, similar concepts to convey the information required to execute a complex motor task. The evidence provided here shows that participants were able to draw on the similarities between the landing of a feather and safe-landing characteristics, such as soft, slow and silent. The next step is to investigate the efficacy of our analogy for safe landing with respect to biomechanical measures, such as impact force.

Chapter 4. Investigating the efficacy of a motor analogy designed to promote safe landing from unexpected falls

4.1 Abstract

Introduction. Falls can cause significant health problems among older adults. Previous research into self-initiated falls implied that motor analogies can help people land more safely when falling, reducing the risk of injury. However, falls often occur unexpectedly and the efficacy of motor analogies for unexpected, rather than self-initiated, falls is unknown. **Method**. Thirty young adults were randomly allocated to an analogy or control group. Participants adopted a quiet standing position and a "nudge" was applied to their shoulder unexpectedly, causing a fall in one of four randomised directions (backward, forward, left-side, right-side). The analogy group was instructed to "land like a feather", whereas the control group was instructed to "land safely". Acceleration data (g) were extracted from thirteen inertial measurement unit sensors attached to different body segments and fracture risk (FR) ratios, defined as the ratio of force at impact divided by the load necessary to cause a fracture, were calculated using the data from the wrist sensors. **Results**. The analogy group displayed significantly lower maximum acceleration at ground contact in their upper (arm, wrist, and hand sensors: 9 to 13% reduction) and lower (thigh and leg sensors: 6 to 10% reduction) extremities compared to the control group (all $p \leq 0.05$), but not in the head or trunk sensors (all $p > 0.05$). Additionally, the analogy group displayed significantly lower wrist FR ratios at the wrist (11 to 17% reduction) compared to the control group (all $p \leq 0.05$). **Discussion.** A common landing strategy during unexpected falls is to employ the extremities to reduce the risk of injury to the trunk, head, and important body organs, which in turns increases the likelihood of extremity fractures. Our findings suggest that analogy instructions may reduce the likelihood of extremity injuries, especially the upper extremities, without increasing the risk of head and trunk injuries. **Conclusion**. Motor analogies have the potential to promote safer landing and reduce the risk of injury during accidental falls. Further research is needed to establish the efficacy of this approach for reducing fall-related injuries in older adult populations.

4.2 Introduction

Accidental falls in the older adult population can lead to frailty, immobility, and decline in functional ability (Berg & Cassells, 1992). Despite efforts from healthcare professionals and researchers to prevent falls, approximately 30 to 60% of older adults experience accidental falls each year (Rubenstein, 2006). Much of the research addressing falls in the older adult population has focused on reducing the occurrence of falls by identifying people at risk of falling (Maranesi et al., 2015; Patel et al., 2020; Pradhan et al., 2019) or implementing fall prevention interventions (see review by Sherrington et al., 2020). However, establishing an effective fall prevention programme is challenging (Rubenstein, 2006) and these programmes are often only successful in reducing overall rates of falling with little to no effect on other fall-related consequences, such as fractures, hospitalisations, and quality of life (Hopewell et al., 2020). Therefore, it is important to investigate complementary approaches that may serve to reduce fall-related injuries, such as learning how to land safely when a fall cannot be prevented (DeGoede et al., 2003; Hsieh & Sosnoff, 2020). However, this area of research has been under investigated. According to a systematic review by Moon and Sosnoff (2016), 13 studies have investigated safe landing techniques. The review revealed that a variety of safe landing techniques have been proposed to attenuate the potential risk of damage to different body parts when falling in different ways (e.g., different fall directions). These include, squatting during a backward fall (Tan et al., 2006), slightly flexing the elbows during a forward fall (Lo et al., 2003), and “roll-and-slap” (a martial arts technique) during a sideways fall (Groen et al., 2010; Groen et al., 2007; Groen et al., 2008; Weerdesteyn et al., 2008). Additionally, the review also revealed that only one study has investigated safe landing in older adults (i.e., Groen et al., 2010).

The variety of safe landing techniques that are necessary to reduce severity of injury during different types of fall raises issues associated with cognitive deficiencies that typically accompany ageing, such as slowed reaction times, reduced attentional resources, and lesser working memory capacity (Cabeza, 2002; Thomas et al., 2019; Westlake et al., 2016). Without considerable practice at landing safely, which is impractical for older adults, it is unlikely that most older adults can recall and deploy a safe landing strategy that is appropriate for the type of fall that is occurring in the very brief duration (approximately 0.4 seconds) that it takes to arrive on the ground once an unexpected fall is initiated. This challenge is further compounded by the fact that older adults typically do not learn as quickly as younger adults and fail to reach similar levels of proficiency (McNay & Willingham, 1998; Serbruyns et al., 2015; Voelcker-Rehage, 2008). However, it has been argued that these age-related deficiencies mainly affect effortful memory processes, while automatic memory processes show little to no age deficits (Chauvel et al., 2012; Hoyer & Verhaeghen, 2006).

We know from the motor learning literature that instructions that entail less explicit information about technique place less demand on working memory and are processed more automatically and more quickly than explicit instructions (Masters, 1992; Masters et al., 2020; Steenbergen et al., 2010). This form of motor skill acquisition is referred to as implicit motor learning, which aims to minimize the accumulation of explicit knowledge of the underlying rules governing the mechanics of movements (Masters, 1992, 2000). Hence, an implicit approach may be preferable for leaning new motor skills in older populations (Chauvel et al., 2012; Tse, Wong, et al., 2017). One such approach uses motor analogies to convey information in a non-explicit form that reduces conscious knowledge about how to move. It has been argued that this approach results in implicit motor learning (e.g., Masters, 2000; Liao & Masters, 2001). Motor analogies use a concept that is familiar to the learner to convey the complex structure of the motor skill that is to be learned (Liao & Masters, 2001; Masters, 2000). For instance, Liao and Masters (2001) used a right-angled triangle analogy to teach novices how to hit a topspin forehand shot in table tennis. Participants were instructed to swing the bat up the hypotenuse of a right-angled triangle when striking the ball. When compared to participants who were provided explicit rules about how to hit a topspin forehand, participants using the analogy demonstrated motor behaviours akin with implicit motor learning (including more stable performance under stressful conditions and secondary task loading). A similar motor analogy (i.e., swing the bat up the side of a mountain) was provided to novice older adults, who displayed preserved skill level over time and robust performance under dual-task conditions (Tse, Wong, et al., 2017). Motor analogies have also been used to improve dynamic balance during rehabilitation (Kim et al., 2021) and gait in Parkinson disease (Jie et al., 2016) and stroke (Kleynen et al., 2014). Analogies are simple to retrieve from memory (Donnelly & McDaniel, 1993), can rapidly deploy attention during movement (Koedijker et al., 2011), facilitate the development of mental representations in long term memory (Meier et al., 2020), and may even speed up the motor learning process (Zacks & Friedman, 2020). These qualities, combined with the reduced need to deploy working memory to process explicit instructions (Masters & Liao, 2003; Masters et al., 2020;

Meier et al., 2020; Poolton & Masters, 2014), suggest that analogies may offer a suitable method by which to teach safe landing to older adults.

To develop a motor analogy that promotes safe landing, Masters et al. (2018) used focus group interviews with fallers and fall experts to identify three descriptors that characterise a safe fall: “soft, slow, silent”. Masters et al. (2018) suggested that “land like a snowflake” is a motor analogy that evokes representations of these descriptors–snowflakes are soft, slow and silent. Subsequently, Oladi, Uiga, Hébert-Losier, and Masters (under review/Chapter 2) tested whether instructions to “land like a snowflake” resulted in safer landing characteristics than control instructions in young adult participants. Oladi et al. (under review/Chapter 2) found that participants who used the motor analogy displayed increased free-fall duration and impact duration, and decreased maximum acceleration when compared to participants in the control group. Oladi et al. (under review/Chapter 2) concluded that the motor analogy may have promoted safer landing. However, the participants in the study were required to self-initiate their falls (forward, backward, leftward), which may have provided them with the opportunity to pre-programme a landing strategy prior to initiating the fall. In an accidental fall, there is rarely enough time to recall and pre-programme a landing strategy. Additionally, Oladi et al. (under review/Chapter 2) did not provide participants in the control group with any instructions about how to land. Control participants were merely instructed to “land on the ground”. Therefore, the observed differences may be attributable to receiving an instruction (any instruction), rather than specifically to the motor analogy that was used. Furthermore, Oladi et al. (under review/Chapter 2), noted that when completing the priming task (i.e., completing a crossword puzzle), some participants required hints about the landing characteristics of a snowflake and were not able to make an immediate connection between snowflakes and soft, slow, and silent characteristics. This lack of immediate connection may have been because participants were not well acquainted with "snowflakes", presumably due to the relative lack of snow precipitation in the more northern parts of New Zealand, where most of the participants lived. To be effective, analogies need to be relevant and meaningful to the learner. That is, the explanatory concept needs to be familiar and meaningful so that there are strong and obvious parallels with the to-be learned concept or task (Ngu & Yeung, 2012; Paatz et al., 2004). Hence, when developing a motor analogy, it is important to use a concept that the learner is directly experienced with and/or that the learner can instantly relate to the concept or task to-be-learned (Zacks & Friedman, 2020).

This experiment addressed these shortcomings. Falls were unexpected (forward, backward, leftward, rightward), participants in the control group were instructed to "land safely on the ground", and a more culturally relevant analogy was used to convey the underlying representations of soft, slow, and silent–that is, participants were instructed to "land like a feather". The latter analogy was deemed to be a more general, and thus familiar, concept than the snowflake one.

A further improvement to the previous experimental design was the calculation of a new variable to investigate the risk of wrist fracture. During a fall, people often use their upper extremities to protect their head and vital organs (Ruiz-del-Solar et al., 2009). For instance, video analysis of real-life falls of older adults in long term care showed that 84% of the falls involved hand impact (Choi et al., 2015). Consequently, it is important to assess the risk of upper extremity injury when landing from falls. We therefore calculated wrist fracture risk (FR) ratios for all participants in the current experiment.

Thus, the goal of this study was to test the efficacy of a relevant motor analogy, "land like a feather", for promoting safe landing from falls in a backward, forward, rightward, or leftward direction that were not self-initiated. To evaluate the quality of the landings, we attached 13 Inertial Measurement Units (IMUs) to different body segments of participants to calculate impact force normalised by mass (i.e., maximum acceleration), duration of fall, duration of impact, and FR ratio. The present experiment is the first to investigate the effect of a motor analogy on landing characteristics of an unexpected fall in participants instructed to “land like a feather” (the analogy group) compared to participants instructed to “land safely” (the control group). We hypothesised that participants in the analogy group would: (1) fall more slowly (i.e., longer free-fall duration), (2) land with lower maximum acceleration, (3) display longer impact duration, and (4) demonstrate lower wrist FR ratios.

4.3 Method

4.3.1 Participants

A sample size estimation was conducted using a customizable statistical spreadsheet (xSampleSize.xlsx, www.sportsci.org). We used data from Oladi et al. (under review/Chapter 2) (smallest difference = 0.82 g; between subject SD = 0.65 g) for the calculations, with the maximum acceleration value from the one-dimensional signal magnitude vector (SMV_{max}, explained under Data analysis) as our primary outcome. Sample size requirements were calculated from standard two-tailed hypothesis equations using an 80% power ($\beta = 0.20$) and 5% significance level ($\alpha = 0.05$). The calculations resulted in a total sample size minimum requirement of 22 participants.

Thirty young adults were therefore recruited from the university campus. After providing informed consent and demographic information, they were randomly allocated to a motor analogy ($n = 15$) or control ($n = 15$) group using a random generator computer programme. A PAR-Q+ questionnaire was administered to determine whether pre-existing conditions or injuries prohibited participation. Independent sample *t*-tests showed no significant between-group differences in age, height, or mass (see Table 6, Demographic characteristics). The proportion of males and females between groups was similar (Chi square test $p = 0.282$). The experiment was approved by the Human Research Ethics Committee (Health) of the institution.

Table 6. Demographic characteristics of participants (mean ± standard deviation).

	Analogy ($n = 15$)	Control ($n = 15$)	All ($n = 30$)	Between-group difference p value (two-tailed)
Age (years)	20.5 ± 2.5	20.4 ± 2.4	20.5 ± 2.4	0.94
Height (cm)	171.5± 9.6	175.5 ± 10.8	173.5 ± 10.3	0.29
Mass (kg)	72.3 ± 11.8	79.8 ± 15.9	75.1± 14.1	0.27
Gender	9 females 6 males	6 females 9 males	15 female 15 male	0.282

4.3.2 Measurements and instrumentation

A two-dimensional video camera (Canyon, 25 frames per second) and 13 Delsys Trigno$^{\text{TM}}$ (Delsys Inc., Natrick, MA) inertial measurement units (IMUs) were used to assess kinematics of each fall. The video camera was positioned three meters from the side of participants on a 1.3 m high tripod. Acceleration data from the IMU sensors were recorded at a frequency of 148.15 Hz using EMGworks Acquisition software (Version 4.5.4). In addition to the three IMU sensor placements used by Oladi et al. (under review/Chapter 2), we employed 10 additional sensors to gain more information regarding other body parts. Specially, the 13 sensors were attached over the following body segments using double-sided tape: head, chest (aligned with the sternum), lower back (aligned with L3), upper arms (dorsal), wrists (dorsal), hands (dorsal), thighs (lateral), and lower legs (lateral). Figure 13 demonstrates the placement of the IMU sensors on one participant.

