Declaration

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This Dissertation entitled 'The effects of segmental vibration on hamstring range of motion' is submitted in partial fulfilment for the requirements for the Unitec degree of Master of Osteopathy.

CANDIDATE'S DECLARATION

I confirm that:

- This Dissertation represents my own work;
- The contribution of supervisors and others to this work was consistent with the Unitec Regulations and Policies.
- Research for this work has been conducted in accordance with the Unitec Research Ethics Committee Policy and Procedures, and has fulfilled any requirements set for this project by the Unitec Research Ethics Committee.
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The effects of segmental vibration on hamstring range of motion

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A dissertation submitted in partial fulfilment of the requirements
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ABSTRACT

Introduction. There has been a growing focus within literature on the neuromuscular effects of whole-body and local vibration. The body of knowledge suggests that such effects may include improvement of muscular flexibility, as well as enhancement of stretching methods. The aim of this study was to investigate the effect of segmental vibration on the flexibility of the hamstring muscles when applied to the muscles at their resting length. **Methods.** Thirty-one recreationally-active male participants (aged 25.5 ± 4.9yrs, weight 80.5 ± 10.7kg, height 180.5cm ± 6.5cm) gave consent to participate in the study. Prior to initial baseline measurements, participants undertook a five-minute warm-up on a bicycle ergometer at a self-selected yet challenging speed, followed by two familiarisation trials of the active knee extension test (AKE) and passive straight leg raise test (PSLR) on both legs. During a single experimental session each participant underwent flexibility testing at three time points (baseline, Post 1, Post 2) measured with electrogoniometry. The AKE and PSLR tests were performed three times on each leg, at each time-point. The mean baseline AKE measurements were used to determine which leg was least flexible and would receive the vibration intervention (experimental), while the other leg acted as the control. The vibration device consisted of an oscillatory platform powered by a motor that generated a random waveform. Vibration (34 Hz, amplitude 3 mm, acceleration 42.2 $m.s^{-2}$) was applied to the posterior thigh of the experimental leg for five one-minute periods alternating with one-minute rest intervals. Immediately after vibration Post 1 range of motion was recorded for both the AKE and PSLR on both legs. The Post 2 measurements were recorded ten minutes following the cessation of vibration. **Results.** The smallest detectable difference (SDD) calculated from a pilot reliability study was 3.7º and 4.6 º for the AKE and PSLR tests respectively. Taking into consideration the SDD, the likelihood that the true difference between the experimental and control group for the AKE was less than/equivalent/greater than the measured difference between the groups was 0/85/15% for baseline v Post 1 respectively, and 0/53/47% for Post 1 v Post 2 respectively. Corresponding data for the PSLR were 0/98/2% and 0/100/0% respectively. **Conclusion.** Segmental vibration applied at the specified parameters had no clinically significant effect on hamstrings flexibility measured by the PSLR. There was some indication of a potential clinically negative effect on the control leg measured by AKE, that may have been due to diminishing effects of warm-up or neurologically mediated crossed effects. Further investigation is required to examine whether effects persist beyond the Post 2 time-point.

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ABBREVIATIONS

ANOVA	Analysis of variance
AKE	Active knee extension test
CI	Confidence interval
CV	Coefficient of variance
ES	Effect size
Hz	Hertz
ICC	Intra-class correlation
MET	Muscle energy technique
ms^{-2}	Metres per second squared
MVC	Maximal voluntary contraction
P1	Post 1
P2	Post 2
PNF	Proprioceptive neuromuscular facilitation
PSLR	Passive straight leg raise test
ROM	Range of motion
SD	Standard deviation
SDD	Smallest detectable difference
SEM	Standard error of measurement
SPSS	Statistical package for the social sciences
SW	Within-subject deviation
WBV	Whole-body vibration

CHAPTER 1: INTRODUCTION

INTRODUCTION

Osteopaths are holistic musculoskeletal practitioners who have a sound knowledge of normal acceptable orthopaedic ranges of motion and desired flexibility of independent joints of the body. They treat a broad spectrum of patients from healthy adults, to athletes, the elderly and physically disabled, and recognise that the functional flexibility demands are very different for each subset of the population. While the aim of treatment is to incorporate and balance the physical, mental, social and spiritual domains to achieve a balanced state of health, these practitioners also wish to achieve good treatment outcomes as effectively and efficiently as possible (Seffinger et al., 2003). Therefore, practitioners cannot rely only on the treatment within the clinical session, but must also incorporate further measures to be taken by the patient in their own time. Within the scope of some osteopathic diagnoses poor flexibility that limits joint range of motion may contribute to the presenting symptomatic and biomechanical picture, increasing the risk of further injury, and therefore require prescription of exercises in an attempt to correct musculature imbalances (Kuchera, 2003).