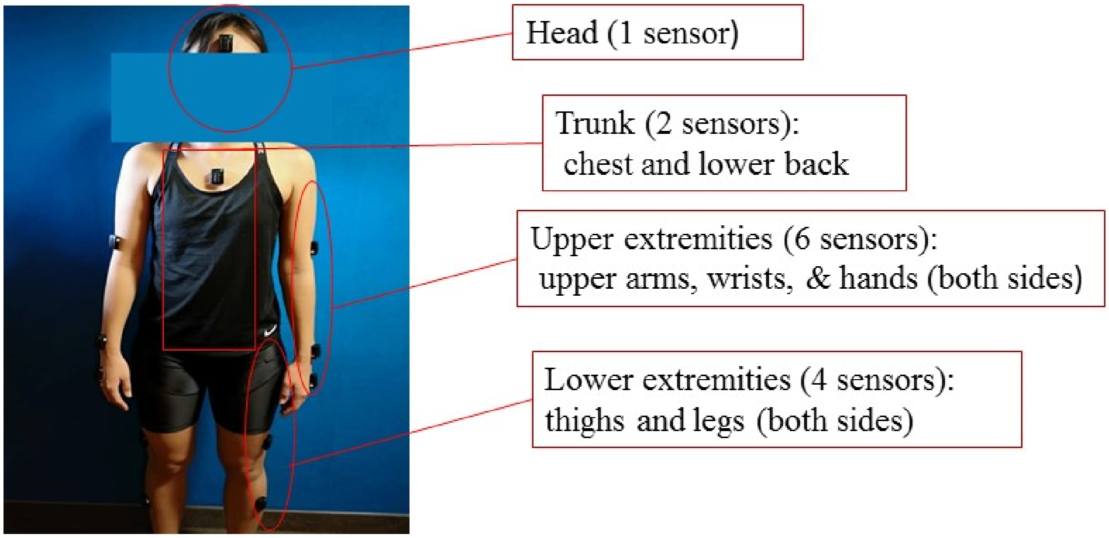

Figure 13. Positioning of inertial measurement units on different body segments.

4.3.4 Procedure

Participants allocated to the analogy group were required to complete a three-word crossword puzzle designed to prime them about how feathers land on the ground: soft, slow, and silent (see Figure 14, Panel A). Participants allocated to the control group completed a similar crossword puzzle that used names of birds as neutral primes: swallow, shag, and swan (see Figure 14, Panel B). Hints were provided if participants had difficulty completing the crossword. The IMUs were then secured in position and participants were asked to stand on a surface-level platform (27 x 32 cm) with either their back or front facing a fully padded landing area. One of the researchers placed her hands on the participants' shoulder and unexpectedly applied a gentle impulse (nudge) in a different direction (backward, forward, leftward, rightward). Participants were instructed to allow the nudge to cause them to lose balance so that they fell onto the padded area in the direction in which the nudge was applied. Participants either faced the padded area or faced away from the padded area. When they faced the padded area, the researcher nudged the right shoulder to cause a forward or leftward fall. When the participant faced away from the padded area, the researcher nudged the left shoulder to cause a backward or rightward fall. Participants in the analogy condition were instructed to “land like a feather”, whereas participants in the control condition were instructed to “land safely on the ground”. The order of the falls was randomised using a random order generator. The experimental procedure was repeated twice within the same session (with a different order of falls on each occasion); in total, each participant therefore fell eight times (twice in each direction) during the experimental procedure.

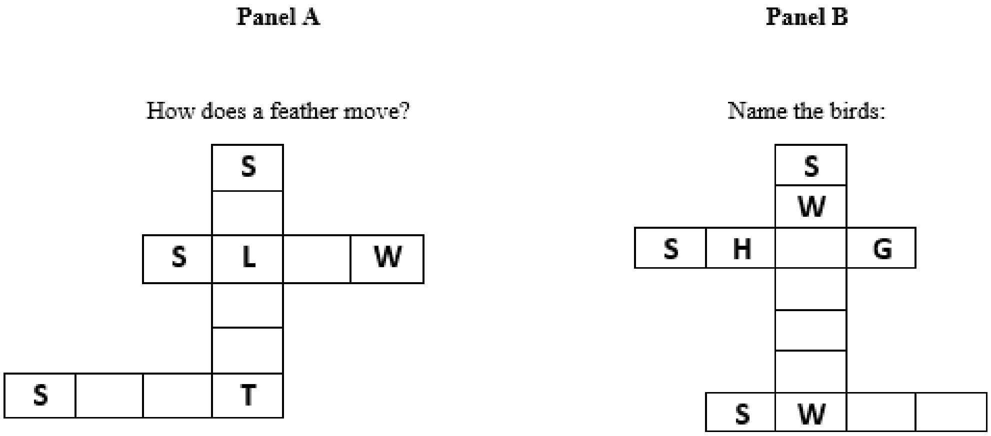

Figure 14. Crosswords for priming participants in the analogy (Panel A) and control (Panel B) group. Panel A: soft, slow, silent. Panel B: swallow, shag, swan.

4.3.5 Data analysis

The acceleration data were exported in an excel format and processed using Matlab (R2017b, MathWorks Inc., Natic, USA). The data were low-pass filtered at 4 Hz using a 2nd order Butterworth filter (Bartlett, 2002; Bourke et al., 2010; Karantonis et al., 2006; Mathie et al., 2004). A median filter with $n = 3$ was subsequently applied to the accelerometer data to remove any abnormal noise spikes (Karantonis et al., 2006). A one-dimensional signal magnitude vector (SMV), or resultant acceleration, was calculated from the tri-axial accelerometer data using the following standard equation (Ellis et al., 2016; Gjoreski et al., 2016; Kamada et al., 2015; Mannini et al., 2013a; Zhang et al., 2012).

$$SMV\ (g) = \sqrt{a_x{}^2 + a_y{}^2 + a_z{}^2}$$

Start of fall ($\text{Start}_{\text{Fall}}$), initial body contact with the ground ($\text{Contact}_{\text{First}}$), and end of fall ($\text{End}_{\text{Fall}}$) were extracted from the SMV of the lower back sensor. Subsequently, these events were used to compute free-fall duration and impact duration in seconds (s). Free-fall duration was defined as the time period between $\text{Start}_{\text{Fall}}$ to $\text{Contact}_{\text{First}}$, whereas impact duration was defined as the time period between $\text{Contact}_{\text{First}}$ to End_{Fall}. Maximum acceleration (SMV_{max}, g) was extracted from the 13 sensors: head (HD), chest (CH), lower back (LB), right arm (RAm), left arm (LAm), right wrist (RWr), left wrist (LWr), right hand (RHn), left hand (LHn), right thigh (RTh), left thigh (LTh), right leg (RLg), and left leg (LLg). Additionally, time of impact (T_{i}) was extracted from all 13 sensors (i.e., the time-point SMV reached SMV_{max}). Figure 15 displays $\text{Start}_{\text{Fall}}$, $\text{Contact}_{\text{First}}$, End_{Fall}, SMV_{max}, and T_{i} extracted from the lower back IMU sensor of a participant performing a backward fall.

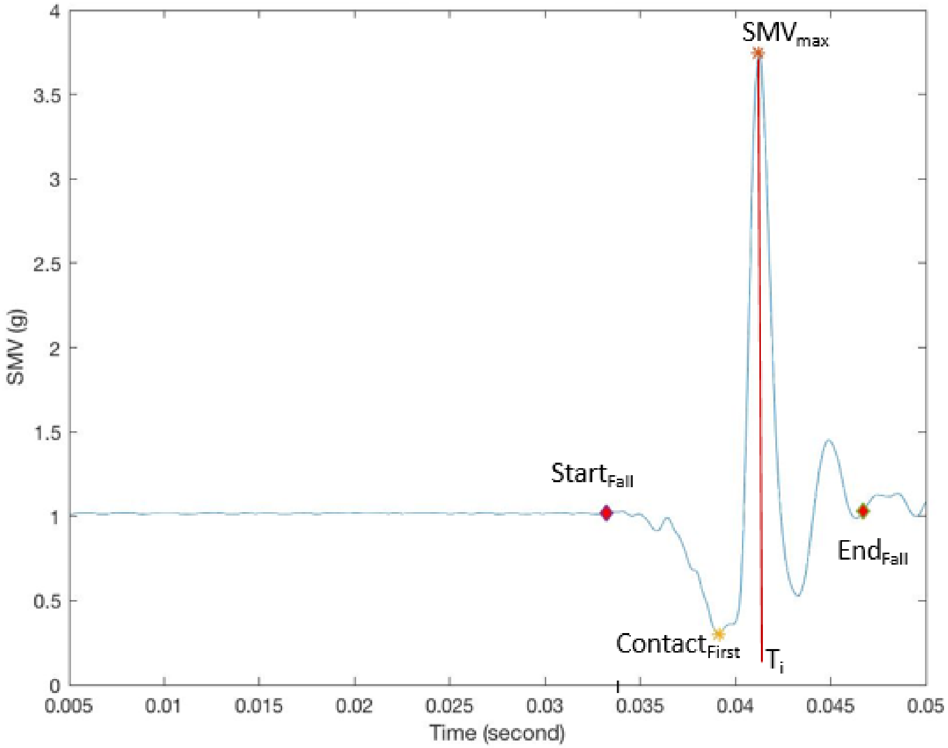

Figure 15. Signal magnitude vector (SMV) extracted from the lower back inertial measurement unit during an unexpected backward fall. Start$_{Fall}$: start of fall, Contact$_{First}$: initial body contact with the ground, T$_i$: time of impact, End$_{Fall}$: end of fall.

The fracture risk of different body parts depends on the severity of the impact and the capacity of the bones to resist the impact (Groen et al., 2006). Therefore, fracture risk (FR) ratio was defined as the ratio of force at impact (T$_i$) divided by the load necessary to cause a fracture (DeGoede et al., 2003; Hayes et al.,1996; Melton 3rd & Cummings, 1987; Nevitt, 1994). To calculate the force applied to the wrists, the SMV of the wrist sensors at T$_i$ was multiplied by the scaling factor for the forearm mass (%mass) provided by Dumas et al. (2007), and then multiplied by the gravitational acceleration constant 9.807 m/s^2 (i.e., to convert g to m/s^2).[7] Finally, the force applied to the participant's wrist sensors was divided by the load required to fracture the radius bone based on cadaveric studies (Augat et al.,

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[7] The sensors were not placed on the Center of Mass (COM) of the relevant segments, which could have caused some errors in our estimations of these variables.

1996). FR ratio is an estimation of the percentage of force that is likely to fracture the wrist. An FR ratio of 1.0 indicates that the load (e.g., from a fall) equals the force required to fracture the radius bone. A smaller FR ratio (i.e., less than 1.0) indicates a lower risk of fracture. However, it is important to note that we calculated the FR ratio using a simple model that did not take into account factors, such as, the weight of other body parts, direction of fore applied, bone density, connective tissue, etc. Hence, a more complex model of the FR ratio would be expected to yield higher FR values.

4.3.6 Statistical analysis

Mean and standard deviation (SD) values were calculated for each variable and differences between groups were examined using IBM SPSS Statistics 25 (IBM® SPSS Statistics Software). To mitigate the risk of Type 1 error from multiple statistical tests, a 2 x 4 mixed model multivariate analysis of variance (MANOVA) was conducted as an omnibus test (Huberty & Petoskey, 2000) of the impact of group (analogy, control) and fall direction (forward, backward, leftward, rightward) on all of the variables of interest (free-fall duration, impact duration, and SMV_{max} of the 13 sensors located on the head, chest, lower back, left and right arms, wrists, hands, thighs, and legs). In the event of a statistically significant MANOVA effect, further examination of the variables was conducted separately using ANOVAs, followed by Tukey's honestly significant difference tests where appropriate. The strength of the partial eta squared values (effect size) was interpreted using the following thresholds: small = 0.01, medium = 0.06, and large = 0.14 (Olejnik & Algina, 2000), and trivial when < 0.01. To control for the multiplicity problem caused by conducting multiple statistical tests (Type 2 error), the Benjamini–Hochberg (B-H) method was used. This procedure controls the α level using successive modified Bonferroni corrections (Benjamini & Hochberg, 1995). To conduct the B-H adjustment, the following steps were taken: the *p* values were listed in an ascending order; a rank was assigned to each *p* value; and the adjusted α levels were calculated using the assigned ranks (Glickman et al., 2014). The adjusted *a* levels using the B-H procedure are presented in Table 7.

Table 7. Benjamini-Hochberg adjusted a values and False Discovery Rate (FDR) for each biomechanical variable, presented in ascending order for condition and fall direction

Benjamini-Hochberg Values							
Condition				Fall direction			
Variable	*p*-values ascending order	FDR	$p \leq$ FDR	Variable	*p*-values ascending order	FDR	$p \leq$ FDR
Left wrist-SMV_{max}	0.000	0.003	Yes	Lower back-SMV_{max}	0.000	0.003	Yes
FR ratio -Left wrist	0.001	0.006	Yes	Left leg-SMV_{max}	0.000	0.003	Yes
Left Thigh-SMV_{max}	0.002	0.009	Yes	Right Thigh-SMV_{max}	0.000	0.003	Yes
Right arm-SMV_{max}	0.002	0.009	Yes	Chest-SMV_{max}	0.001	0.006	Yes
Left arm-SMV_{max}	0.003	0.012	Yes	Left Thigh-SMV_{max}	0.001	0.006	Yes
Left hand-SMV_{max}	0.004	0.015	Yes	Impact duration	0.001	0.006	Yes
Right hand-SMV_{max}	0.005	0.018	Yes	Right leg-SMV_{max}	0.002	0.009	Yes
Left leg-SMV_{max}	0.006	0.021	Yes	Right Hand-SMV_{max}	0.008	0.012	Yes
Right wrist-SMV_{max}	0.012	0.024	Yes	Right wrist-SMV_{max}	0.011	0.015	Yes
Right Thigh-SMV_{max}	0.024	0.026	Yes	Left hand-SMV_{max}	0.035	0.018	No
FR ratio -Right wrist	0.029	0.029	Yes	FR ratio -Right wrist	0.036	0.021	No
Right leg-SMV_{max}	0.047	0.032	No	Head-SMV_{max}	0.037	0.021	No
Chest-SMV_{max}	0.091	0.035	No	Left wrist-SMV_{max}	0.052	0.024	No
Free-fall duration	0.157	0.038	No	Left arm-SMV_{max}	0.079	0.026	No
Lower back-SMV_{max}	0.221	0.041	No	FR ratio-Left wrist	0.083	0.029	No
Head-SMV_{max}	0.591	0.044	No	Free-fall duration	0.101	0.032	No
Impact duration	0.647	0.047	No	Right arm-SMV_{max}	0.807	0.035	No

False Discovery Rate (FDR) was calculated in the following way: $(^{i}/_{n}) \times 0.05$
i: rank of *p* value
n: number of variables

4.4 Results

Means and standard deviations for each group (analogy, control) by direction (forward, backward, leftward, rightward) for each dependent variable (free-fall duration, impact duration, wrist FR ratios, SMV_{max} of the 13 sensors) are presented in Table 8.

Table 8. Mean ± standard deviation of the SMVmax for the 13 sensors: head (HD), chest (CH), lower back (LB), right arm (Ram), left arm (Lam), right wrist (RWr), left wrist (LWr), right hand (RHn), left hand (LHn), right thigh (RTh), left thigh (LTh), right leg (RLg), Left leg (LLg), freefall duration, impact duration, fracture risk (FR) ratio of left wrist (LWr-FR ratio), and right wrist (RWr-FR ratio) in in the control group (Cn) and motor analogy (An) group, as a function of fall direction (backward, forward, leftward, rightward).

	Backward		Forward		Leftward		Rightward	
Measured Variables	Cn	An	Cn	An	Cn	An	Cn	An
HD-SMV_{max} (g)	3.38±0.72	3.10±0.82	2.78±0.62	2.95±1.08	3.00±0.46	2.93±0.71	2.98±0.61	2.95±0.72
CH-SMV_{max} (g)	3.82±0.74	3.49±0.84	3.00±0.82	2.96±1.03	3.36±0.83	3.17±0.71	3.49±1.03	3.27±0.94
LB- SMV_{max} (g)	4.46±0.97	4.26±1.05	3.26±0.71	3.00±1.06	3.71±0.90	3.60±0.92	3.91±1.27	3.85±1.09
LWr- SMV_{max} (g)	4.53±1.32	4.04±1.59	4.61±1.03	4.22±1.14	4.96±1.73	3.84±1.21	4.63±0.93	4.44±1.71
RWr-SMV_{max} (g)	5.15±1.52	4.45±1.44	4.26±1.08	4.20±1.20	4.98±1.36	4.08±1.10	4.48±1.21	4.03±1.76
RAm-SMV_{max} (g)	4.70±1.34	4.26±1.25	5.33±1.19	5.14±1.58	5.06±1.78	4.25±1.20	5.25±1.07	4.87±1.40
LAm-SMV_{max} (g)	5.31±1.24	4.44±1.09	4.98±1.27	4.80±1.24	5.41±1.38	4.68±1.18	4.85±1.57	3.89±1.82
RHn-SMV_{max} (g)	4.87±1.47	4.51±1.52	5.66±1.52	5.37±1.72	5.38±1.99	4.32±1.23	5.72±1.42	5.11±1.52
LHn-SMV_{max} (g)	5.64±1.58	4.77±1.23	5.15±1.48	5.18±1.57	5.53±1.43	4.85±1.31	4.91±1.56	4.08±2.00
RTh-SMV_{max} (g)	3.34±0.69	3.32±0.68	3.61±1.21	3.05±0.85	3.06±0.81	2.76±0.69	3.55±0.62	3.49±0.60
LTh-SMV_{max} (g)	3.44±0.66	3.18±0.61	3.69±1.17	2.98±1.08	3.57±0.86	3.22±0.63	2.84±0.60	2.85±0.46
RLg-SMV_{max} (g)	2.89±0.66	3.02±0.62	3.22±0.88	2.82±0.63	2.78±0.73	2.59±0.52	3.28±0.64	3.04±0.62
LLg-SMV_{max} (g)	3.02±0.65	2.90±0.60	3.35±0.94	2.67±0.82	3.28±0.70	3.09±0.69	2.58±0.58	2.57±0.37
Freefall duration (s)	0.81±0.12	0.72±0.18	0.71±0.21	0.73±0.23	0.82±0.18	0.76±0.16	0.80±0.17	0.80±0.17
Impact duration (s)	1.05±0.18	0.99±0.19	1.08±0.20	1.17±0.27	1.03±0.19	1.00±0.17	1.02±0.15	0.96±0.19
RWr-FR ratio	0.014±0.05	0.012±0.05	0.016±0.05	0.016±0.06	0.016±0.07	0.012±0.04	0.016±0.05	0.015±0.06
LWr-FR ratio	0.016±0.06	0.013±0.04	0.015±0.05	0.014±0.05	0.017±0.06	0.014±0.05	0.014±0.06	0.011±0.07

MANOVA revealed main effects of group [F(17, 211) = 2.12, $p = 0.007$; Wilks' Lambda = 0.85; $\eta_p^2 = 0.14$] and fall direction [F (51, 628) = 4.67, $p < 0.001$; Wilks' Lambda = 0.38; $\eta_p^2 = 0.27$]. A significant interaction was not evident between group and fall direction [F (51, 628) =1.12, $p = 0.09$; Wilks' Lambda = 0.74; $\eta_p^2 = 0.09$]. Two-way ANOVAs were therefore used to examine the main effects of group and fall direction on each variable separately, but not the interactions.

Two-way ANOVAs (group × fall direction) revealed statistically significant main effects of group for the following dependent variables: $\mathrm{SMV}_{\mathrm{max}}$ of the RAm, LAm, RWr, left wrist, RHn, LHn, RTh, LTh, and LLg sensors (see Table 9 for a summary). Participants in the analogy group displayed significantly lower wrist fracture ratios (Figure 16) and smaller $\mathrm{SMV}_{\mathrm{max}}$ values for the upper (Figure 17) and lower (Figure 18) extremities compared to the participants in the control group. Differences across variables were associated with small effect size values, except for LWr where differences were moderate. For fall direction, a statistically significant main effect was evident for impact duration and $\mathrm{SMV}_{\mathrm{max}}$ of the following sensors: chest, lower back, right wrist, right hand, thighs, and legs. Differences were small to large depending on the variable examined.

Table 9. ANOVA summary (as a function of group and fall direction) for: free-fall duration, impact duration, right and left wrist fracture risk (RWr-FR, LWr-FR) ratio, and $\mathrm{SMV}_{\mathrm{max}}$ of sensors located on the head (HD-$\mathrm{SMV}_{\mathrm{max}}$), chest (CH-$\mathrm{SMV}_{\mathrm{max}}$), lower back (LB- $\mathrm{SMV}_{\mathrm{max}}$), right arm (RAm-$\mathrm{SMV}_{\mathrm{max}}$), left arm (LAm-$\mathrm{SMV}_{\mathrm{max}}$), right wrist (RWr-$\mathrm{SMV}_{\mathrm{max}}$), left wrist (LWr-$\mathrm{SMV}_{\mathrm{max}}$), right hand (RHn-$\mathrm{SMV}_{\mathrm{max}}$), left hand (LHn-$\mathrm{SMV}_{\mathrm{max}}$), right thigh (RTh-$\mathrm{SMV}_{\mathrm{max}}$), left thigh (LTh-$\mathrm{SMV}_{\mathrm{max}}$), right leg (RLg-$\mathrm{SMV}_{\mathrm{max}}$), left leg (LLg-$\mathrm{SMV}_{\mathrm{max}}$).

	Group			**Fall Direction**			**Group × Fall Direction**		
Variable	F	*p* value	η_p^2	F	*p* value	η_p^2	F	*p* value	η_p^2
Free-fall duration (s)	2.02	0.15	0.00	2.09	0.10	0.02	1.18	0.31	0.01
Impact duration (s)	0.20	0.64	0.00	5.33	**<0.001***	0.06	1.77	0.15	0.02
HD-$\mathrm{SMV}_{\mathrm{max}}$ (g)	0.28	0.59	0.00	2.87	0.03	0.03	0.95	0.41	0.01
CH-$\mathrm{SMV}_{\mathrm{max}}$ (g)	2.87	0.09	0.01	6.05	**0.001***	0.07	0.28	0.83	0.00
LB- $\mathrm{SMV}_{\mathrm{max}}$ (g)	1.50	0.22	0.00	15.2	**<0.001***	0.16	0.11	0.95	0.00
RAm-$\mathrm{SMV}_{\mathrm{max}}$ (g)	9.44	**0.002***	0.03	0.32	0.80	0.00	1.26	0.28	0.01
LAm-$\mathrm{SMV}_{\mathrm{max}}$ (g)	8.77	**0.003***	0.03	2.28	0.07	0.02	1.07	0.35	0.01
RWr-$\mathrm{SMV}_{\mathrm{max}}$ (g)	6.46	**0.01***	0.02	3.82	**0.01***	0.04	0.53	0.65	0.00
LWr-$\mathrm{SMV}_{\mathrm{max}}$ (g)	14.6	**<0.001***	0.06	2.61	0.05	0.03	0.96	0.40	0.01
RHn-$\mathrm{SMV}_{\mathrm{max}}$ (g)	7.96	**0.005***	0.03	4.01	**0.008***	0.05	0.71	0.54	0.00
LHn-$\mathrm{SMV}_{\mathrm{max}}$ (g)	8.56	**0.004***	0.03	2.91	0.03	0.03	1.11	0.34	0.01
RTh-$\mathrm{SMV}_{\mathrm{max}}$ (g)	5.16	**0.02***	0.02	6.14	**<0.001***	0.07	1.46	0.22	0.01

LTh-SMV$_{max}$ (g)	9.94	**0.002***	0.04	5.74	**0.001***	0.07	2.02	0.11	0.02
RLg-SMV$_{max}$ (g)	3.97	0.04	0.01	4.99	**0.002***	0.06	1.61	0.18	0.02
LLg-SMV$_{max}$ (g)	7.61	**0.006***	0.03	7.82	**<0.001***	0.09	2.70	0.04	0.03
RWr-FR ratio	4.80	**0.02***	0.02	2.90	0.03	0.03	0.73	0.53	0.00
LWr-FR ratio	12.0	**0.001***	0.05	2.25	0.08	0.02	0.69	0.55	0.00

Abbreviation: η_p^2, partial eta squared; df, degree of freedom

* Statistically significant (p value is less than the adjusted α level using the Benjamini–Hochberg procedure)

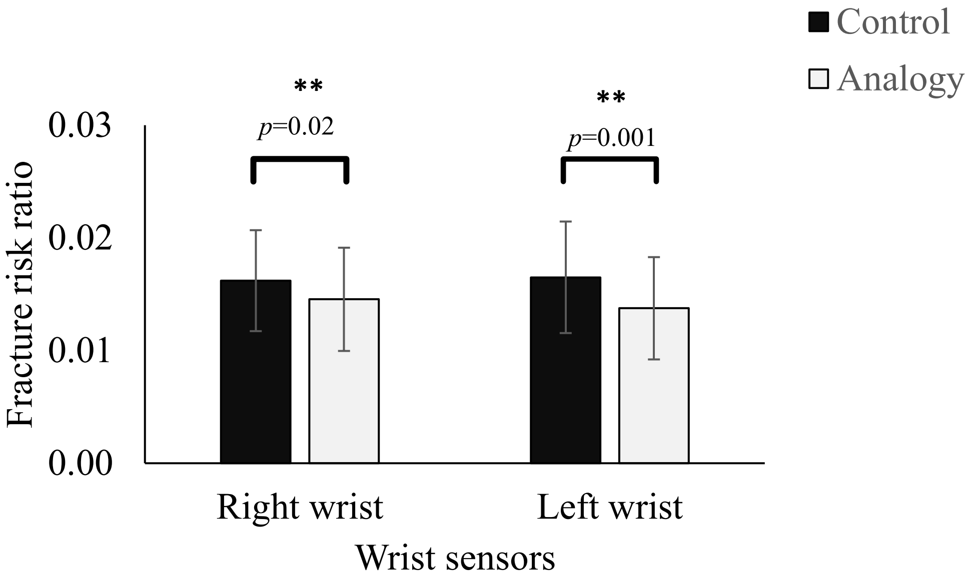

Figure 16. Mean fracture risk (FR) ratio of the right and left wrists for the analogy and control group, calculated from the wrist sensors, across all fall directions. Error bars represent standard deviations. * Statistically significant (p value is less than the adjusted α level using the Benjamini–Hochberg procedure).

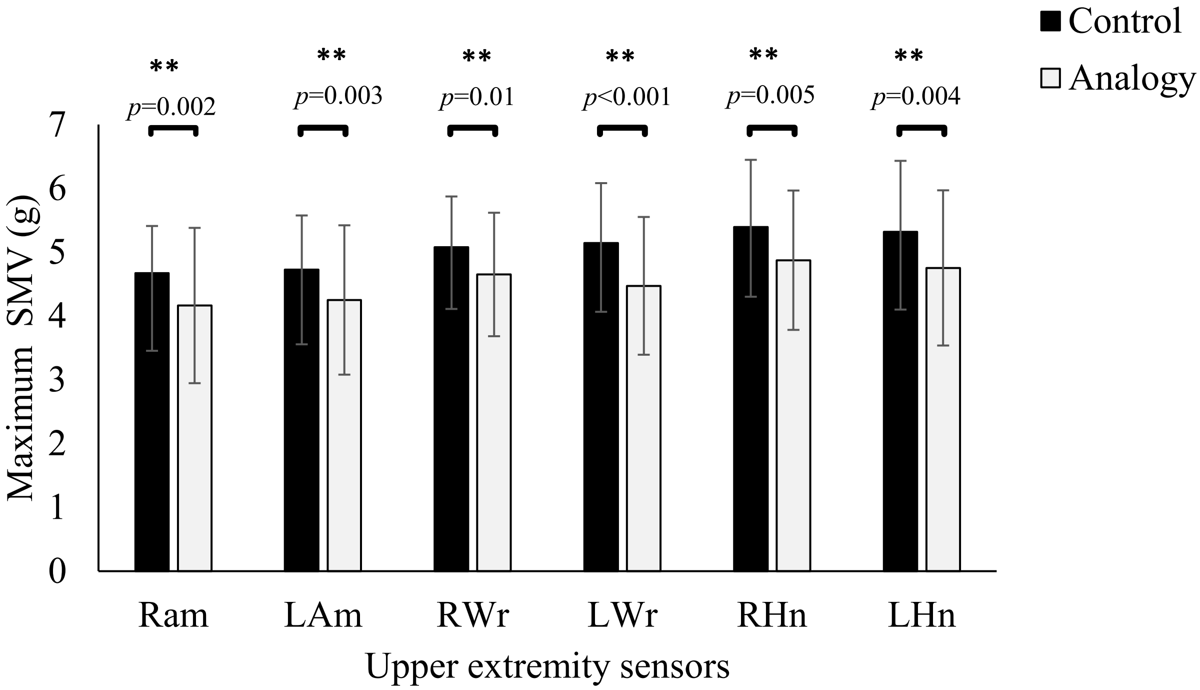

Figure 17. Mean $\mathrm{SMV}_{\max}$ of right and left arms (RAm, LAm), right and left wrists (RWr, LWr), and right and left hands (RHn, LHn) for the analogy and control groups, across all fall directions. Error bars represent standard deviations. ** Statistically significant (p value is less than the adjusted α level using the Benjamini–Hochberg procedure).

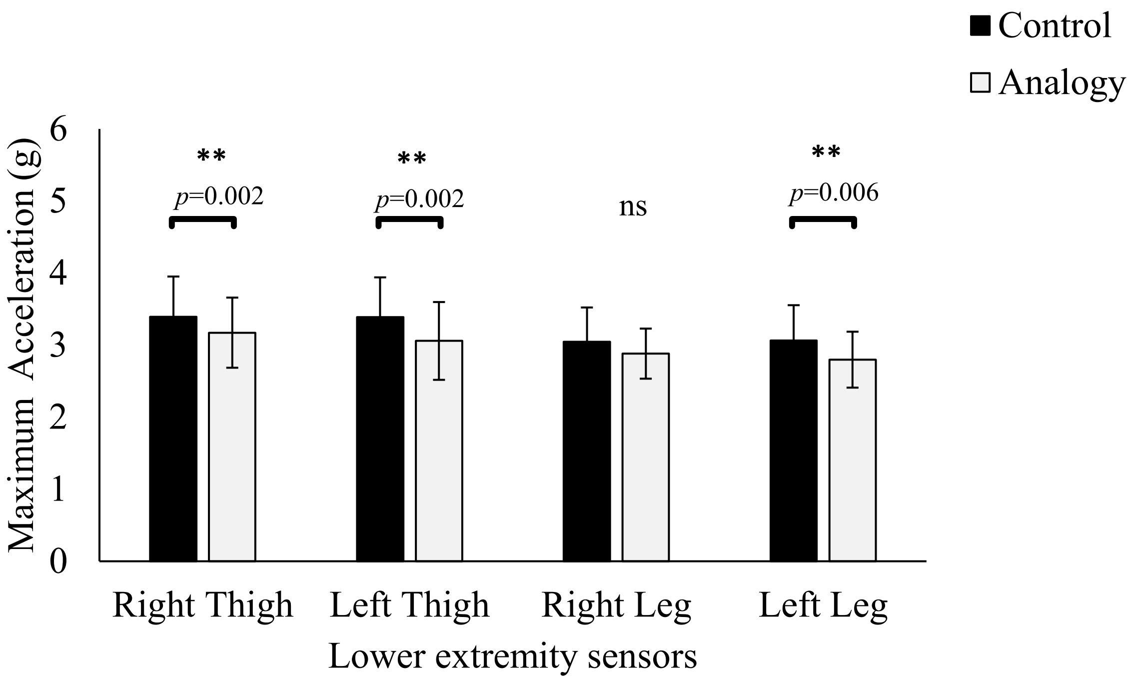

Figure 18. Mean SMVmax of right and left thigh, and right and left leg for the analogy and control groups, across all fall directions. Error bars represent standard deviations. ** Statistically significant (p value is less than the adjusted α level using the Benjamini–Hochberg procedure).

4.5 Discussion

This experiment investigated the efficacy of a motor analogy that was designed to promote safe landing following an unexpected fall. Biomechanical measures were extracted from forward, backward, leftward, and rightward falls and compared between an analogy ("land like a feather") and control ("land safely") group. Lower $\mathrm{SMV}_{\mathrm{max}}$ values and higher free-fall duration and impact duration are likely, in our view, associated with safer landings (Oladi et al., under review/Chapter 2). Contrary to the findings of Oladi et al. (under review/Chapter 2), free-fall duration and impact duration were not significantly different between the two groups. This finding suggests that participants in both groups fell with similar speed. The inconsistency between the two studies may be associated with examining unexpected falls instead of self-initiated falls. Self-initiating a fall may allow a person to have more control over their fall, which is likely to result in longer falls with longer free-fall and impact durations. The difference may also be due to differences in the instructions provided to controls, where participants in the current study were told to "land safely"" rather than to "land on the ground". The additional instruction to "land safely" might have altered their landing strategies.

SMV$_{\text{max}}$ of the head, chest, and lower back sensors were similar between the analogy and control groups. This finding indicates that participants in both groups experienced similar magnitudes of impact force to their head and trunk. However, SMV$_{\text{max}}$ of the upper arms, wrists, hands, thighs, and left leg were significantly lower in the analogy compared to the control group. This finding suggests lesser impact forces at the upper (arms, wrists, hands: 9 to 13% reduction) and lower (thighs, left leg: 7 to 10% reduction) extremities in the analogy compared to the control group given Newton's second law of motion (i.e., force equals mass times acceleration)[8] .A common fall management strategy for protecting vital body parts, such as the trunk, head, hips, and important organs, is to use the extremities to break/stop the fall (Ruiz-del-Solar et al., 2009). Taken together, our findings (i.e., similar impact force for head and trunk in both groups, with lower impact forces at the extremities for the analogy group) infer participants in the analogy group may have manipulated their extremities in mechanically advantageous ways during the different falls, which not only reduced the impact forces at the extremities but also protected vital body parts like the trunk and the head.

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[8] Participants in the analogy group displayed 12% reduction in right arm, 11% reduction in left arm, 9% reduction in right wrist, 13% reduction in left wrist, 11% reduction in both right and left hands, 7% reduction in right thigh, 10% reduction in left thigh, and 8% reduction in left leg sensors.

Perhaps the functional relationship between the motor analogy ("landing of a feather") and "soft, slow, and silent" characteristics resulted in movement sequences that ultimately changed the geometry of the body, such that impact forces applied to the extremities were reduced and the kinetic energy was spread through a wider contact area–potentially resulting in safer landing.

Our results indicate that the participants in the analogy group had significantly lower left wrist FR ratios (17% reduction) and right wrist FR ratios (11% reduction) compared to participants in the control group. One of the goals for achieving safe landing is to configure the body in a manner that reduces the risk of fracture upon impact (DeGoede & Ashton-Miller, 2002; DeGoede et al., 2003). Our findings suggest that participants in the analogy group were better able to achieve this goal with respect to FR ratios of both wrists. Wrist fractures typically occur when an individual reaches out the arm/arms in a protective response to a fall (Silman, 2003). Our finding highlights the potential impact of using motor analogies to reduce wrist fractures in older adults. Hand impacts are very common in falls (eg., Choi et al., 2015), with wrist fractures the most common injury (Arnold et al., 2016). It is estimated that each year wrist fractures alone cost more than US $500 million dollars (Burge et al., 2007) and can increase the risk of future fragility fractures by 55% within 10 years (Orces & Martinez, 2011).

In alignment with Oladi et al. (under review/Chapter 2), there were no significant interactions between fall direction and group in any of the measured variables. A major challenge for safe landing is to use a landing strategy that is appropriate for the fall direction and environment. The lack of an interaction provides additional evidence that the observed differences between the analogy and control groups were independent of direction of fall. That is, it appears that the motor analogy is likely to have encouraged safer landing regardless of the direction in which the fall occurred. Given the difficulties that older adults encounter in processing information rapidly (Nettelbeck & Burns, 2010) and in learning new skills (Serbruyns et al., 2015; Voelcker-Rehage, 2008), promotion of safer landing via a single analogy, rather than multiple sets of instructions about appropriate technique, is overall preferable.

Oladi et al. (under review/Chapter 2) identified lack of familiarity with the concept of a snowflake landing (i.e., soft, slow, and silent) as a factor that reduced the efficacy of the analogy. Consequently, we sought to use a more familiar analogy ("and like a feather"), which our New Zealand participants (and participants in general, we hope) would be more familiar with. Considering our findings, we deem the motor analogy "land like a feather" to be a more suitable option for promoting safe landing to a wider population.

The experiment was not without limitations. Perhaps most obviously, young adults rather than older adults were sampled. There is little reason to think that our approach will be less effective for older adults; nevertheless, it is vital to broaden the scope to older adult populations. Another limitation is that an experimenter caused the unexpected falls, which could result in variations in the force that was applied to the participant's shoulder. Additionally, participants were aware that they would fall, despite being unaware of when or in which direction they would fall. Furthermore, participants did not face the same direction for all directions of fall (i.e., they faced toward the padded area for forward and leftward falls and away from the padded area for backward and rightward falls). Consequently, although there were only two falls in each direction, participants may have realised that they would fall in one of only two directions, thus compromising the unpredictability of falls design. Finally, sensors were not available to acquire information about impact force to the hip (or the hip FR ratio). Different sensor placements in future experiments can address these issues.

Despite these limitations, this experiment sheds important light on the effects of using a relevant motor analogy (“land like a feather”) to promote safer landing in the event of an unexpected fall. Compared to the control group, participants in the analogy group appeared to avoid significant impact to their vital body parts (i.e., trunk and the head), yet displayed lower SMV_{max} at their upper and lower extremities. These findings provide evidence that a relevant motor analogy potentially can reduce the risk of injury (i.e., particularly wrist fracture) in an accidental fall. Further research is needed to establish the efficacy of safe landing analogies within the older adult population.

Chapter 5. Testing the efficacy of a motor analogy designed to promote safe landing by older adults who fall accidentally: A study protocol for a randomised control study

5.1 Abstract

Introduction. Falling is associated with adverse effects on the health of older people. The majority of research into falls among older people has focused on prevention, with less attention to 'how to fall safely'. Previous research suggests that motor analogies can be used to promote safe landing by young adults; however, the efficacy of this technique for older people remains unknown. This study aims to determine whether a motor analogy is useful for promoting safe falling in the older adult population. **Methods and analysis**. The study adopts a randomised, controlled, single-blinded study design. People 65 years and older will be randomly allocated to a control condition or a motor analogy condition. They will receive a nudge in a forward, backward, or sideways direction (randomised order), which will initiate a fall. The nudge will occur at variable (randomised) time points, so participants will not be aware of when they will fall. Participants in the motor analogy condition will be instructed to 'land like a feather', whereas participants in the control condition will be instructed to 'land safely'. The primary outcome parameters are maximum impact force (normalised by mass) applied to different body segments during impact and fracture risk ratio of wrists and hips. A 2-way MANOVA will be conducted to examine differences between the motor analogy and control conditions as a function of the different variables. **Ethics and dissemination**. The University of Waikato Human Research Ethics Committee (Health 2021#45) has granted ethical approval. Outcomes will be disseminated through publication

in peer-reviewed journals and presentations at conferences. **Trial registration**. Australian New Zealand Clinical Trials Registry ACTRN12621001189819. Registered on 6 September 2021.

Keywords: Older adults; Falls; Safe landing; Motor analogy

5.2 Introduction

Accidental falls can adversely affect the health of older people and are second only to traffic incidents as the most common cause of death (Chou et al., 2021). Millions of older adults fall each year. Not only are falls associated with high personal costs, such as reduced well-being, but also health care sectors are heavily burdened (Arnold et al., 2016; Greenberg et al., 2021). For instance, every year in New Zealand 18% of the total cost of injury is due to falls (Deverall et al., 2019). The government estimates that by the year 2025 fall-related injuries will cost the country around $418 million dollars annually (Barry & Kaye, 2016). Researchers and health care professionals have investigated various interventions to reduce the occurrence of falls; nevertheless, it is estimated that around 30-60% of older adults fall unexpectedly annually (Rubenstein, 2006). The complex nature of falls, combined with intrinsic (e.g., impaired balance, reduced cognitive status, poor vision, etc.) and extrinsic (e.g., slippery floors, loose rugs, poor lighting, etc.) risk factors, increases the difficulty of establishing effective fall prevention interventions (Ambrose et al., 2013).

In a systematic review and meta-analysis of multifactorial fall prevention programmes, Hopewell et al. (2020) found that prevention programmes may reduce fall rates, but have little to no effect on other fall-related consequences, such as fractures, hospital admission or medical attention and health-related quality of life (Hopewell et al., 2020). To address the multidimensional nature of falls and to mitigate their negative effects on health, complementary approaches are needed to accompany fall prevention interventions. Consistent with this position, a small number of researchers have proposed that fall-related injuries can be reduced by learning ‘how to land safely’ when a fall occurs (Hsieh & Sosnoff, 2020; Moon & Sosnoff, 2016). A systematic review by Moon and Sosnoff (2016) revealed that only thirteen studies have investigated safe landing techniques, and that most of the studies (12 out of 13) tested young adults rather than older adults. Landing techniques varied according to the direction of fall. For instance, to land safely from sideways falls, participants were instructed to use the martial arts technique of roll and slap (Groen et al., 2010; Groen et al., 2007; Groen et al., 2008; Weerdesteyn et al., 2008). Different techniques were instructed for forward (e.g., “land with a slightly flexed elbow angle”) (Lo et al., 2003) and backward (e.g., “bend the hips and knees”) falls (Tan et al., 2006).

Older adults generally learn more slowly than younger adults and fail to reach similar levels of expertise (McNay & Willingham, 1998; Serbruyns et al., 2015; Voelcker-Rehage, 2008), so their capacity to learn a different assortment of safe landing techniques that can be used appropriately when falling is questionable. For example, age-related declines in the ability to store and manage information (via working memory) (Light & Anderson, 1985; Voelcker-Rehage, 2008) make comprehension of explicit instructions (e.g., how to land safely) more challenging during learning. Additionally, older adults generally display impaired reaction times (Hultsch et al., 2002; Mendelson et al., 2009), which increases the difficulty associated with selecting and executing the appropriate technique during a fall. It takes approximately 0.3 seconds to recover balance when falling from standing height, with impact occurring after approximately 0.7 seconds if recovery is not possible (Le Goic et al., 2018) so there is minimal opportunity between the balance recovery phase and impact with the ground (i.e., 0.4 seconds) for older people to explicitly choose (and use) an appropriate safe landing technique.

Consequently, an approach to landing safely is required that involves less explicit information about technique and can be processed more quickly (i.e., less resource demanding). Motor analogies may achieve this goal. Analogies leverage a concept that is already well known by the learner in order to convey the complex structure of the motor skill (Liao & Masters, 2001; Masters, 2000). Motor analogies are often used to teach movement skills to novices by comparing the movements with a similar, well-known concept, such as, “imagine you are putting a cookie in a cookie jar on a high shelf” (for a basketball free-throw) (Lam et al., 2009b) or “strike the ball while bringing the bat up the hypotenuse of a triangle” (for a table tennis topspin forehand) (Liao & Masters, 2001). Such analogies are thought to promote implicit motor learning, which seeks to minimise accrual of conscious knowledge of the underlying rules governing the mechanics of movements (Masters, 1992, 2000). Implicit motor learning has been shown to impose fewer demands on cognitive resources than explicit motor learning (Masters, 1992; Masters et al., 2020; Steenbergen et al., 2010) and, importantly, has been shown to result in better learning by older adults (Chauvel et al., 2012; Tse, Wong, et al., 2017).

Motor analogies have been shown to be beneficial for skill learning in the older adult population, resulting in preserved skill level over time and robust performance under dual-task conditions (Tse, Wong, et al., 2017). They have also been used in rehabilitation settings to improve dynamic balance (Kim et al., 2021) and walking by Parkinson patients (Jie et al., 2016) and stroke patients (Kleynen et al., 2014). These advantages have been attributed to the simplicity of retrieving analogies from memory (Donnelly & McDaniel, 1993) and the role they play in rapidly deploying attention during movement (Koedijker et al., 2011). The potential for analogies to depute for explicit instructions, facilitate development of mental representations in long term memory (Meier et al., 2019), reduce the demands associated with processing information (i.e., lower reliance on working memory) (Masters & Liao, 2003; Masters et al., 2020; Meier et al., 2020; Poolton & Masters, 2014) and hasten processing time (Masters, 2000) makes them a compelling choice for learning safe landing strategies.

Masters et al. (2018) sought to develop a simple motor analogy that promotes safe landing in the event of a fall. They conducted focus group discussions with older fallers, physiotherapists, occupational therapists, martial artists, gymnasts, dancers, parkour enthusiasts, and health and safety experts. Analysis of the focus group transcripts revealed three common themes that were used to describe safe landing: 'soft', 'silent', 'slow'. Based on these themes, two motor analogies with potential to promote soft, slow, silent landing were identified: *land like a snowflake* or *land like a feather*. In a previous experiment, we found that instructions to 'land like a snowflake' caused young adults to land more safely than control instructions ('land on the ground') when self-initiating falls (Oladi et al., 2019). In a second experiment, we found that instructions to 'land like a feather' caused young adults to land more safely than control instructions ('land safely') when falling unexpectedly (Oladi et al., 2020). To evaluate the quality of the landings, we attached inertial measurement units (IMU) to different body segments of participants and extracted measures that we used to calculated impact force and wrist fracture risk ratio. Participants allocated to the motor analogy condition landed with less force and were less likely to fracture a wrist (i.e., lower wrist fracture ratio) than participants allocated to the control condition, regardless of fall direction (forward, backward, sideways). These results suggest that participants allocated to the motor analogy condition were better able to adapt their movements to land safely.

One of the main limitations of these studies was that the motor analogies were tested in a young population; it is yet to be seen whether motor analogies can be used to promote safer landing by older people. It is well-known that ageing is associated with progressive loss of functional capacity (Sampaio et al., 2020). For instance, older people often show a decline in functional balance (Alexander, 1994), ability to learn skills (Raz et al., 2000), and motor planning (Wang et al., 2020). Hence, to account for individual differences in balance status in the proposed study, the primary researcher (a physiotherapist) will administer a short version of the Balance Evaluation Systems Test (Mini-BESTest), which is a clinical balance tool used for identifying balance dysfunction (Horak et al., 2009). Participants will also complete an Activities-specific Balance Confidence (ABC) scale, which is a valid and reliable self-estimation tool for assessing the balance status of older adults with respect to falling (Myers et al., 1998; Powell & Myers, 1995). Furthermore, the Movement Specific Reinvestment Scale (MSRS; Masters et al., 2005) will be administered to gain insight into individual differences in movement planning; the propensity that older people have for movement specific reinvestment has been linked to a need for more time to "plan" future movements (Uiga et al., 2020). Alongside the biomechanical variables used for assessing safe landing, the assessment of functional balance (Mini-BESTest, ABC scale) and propensity for reinvestment (MSRS) will provide valuable information to understand the effectiveness of our motor analogy with respect to older adults.

The goal of this research is to determine whether older people land more safely (i.e., with less risk of injury) when they are encouraged to use a motor analogy, 'land like a feather', if they fall. Based on our previous experiments, we hypothesise that:

- Maximum acceleration (impact force normalised by mass) of various body segments (upper arms, wrists, hands, hips, thighs, and legs) will be significantly lower across all fall directions (forward, backward, sideways) in the motor analogy condition compared to the control condition

- Fracture risk ratio (ratio of force at impact divided by the load necessary to cause a fracture) of the hips and wrists will be significantly lower in the motor analogy condition compared to the control condition

5.3 Method

5.3.1 Study design

This study is a randomised, controlled, single-blinded study for participants aged 65 years and older. After assessment of cognition, functional balance, and physical activity readiness, participants will be randomly allocated to a motor analogy condition or a control condition. The start and end date for data collection are anticipated to fall between 01/07/2022 and 30/12/2022.

5.3.2 Population

The study population will be older adults without leg and/or foot amputation who are able to stand and ambulate without walking aids. Participants will be required to have the ability to stand without help for 1 minute and to walk without a walking aid for 6 meters. Furthermore, all participants should be able to communicate in English, with no psychiatric or neurological impairments that prohibit participation. To screen for dementia, a score above 3 on the Mini-Cog test will be required. The Mini-Cog test has been validated for dementia screening (a score between 1 to 3 is considered "possibly impaired", and a score above 3 is considered "probably normal") (Borson et al., 2003). To screen for physical activity limitations, the researcher will administer a physical activity readiness questionnaire (PARQ$^+$). The PARQ$^+$ offers safe screening of older adults prior to engaging in exercise or physical activity

(Cardinal & Cardinal, 2000; Cardinal et al., 1996). Participants who answer 'yes' to 2 or more of the PARQ$^+$ questions (i.e., require a doctor consultation for physical activity) will be excluded.

5.3.3 Randomisation procedure and Blinding

5.3.3.1 Randomisation procedure

All participants who fulfil the inclusion criteria will be randomly assigned to either the motor analogy condition or the control condition using a random generator computer programme. The randomization procedure (and outcome) will only be available to the lead investigator, who will not share this information with the participants or the research assistant.

5.3.3.2 Blinding

The research assistant who will be delivering the nudge that causes the participant to fall onto the padded surface will be blind to whether the participant has been allocated to the motor analogy condition or the control condition. Participants will not be informed about the experimental condition to which they have been assigned (motor analogy or control). Participants will also be blind to the direction in which they will be nudged (forward/backward/sideways).

5.3.4 Measurements and instrumentation

A 2D video camera (Canon, 25 frames per second) and Delsys Trigno^{TM} (Delsys Inc., Natrick, MA) inertial measurement units (IMU) will be used for data collection. The video camera will be positioned 3 meters from the left side of participants on a tripod (height 1.3 meters). The researcher will place IMU sensors on 15 different body segments. Acceleration data from the IMU sensors will be recorded at a frequency of 148.15 Hz using EMGworks Acquisition software (Version 4.5.4). A hand-held dynamometer (MyoMeter, M550; range:

0-50 kg) will be used to record the force applied when nudging participants to initiate each fall.

5.3.5 Procedure

Eligible participants will be invited to the human performance science lab at the University of Waikato for a data collection session that will last around 70-80 minutes. Figure 19 provides a flow diagram to illustrate the stages of data collection. Each consecutive component of the diagram is described in the subsequent section (e.g., Demographics, Questionnaires, Sensor placement etc).

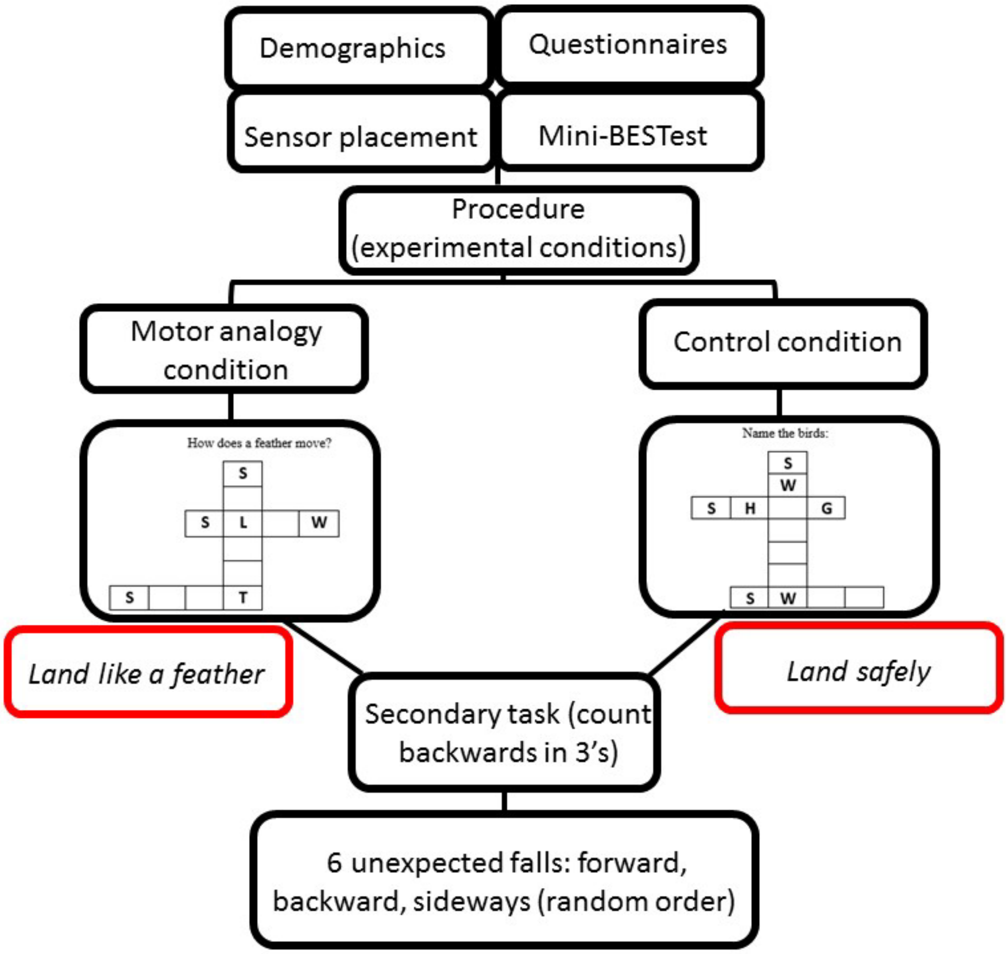

Figure 19. Flow diagram of the data collection session.

5.3.6 Demographics

At the beginning of the data collection session, demographic information will be collected: age, gender, height (cm), mass (kg), history of fall, walking aids, and educational level.

5.3.7 Questionnaires

Two psychometric questionnaires will be administered:

1. Activities-specific Balance Confidence (ABC) scale: This 16-item scale assesses confidence in ability to maintain balance during a range of indoor and outdoor functional activities (e.g., “How confident are you that you will not lose your balance or become unsteady when you walk around the house?”). The items of the scale are rated from 0% (lowest level of confidence) to 100% (highest level of confidence). This scale is a valid and reliable tool for measuring balance confidence in older adults (Schepens et al., 2009).
2. Movement Specific Reinvestment Scale (MSRS): This scale comprises 10 items divided into two subscales. The Conscious Motor Processing subscale measures propensity to consciously control movements (e.g., “I try to think about my movements when I carry them out”). The Movement Self-consciousness subscale measures propensity to monitor “style” of movement (e.g., “I am self-conscious about the way I look when I am moving”). The items are rated on a 6-point Likert scale from strongly disagree (1) to strongly agree (6). Thus, cumulative scores range from 10 to 60, with higher scores reflecting higher propensity for movement-specific reinvestment. The MSRS has been shown to have high internal consistency and test–retest reliability (Malhotra et al., 2015).

5.3.8 Sensor placement

Fifteen IMU sensors will be attached over the following body segments using double-sided tape: head, chest (aligned with the sternum), lower back (aligned with L3), upper arms (dorsal), wrists (dorsal), hands (dorsal), hips (greater trochanter) thighs (lateral), lower legs (lateral). Figure 20 demonstrates the placement of the IMU sensors on the participants.

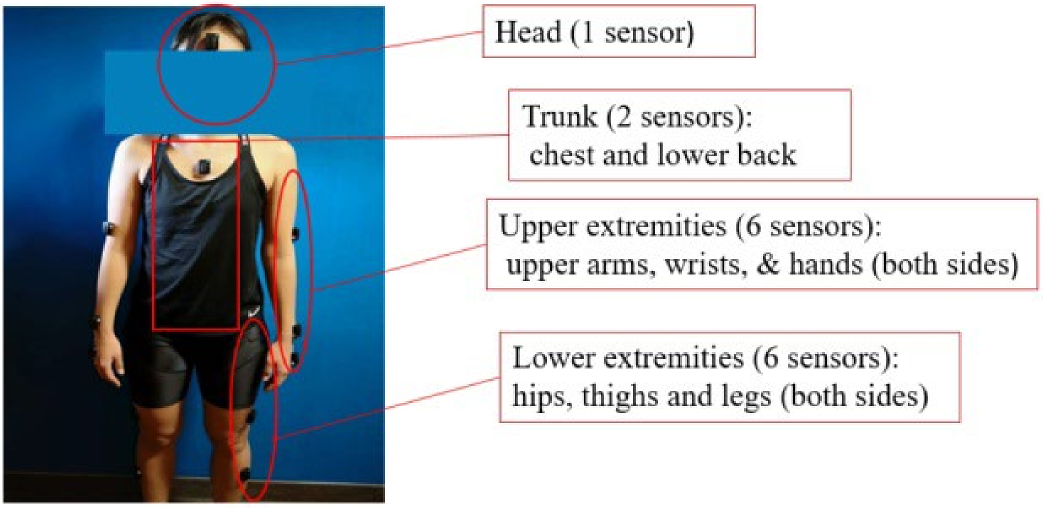

Figure 20. Positioning of inertial measurement units on different body segments.

5.3.9 Mini-BESTest

The researcher will administer a short version of the Balance Evaluation Systems Test (Mini-BESTest), which is a standardized clinical balance tool used to assess functional balance (Marques et al., 2016; O'Hoski et al., 2015; Padgett et al., 2012; Sibley et al., 2015). This test has a maximum score of 28 points, with higher scores indicating better balance.

5.3.10 Crossword puzzle

Participants in the motor analogy condition will be required to complete a three-word crossword puzzle designed to prime them about how feathers land on the ground: soft, slow, silent (Figure 21, Panel A). Participants in the control condition will be asked to complete a similar crossword puzzle that uses names of birds as neutral primes: swallow, shag, swan (Figure 21, Panel B).

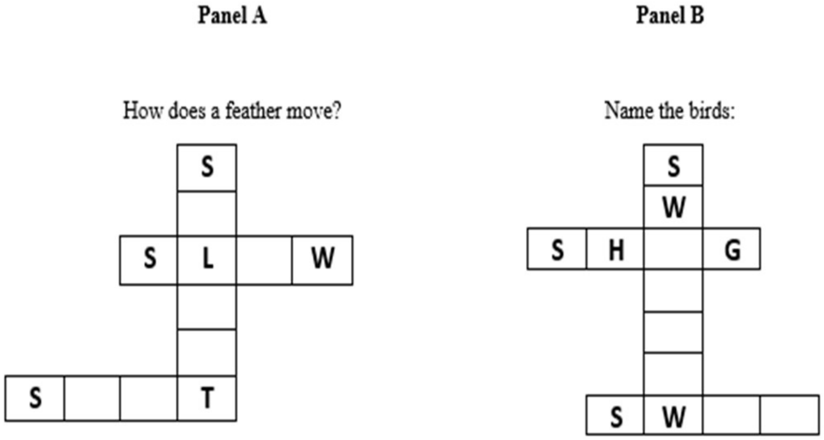

Figure 21. Crossword puzzles for priming participants. Panel A: soft, slow, silent. Panel B: swallow, shag, swan.

5.3.11 Experimental conditions

Participants in the motor analogy condition will be instructed to "land like a feather", whereas participants in the control condition will be instructed to "land safely". They will stand on a surface-level platform (27cm x 32cm) facing a fully padded landing area. A research assistant will apply a gentle impulse (nudge) to the left shoulder of participants, who will be instructed to fall in the direction in which the nudge is applied. If the nudge does not yield a fall the trial will not be repeated (the subsequent trial in the sequence will be initiated). The nudge will be applied in a forward, backward, or sideways direction. Order of fall direction will be randomised using a random order generator. The research assistant will be blinded to condition (motor analogy/control) and each nudge will be applied using a hand-held dynamometer. The load cell will be placed on the participant's shoulder and the research assistant will apply a nudge via the surface of the dynamometer. The integral of the force with respect to time will be calculated (i.e., impulse). The impulse required to initiate each fall will be recorded and used as a covariate in the statistical analysis to control for potential differences in nudge force. To reduce the likelihood that participants will anticipate the nudge, they will be required to count backwards in 3's during each trial (a concurrent secondary task). Nudges will occur at variable time points during counting. To familiarise participants with the experimental procedure, one practice trial will be conducted. The direction of the fall during the practice trial (forward, backward, sideways) will be randomised across participants. Afterwards, the experimental procedure will be repeated twice (with a different order of falls on each occasion). Hence, each participant will fall six times during the experimental procedure.

Prior experience of activities, such as dancing, gymnastics, sports (e.g., rugby, surfing, parkour, etc.), martial arts (e.g., taï-Chi, judo, taekwondo, etc.) may affect participants' landing strategies. Thus, after data collection, the experimenter will record information regarding participants' experience of these activities (e.g., type of activity, years of participation, level of ability, type of fall strategy learned etc). This information will be used to support interpretation of the findings of our study.

5.3.12 Public involvement Statement

Initially, people with an interest in falling (e.g., older adults, health care professionals, physiotherapists, fall experts etc) were consulted about safe landing via focus groups. Key themes were used to design motor analogies with potential to facilitate safe landing in the event of a fall. After testing the efficacy of the motor analogies using young adults, we consulted with fall prevention leaders in New Zealand about testing the analogies in older adults. We also engaged with the community through fall prevention classes and retirement homes, with a goal to determine the level of interest that older adults have in safe landing, and to take their feedback into account when designing the proposed study. We plan to disseminate our findings among fall prevention leaders and interested older adults who have provided us with their contact information.

5.3.13 Primary outcome

The acceleration data recorded by the IMUs will be exported in excel format and processed using Matlab (R2017b, MathWorks Inc., Natic, USA). Start of fall (Start) and end of fall (End) will be extracted from a one-dimensional signal magnitude acceleration vector (SMV) of the lower back unit. Figure 22 displays exemplar data from a backward fall.

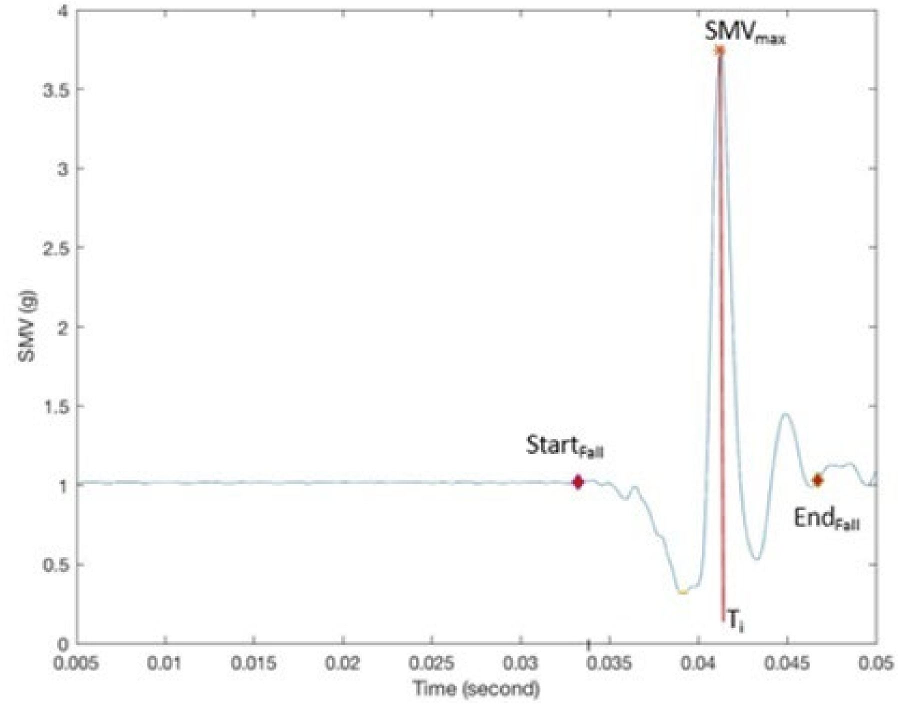

Figure 22. Signal magnitude vector (SMV) of the lower back inertial measurement unit during a backward fall. Start of fall (StartFall), time of impact (Ti) and end of fall (EndFall) are displayed.

To determine the beginning and end of a fall, a threshold will be calculated using a 100 ms moving window applied to the SMV data. Subsequently, the relative standard deviation (RSD) of the windows will be calculated. The generated RSDs will be averaged and used as a threshold for identifying the start and the end of the fall for each trial. RSD has previously been used to compute thresholds for identifying cancer cells (Ericson et al., 2003), optic-nerve signals (Hay & Chesters, 1972), and in various human motion dynamics studies (Venture et al., 2009). The start of the fall will be defined by the SMV crossing the threshold into the trench preceding its maximum value (SMV_{max}) (Degen et al., 2003; Kangas et al., 2007; Kangas et al., 2011). The end of the fall will be defined by SMV crossing the threshold after it reached its maximum value (SMV_{max}). The start and end of fall identification method will be verified using the video recordings. Maximum acceleration (SMV_{max}, g) will be extracted from all 15 IMUs.

The fracture risk of different body parts depends on the severity of the impact and the capacity of the bones to resist the impact (Groen et al., 2006). Therefore, fracture risk ratio will be defined as the ratio of force at impact divided by the load necessary to cause a fracture (DeGoede et al., 2003; Melton 3rd & Cummings, 1987). To calculate the force applied to the wrists and hips, the SMV of the wrist units at time of impact will be multiplied by the scaling factors for the forearm and femoral head mass (%mass) provided by Dumas et al. (2007), and then multiplied by 9.807 (convert g to m/s^2). Finally, the force applied to the participant's wrist and hip IMUs will be divided by the load required to fracture the radius bone and femur head based on cadaveric studies (Augat et al., 1996). This measurement does not include the direction of force applied to the wrist and hips; hence, it is an estimation of the fracture risk ratio.

5.3.14 Sample size

Sample size estimation was conducted using a customisable statistical spreadsheet (xSampleSize.xlsx, www.sportsci.org). Sample size requirements were calculated from standard two-tailed hypothesis equations using an 80% power ($\beta = 0.20$), and 5% significance level ($\alpha = 0.05$). We used data from our previous research with young adults (smallest difference=0.22 m/s^2; within subject SD= 0.28 m/s^2; between subject SD=0.32 m/s^2) for the calculations, with maximum acceleration (impact force normalised by mass) as our primary outcome. The calculations resulted in a minimum group size of 32 participants per condition. To account for 20% attrition rate, this study aims to recruit 38 participants per condition.

5.3.15 Data integrity and analysis

The lead investigator will monitor data integrity by regularly examining data files for omissions and errors. The demographics, questionnaire scores, and outcome measures will be used to compare the conditions (motor analogy vs control). The means and SD of variables will be calculated and differences between the conditions will be examined using IBM SPSS Statistics 25 (IBM SPSS Statistics Software). A two-way between-groups multivariate analysis of variance (MANOVA) will be conducted to explore the effect of condition (motor analogy, control) and fall direction (forward, backward, sideways) on the following variables of interest: SMV_{max} (g) of the 15 IMUs located on the body segments displayed in Figure 2. Significant main effects and interactions will be further scrutinised using analysis of variance (ANOVA) of variables separately. To control for the multiplicity problem caused by conducting multiple statistical tests, the Benjamini–Hochberg (B-H) method will be used to control the alpha level using successive modified Bonferroni corrections (Benjamini & Hochberg, 1995). All participants will be included in the analyses and will be given an anonymous participation ID to protect confidentiality. Only study investigators will have access to the raw data. All datasets used or analysed during this study will be available from the corresponding author upon reasonable request.

5.3.16 Ethics and dissemination

The University of Waikato Human Research Ethics Committee (Health 2021#45) approved the study protocol. The results of the trial will be submitted to international peer-reviewed journals and presented at conferences.

5.4 Discussion

Falls can cause significant health problems for older adults and can result in frailty, immobility, and decline in functional ability. The use of motor analogies to promote safe(r) landing is promising approach that has potential to reduce the severity of injuries that occur during accidental falls. In this paper, we described the methodology for a randomised controlled single-blinded study that investigates the efficacy of using a motor analogy to promote safer landing by older adults.

The project requires work with older people; hence, extreme caution is required to ensure the safety of our participants. One of the conditions of participation in this study is that participants can walk without assistance for at least 6 meters (twice the length of the 3-meter walk test in the Min-BESTest) in a controlled laboratory environment. Older people who cannot walk for 6 meters without assistance, or stand without a walking aid for at least one minute, will be excluded from the study. Thus, the exclusion criterion requires the participants to be comfortable when walking and standing independently. Additionally, we will administer the PARQ$^+$ and participants who answer 'yes' to 2 or more of the questions will be excluded. The PARQ$^+$ is sensitive to underlying conditions, such as osteoporosis, cardiovascular problems, respiratory disease, previous surgery, arthritis, chronic conditions, high blood pressure, back problems, stroke, etc. Therefore, if a participant is not in a healthy physical condition, they will not participate. This approach therefore excludes frail older adults from our participant pool, which is necessary due to the risk of injury associated with our fall intervention.

In studies that examine older people, criteria often are designed to exclude those with cognitive impairments. However, previous studies have reported that motor learning interventions can be effective for people with cognitive and/or communicative impairments (Jie et al., 2018). In this study, we therefore attempt to include a sample that is more representative of older adults. A mini cognition test (Mini-Cog) will be administered to assess the likelihood of dementia. A score between 1 to 3 is considered “possibly impaired”, and a score above 3 is considered “probably normal” (Borson et al., 2003). Only participants who score below the cut-off point of 3 will be excluded; hence, this will provide us an opportunity to assess the effect of motor analogies on older adults within different ranges of cognition, which is consistent with our ultimate goal to develop a simple solution for safe landing that is applicable to the widest possible audience.

Chapter 6. General discussion

Approximately one in three individuals over the age of 65 is expected to experience a fall annually (Tromp et al., 2001). Considering the rapid growth of the ageing population (older adults will reach 16% of total world population in the next 30 years), the burden of falling in this population is a major public health problem (Abreha et al., 2021). Fall prevention programmes are a common approach for mitigating fall-related injuries. However, compliance to fall prevention interventions is often a problem. For instance, the Otago Exercise Programme (OEP), is a globally embraced evidence-based exercise programme, which requires participants to complete balance and strength exercises 3 times a week for half an hour, over a period of 12 months. A systematic review of OEP revealed low compliance to the programme with 30% of the participants dropping out after 2 months and only 36.7% of the participants adhering to the full intervention (Martins et al., 2018). Additionally, although fall prevention interventions can reduce the frequency of falls, they have little or no effect on other fall-related outcomes (i.e., fractures, hospital admission, medical attention, quality of life) (Hopewell et al., 2020). One complementary solution for reducing fall-related injuries is to learn how to land safely. However, safe landing from falls is challenging to learn because it requires the faller to have mastered multiple landing techniques and to implement the appropriate technique in a short amount of time. This thesis sought to explore motor analogies as a practical solution for achieving safe landing (i.e., less risk of injury). The main findings of this thesis are presented in the following section.

6.1 Main findings

Chapter 2 investigated the efficacy of using a motor analogy that embodied characteristics associated with safe landing (i.e., soft, slow silent etc.) as suggested by (Masters et al., 2018).

Young adults were instructed to “land like a snowflake” (motor analogy) or to “land on the ground” (control) after self-initiating falls in different directions (i.e., backward, forward, sideways). Biomechanical variables, including free-fall duration, impact duration, and maximum acceleration (SMV_{max}) applied to lower back and wrists, were measured. Regardless of fall direction, participants instructed to use the motor analogy displayed longer fall and impact durations, and less SMV_{max}, compared to participants in the control condition. These findings suggest that using a motor analogy may reduce the severity of injuries that can be expected should a fall occur in real life.

Some participants reported a lack of familiarity with the characteristics of snowflakes, which inspired the experiment that was reported in Chapter 3. Three online experiments were conducted to investigate whether participants associated a feather approaching the ground with safe landing characteristics. Participants were primed with an image of a feather (Experiment 1, young adults) or the words “land like a feather” (Experiment 2, young adults; Experiment 3, older adults) and then completed a lexical decision task in which they discriminated words related to safe landing, words that were antonyms of the words related to safe landing or words unrelated to landing. Discrimination responses were generally more rapid for words related to safe landing (i.e., soft, slow, silent etc), suggesting that a feather analogy may be appropriate for both young and old adults because it is likely to evoke mental representations of soft, slow, silent movements associated with safer landing.

The next step was to assess the efficacy of a feather analogy for landing from falls in unexpected directions. Chapter 4 therefore tested the effect of the motor analogy, “land like a feather”, on landing characteristics when participants fell in different directions (i.e., backward, forward, leftwards, rightwards). Compared to participants instructed to land safely (control), young adults instructed to use the motor analogy landed with less SMV_{max} at their extremities regardless of fall direction.

Finally, our aim was to explore the efficacy of the feather analogy in older adults. Chapter 5 describes a protocol for a randomised controlled study investigating the motor analogy (‘land like a feather’) in the older adult population. The study gained ethics approval and has been registered in the Australian New Zealand Clinical Trial Registry. However, due to Covid-19 restrictions data collection has been delayed.

6.2 Theoretical implications

Landing safely when a fall occurs is not easy: falling in different directions requires different safe landing strategies (Moon & Sosnoff, 2016), safe landing techniques can only protect specific body parts (i.e., rotating sideways while falling reduces the risk of head impact, but increases the risk of hip impact (Komisar & Robinovitch, 2021), and there is little time before impact with the ground (i.e., 0.4 seconds) to choose and use an appropriate safe landing technique. Safe landing techniques are used in several physical activity domains, such as dancing (Gorwa et al., 2019), gymnastics (Marinšek, 2010), parkour (Puddle & Maulder, 2013), and martial arts (van der Zijden et al., 2012). For instance, parkour practitioners are able to reduce kinetic forces associated with high injury risk when landing on the ground (Puddle & Maulder, 2013; Standing & Maulder, 2015). Nevertheless, often the landing technique is tailored to the specific activity, requires practice, and can be physically demanding. Hence, implementation of these techniques by older adults may not be a viable option.

Additionally, ageing causes impaired cognitive and motor responses that lessen the ability of older adults to land safely (Harrington & Haaland, 1992; King et al., 2013; Nettelbeck &

Burns, 2010). Motor analogies are thought to free up cognitive resources (Maxwell et al., 2003), as evidenced by studies showing that learning via motor analogies results in stable motor performance during circumstances that involve dual-tasking, physiological stress or decision making) (Bobrownicki et al., 2015; Lam et al., 2009b; Law et al., 2003; Liao & Masters, 2001; Masters et al., 2008; Poolton et al., 2006; Poolton et al., 2007b; Schlapkohl et al., 2012; Tse, Fong, et al., 2017; Tse & Masters, 2019; Vine et al., 2013). Thus, this method has potential to be particularly useful for people who may display deficits in motor control, such as older adults, children, stroke patients, individuals with Alzheimer's and Parkinson's disease (Masters et al., 2004). Previous research suggests that motor analogies are easy to retrieve from memory (Donnelly & McDaniel, 1993), can rapidly deploy attention during movement (Koedijker et al., 2011), and may even speed up the motor learning process (Zacks & Friedman, 2020). The results of the experiments presented in this thesis point to the effectiveness of using motor analogies to achieve safe landing with respect to biomechanical measures that reflect the magnitude of loads applied to the body at impact. The efficacy of the analogy was evident for different fall directions (i.e., forward, backward, sideways), which makes the approach especially useful for landing safely, considering that different fall directions require different landing techniques. This thesis provides evidence that an easy to envision motor analogy can promote desired movement patterns that ultimately achieve safe landing.

From a cultural perspective, the thesis expands our knowledge regarding the relevance of the analogy to the culture in which it is used. During the course of the research, the "land like a snowflake" analogy replaced with "land like a feather". This change was made to better communicate the underlying concept of the motor analogy to participants from the North Island of New Zealand, who seemingly had little experience of snow precipitation. Motor analogies map new knowledge (target) to a well-known concept (base), so the learner can organise the new knowledge by structuring the information based on the well-known concept (Starr et al., 2018). In the quest to develop a suitable motor analogy (more culturally relevant and meaningful) for safe landing, we demonstrated in Chapter 3 that the landing of feather (base) is linked to descriptors identified by Masters et al. (2018) as relevant for safe landing (target). Hence, two important processes that are necessary for an analogy to function effectively (i.e., retrieving information from memory and mapping relationships between the base and the target domains (Hummel & Holyoak, 1997) appears to be satisfied by using the motor analogy “land like a feather”.

Moreover, this research adds to our knowledge regarding the implication of using different types of analogies (i.e., heuristic, single metaphor, multiple analogies). Traditionally, motor analogies are designed to guide a specific movement by using “a simple biomechanical metaphor” (Liao & Masters, 2001, p. 308; Masters, 2000). Data from focus group interviews conducted by Masters et al. (2018) suggested that a single biomechanical strategy is unlikely to be efficacious for different types of falls (e.g., forward, backward, sideways) or conditions (e.g., slip, trip, bump, collapse) and environments (e.g., bathroom, sidewalk, stairs). Various analogies were recommended, such as: “fall like you are holding a baby”, “fall like a jellyfish”, “fall like an octopus”, and “tuck and roll”, which means that different biomechanical analogies would be necessary for different fall directions (i.e., “tuck and roll” may work for a sideways fall, but not for forward or backward fall). However, analogy instructions can be designed to provide a “rule of thumb” or heuristic that conveys the fundamental concepts of the to-be-learned skill (Masters, 2000; Todd & Gigerenzer, 2000). Consequently, the aim of the thesis was to develop a single motor analogy that conveys the fundamental concepts for safe landing in a "rule of thumb" or heuristic manner that promotes degeneracy.

Degeneracy is a phenomenon often referred to in the field of biology, which refers to structurally different elements performing a similar, but not identical, function to achieve the same output (Edelman & Gally, 2001; Mason, 2015). Using this inherent phenomenon enables an individual to attain the same performance outcome by adjusting the degrees of freedom of their various structural components (Seifert et al., 2016). Degeneracy is crucial in acquiring a new motor skill, it encourages the learner to try out different movement patterns and adapt the various components of the human movement system to suit the task and environmental conditions (Davids et al., 2003; Tan et al., 2012). Studies exploring the role of degeneracy in motor learning have provided evidence for degeneracy (i.e., achieving the same goal by using different patterns of coordination) and its benefits with respect to adjusting to different constraints in breaststroke swimming (Komar et al., 2015), cricket batting (Pinder et al., 2012), and tennis groundstrokes (Lee et al., 2014). In line with these studies, it is likely that the motor analogies used in this research did not guide the faller towards specific movement patterns, but encouraged the faller to adjust the motor apparatus to achieve the same outcome (e.g., landing safely) regardless of fall direction or fall type. In the experiments presented in Chapters 2 and 4, participants instructed to use a motor analogy when landing displayed characteristics reflective of safer landing than control participants, in all directions of fall (forward, backward, and sideways). In other words, no matter the direction of fall the participants were able to achieve the same outcome (less magnitude of loads applied to their extremities) compared to the control participants. It appears that motor analogies may promote sensorimotor degeneracy, such that, regardless of the direction of fall, the person falling adapts their movements effectively and efficiently to land with less impact force. However, this explanation was not specifically tested in the thesis. Future research should investigate inter-joint relationships and movement variability associated with the motor analogy to establish whether fallers are more adept at deploying different motor patterns in order to land safely. Additionally, previous research has shown that using instructions like, “run softer”, “make your footfalls quieter” (Creaby & Franettovich Smith, 2015), or “make a quieter sound when you land” (Phan et al., 2017) result in decreased impact force, loading rates, and maximum acceleration. Instructions to “land more softly” or “land more quietly” when jumping from a 300 mm height have also been shown to significantly reduce peak vertical ground reaction forces (McNair et al., 2000; Prapavessis & McNair, 1999). Thus, it is not unreasonable to assume that providing instructions, such as land slowly, land softly, or land silently have the capacity to promote safer landing. Future studies need to assess the effect of each of the characteristics associated with safe landing separately, in order to determine the extent to which each contributes to the efficacy of the analogy. In the following section, the practical implications of using motor analogies for safe landing is discussed.

6.3 Practical implications

Practice plays an important role in improving motor performance. Active training for improvement in motor tasks, results in expert level performance (Ericsson, 2008). Motor analogies are often practiced in multiple trials (e.g., 6 blocks of 30 trials—Tse, Wong, et al., 2017), sometimes over a number of days (e.g., 6 blocks of 40 trials over two consecutive days-Lam et al., 2009a). Learning specific safe landing techniques also requires multiple practice sessions (e.g., 5 weekly sessions of 45 minutes—Moon et al., 2019; 3 sessions over 2 weeks-Groen et al., 2010). In this research no practice occurred, and participants were asked to land on mattresses only once (Chapter 2) or twice (Chapter 4) in different directions (backward, forward, sideways), shortly after they were exposed to the motor analogy. Despite, the lack of practice, participants receiving the analogy showed biomechanical differences indicating a safer fall compared to their counterparts. Congruent with these findings, Zacks and Friedman (2020) found that a group receiving an analogy for the first time displayed mastery gains and improvement in co-articulation, which are features associated with hours of practice. It is unclear whether multiple practice trials (using the motor analogy) would have improved the participants' landing. Nevertheless, due to the risk of injury associated with falling, practicing multiple falls is not a feasible option for older adults. Hence, these findings suggest that using motor analogies may be a practical method to promote safe landing for the older adult population without requiring multiple practice trials.

The ability to land with less risk of injury without needing multiple practice sessions, or adhering to long term interventions, is an important potential outcome implied by the findings reported in this thesis. Fall prevention interventions can suffer from low participation rates (Merom et al., 2012), lack of adherence to the full intervention (Martins et al., 2018) and community barriers (i.e., poor access, poor transportation, long travel distances, etc.) (McMahon et al., 2011). A motor analogy, on the other hand, can easily be broadcasted via posters, media advertisements, and brochures. In turn this can result in reaching a wide audience, particularly those who do not have easy access to urban amenities (i.e., geographical constrains, living in rural areas, isolation, etc.). For instance, a simple motor analogy can be publicized in a variety of locations, such as fall prevention programmes, rehabilitation centers, hospitals, shopping malls, churches, etc., and reach many in the community even those in remote rural areas.

Additionally, motor analogies for safe landing might provide a solution for reducing fear of falling, which is an independent predictor of falling (Pena et al., 2019) and negatively influences quality of life (Schoene et al., 2019). Anxiety and fear can cause individuals to consciously control their movements (Baumeister, 1984; Masters, 1992), which causes them to process previously acquired explicit knowledge (e.g., explicitly taught landing instructions). This in turn can disrupt automated processes of motor performance. Masters described this phenomenon in the theory of reinvestment (Masters, 1992; Masters & Maxwell, 2008). It can be argued that older people who are aware that using the analogy will help them to land more safely will display less fear of falling. Therefore, negative consequences associated with fear of falling (e.g., lack of physical activity, reduced social interactivity), are likely to be mitigated.

Moreover, due to the simplicity of using motor analogies, this approach can be validated by studying falls in real-life settings, such as nursing homes, hospitals, and rehabilitation centers. For instance, falls recorded on cameras in nursing homes (Choi et al., 2015) can be used to compare fall outcomes between nursing homes that have exposed their residents to motor analogies and those that have not. Additionally, clinical settings and fall prevention programs can also be used to validate motor analogies as a means for safe landing. For example, in New Zealand fall prevention interventions funded by the Accident Compensation Corporation (e.g., Strong & Stable, Steady as you Go, Sit & be Fit, etc.) potentially could incorporate motor analogies in their programmes and monitor fall-related injuries.

Taken together, this research project generated a small amount of evidence suggesting that it may be feasible to use motor analogies as a practical solution to help people land with less risk of injury when they fall. The findings add to the growing body of research regarding motor learning using analogies. Uutilising motor analogies to promote safer landing has potential to curb costs imposed on the healthcare sector, and to decrease the negative physiological, psychological and social effects associated with falling incidents among older adults. Indeed, even a trivial reduction in the severity of injuries caused by falling has potential to have a dramatic economic impact.

6.4 Limitations and future work

To investigate the efficacy of motor analogies for safe landing, this thesis employed Inertial Measurement Unit's (IMU) to estimate the magnitude of load at impact applied to different body segments. The benefit of using IMUs was that due to the small size of the sensors we could infer impact force applied to different body segments without risking injury to our participants. IMU's do not offer a direct measure of force; however, incorporating equipment that offers a direct measure of force, such as force plates, generates other issues, which could cause measurement errors (i.e., landing directly on a force plate is likely to cause injury so extra padding is required). Additionally, we did not use three-dimensional (3D) camera-based motion capture in the research, which could have provided information about inter-joint relationships and different movement patterns. Lack of easy access, space limitations, and cumbersome setup were among the reasons that 3D motion capture was not used. Furthermore, the fracture risk ratio of the wrists was estimated using a simple model based on the magnitude of force applied to the wrists. The problem with this approach is that it does not take other aspects into account, such as direction of force, shear force, connective tissue and many other important factors that contribute to the risk of fracture. A complex model that incorporates these variables should be considered for future research projects. Ultimately, subsequent studies can incorporate additional biomechanical equipment (i.e., force plates, 3d motion capture, etc.) to investigate biomechanical characteristics of safe landing.

In theory, the relative movement between two adjacent body segments can be determined through six degrees of freedom: three angular and three linear displacements (Grood & Suntay, 1983) and IMU sensors provide this information. Once the orientation of the sensors is known through anatomical calibration, it is possible to estimate joint kinematics (Camomilla et al., 2018) using models that mitigate large errors (Cereatti et al., 2017). Hence, future research can leverage this area by combining IMU sensors and 3D motion capture systems to create a model for safe landing techniques and provide an improved estimation of impact force. Additionally, the falls in Chapter 4 were not truly unexpected by participants. Rather, participants were aware that they would fall at some point, but were not aware of when they would fall or in which direction (forward or leftward/ backward or rightward) they would fall. Furthermore, the falls were induced by applying a nudge to the participant's shoulder. This approach introduces potential issues with inconsistencies in nudge force across participants. These limitations were caused by a lack of equipment that specifically and realistically would produce safe unexpected falls (see, for example, the sliding apparatus used by Hsiao and Robinovitch (1997). Future studies should address these issues by employing experimental setups that safely simulate an unexpected fall.

It is important to acknowledge that different cultures are likely to have a unique interpretation of an analogy based on their history, language, legends, and literature. For example, Poolton et al. (2007a) found that translating an analogy validated for use by English-speaking participants did not convey the intended meaning when used by a Chinese-speaking population. Therefore, the feather analogy may not be well-suited for non-English speaking (e.g., in the Persian language feather is associated with wealth and prosperity 2005 ,علیپور). For example, the indigenous people of New Zealand, the Māori, use a language that is rich in metaphors and analogies. In the Māori culture, feather often represents “anything much prized” and ornaments with feathers are considered to be a “precious treasure, valued possession, darling, chief, man of prowess” (Krupa, 2006, p. 19). Thus, feathers may generate mental representations that are not associated with soft, slow, silent characteristics and therefore may not promote safe landing. Future studies need to assess the relationship between feathers and safe landing characteristics in the Māori population and, if necessary, design an analogy that is more appropriate for the Māori culture and/or other non-English speaking cultures.

The between group (analogy/control) effect sizes reported for the majority of the biomechanical measures were medium to low, which calls into question the extent to which differences (e.g., impact forces) were clinically meaningful. However, this is a common issue when conducting studies in a controlled laboratory environment, which can be resolved by conducting studies in clinical settings. Future research needs to investigate safe landing analogies in more real-world settings, such as clinics, hospitals and rehabilitation centers. For instance, fall prevention programmes can incorporate motor analogies as part of their routine and the effectiveness of the analogies can be determined by monitoring factors associated with the severity and type of injury that occur in subsequent fall incidents (e.g., fractures, hospitalisations, severity of injury, etc.).

Due to Covid-19 restrictions, we were unable to test the efficacy of the motor analogy in the older adult population, which leaves a significant gap in the validation process. Eventually, it might also be useful to stratify our safe landing approach by targeting specific types or category of older faller. Researchers often recommend that injury prevention strategies should target frequent and infrequent fallers separately (van Schooten, et al, 2018). It is therefore likely that to achieve the best outcome with regards to safe landing, different approaches may be required for different types of fallers (e.g., frequent, and infrequent fallers). For example, frequent fallers may benefit more from a safe landing analogy than infrequent fallers because they are aware that they may fall, and thus are motivated to use the analogy. Factors such as number of drugs taken per day, use of psychoactive drugs, vestibular and balance issues, deficiencies in lower limb proprioception and vision all contribute to recurrent falling in older adults (Rossat et al, 2010), so it is unclear to what extent our approach will be effective for frequent fallers. Compared to frequent fallers, however, infrequent fallers are often more mobile and apt to sustain injury. They tend to be more agile and have fewer risk factors or underlying conditions (Deandrea, et al, 2010), so it is possible that the benefits of a safe landing analogy may be greater for infrequent fallers. However, without further trials to ascertain the efficacy of the safe landing approach for different types of older faller it is not possible to make recommendations.

Additionally, age-related hippocampal dysfunction affects working memory negatively (Mitchell et al., 2000). Hippocampal dysfunction has been implicated in not only cognitive aging but also disorders, such as Alzheimer’s disease, schizophrenia, and depression (Small et al, 2011). Considering that motor analogies are thought to reduce the loads on the central control system of working memory, older adults suffering from these conditions may be potential beneficiaries for using motor analogies for safe landing. Future research should investigate safe landing via motor analogies with respect to number of falls, different disorders, and underlying conditions.

Considering that falls are common in the older adult population and that it is unlikely that motor analogies will increase the risk of injury, we believe that it is appropriate for subsequent research to validate the use of motor analogies in real-life settings[9]. For instance, most nursing homes install cameras to monitor the safety of the residents, so these can be used to assess real-life falls (Choi et al., 2015).

6.5 Conclusions

Landing safely when a fall occurs has the potential to reduce the likelihood or severity of injuries that may result, but can be challenging to accomplish, particularly by people who are ageing. One practical approach that can potentially promote safe landing when an accidental fall occurs is to use motor analogies. This thesis provided preliminary evidence for the potential of motor analogies to reduce fall-related injuries. There is much research needed to validate the approach fully, but the journey has started. Future studies need to test the approach in older adults and in different settings. The research adds to the body of knowledge regarding the use of motor analogies for skill acquisition and is useful for researchers seeking to use motor analogies in populations with special constraints, such as children, elderly people, and patients with stroke, Parkinson disease, Alzheimer's disease or other cognitive deficiencies. This novel approach does not require multiple sessions, or adherence to an intervention programme for a long period of time, and is affordable to implement at a community-wide level. Ultimately, the journey ahead will end, we hope, with a unique tool that can be used to alleviate some of the burden of falling on healthcare systems and individuals.

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[9] Although, only when ethical obligations have been met.

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