Currently, static stretching is one mode of exercise that is prescribed to patients to improve flexibility of tissues. Stretching is an effective and proven method for improving an athlete's flexibility (Cronin, Nash, & Whatman, 2008; de Weijer, Gorniak, & Shamus, 2003; DePino, Webright, & Arnold, 2000; Whatman, Knappstein, & Hume, 2006), however, the literature indicates that flexibility gains may accompany deleterious effects on other performance factors such as attenuation of strength (Behm, Bambury, Cahill, & Power, 2004; Cornwell, Nelson, & Sidaway, 2002; Power, Behm, Cahill, Carroll, & Young, 2004). The mixed neuromuscular effects of stretching have lead researchers (Kinser et al., 2008) in the sport science field to warrant further investigation into alternate methods for improving flexibility and range of motion in warm-up that do not have the same consequences. Low-frequency vibration training has been suggested as one of these alternatives, which may be an efficient method of achieving increased joint range of motion while simultaneously improving strength performance (Fagnani, Giombini, Di Cesare, Pigozzi, & Di Salvo, 2006; Issurin, Liebermann, & Tenenbaum, 1994). This dissertation explores ‘segmental’ low-frequency vibration as a potential exercise tool, as it is becoming more popular in the mainstream exercise domain and has been of great interest in research in the last decade. Whilst the effect of vibration on joint range of motion appears promising to highly trained athletes (Kinser et al., 2008; Sands, McNeal, Stone, Russell, & Jemni, 2006) it may also provide another tool to gain effective and efficient results in the other members of the population who may present to the osteopathic treatment clinic. The effects of local vibration on flexibility in the healthy, untrained population are yet to be investigated in depth, and have significance to the field of osteopathic treatment and rehabilitation.

AIMS AND OBJECTIVES

The initial pilot reliability study (Chapter 4) aimed to assess the reliability of both the active knee extension test and passive straight leg raise test when measured by electrogoniometry and a single tester. Additionally it sought to identify the smallest detectable difference (SDD) for both of these range of motion assessment methods to inform the subsequent intervention study.

The intervention study (Chapter 5) was a within-subject repeated measures trial that investigated the extent to which low frequency segmental vibration applied to relaxed muscle produced immediate and short-term clinically significant changes in hamstring flexibility, in healthy recreationally-active male adults. The study also intended to identify trends seen in any effects that were observed.

CHAPTER 2: FLEXIBILITY AND HAMSTRING RANGE OF MOTION ASSESSMENT

INTRODUCTION

Whether the range of a joint is measured in a clinical, athletic or scientific setting, it is important that the outcome measures and equipment or tools used to measure the range of motion are reliable and valid. The reliability of a clinical test procedure ensures a degree of accuracy in diagnosis and repeated measurements over time. Such measures can be used to gauge ongoing effects of clinical treatments or exercise regimens, with a low degree of error. This chapter discusses the general concept of flexibility, with application to the hamstring muscle group. Common indirect measures of hamstring flexibility are explored with regard to factors that influence reliability and validity in the clinical and scientific setting.

FLEXIBILITY

Flexibility defined

There is a lack of consensus regarding a definition of 'normal' flexibility between sports science, physical education, physical therapy and medical disciplines (Alter, 1996; Phillips, 2007). Such disagreement may be due to the different flexibility demands in those fields. For example, the desired and necessary 'normal' flexibility required for a successful gymnast are far greater than for the non-athletic population (Magee, 2008; Sands et al., 2006). Anderson and Burke (1991) have defined two kinds of general joint flexibility as 'static' and 'dynamic' flexibility. They explain that 'static' flexibility describes the "range of motion about a joint" (p. 64) often determined through end-feel, while 'dynamic' flexibility is resistance "throughout the range of motion or joint stiffness" (p. 64). Phillips (2007) highlights that the term 'dynamic flexibility' is also adopted in other disciplines, albeit with a different definition to describe the terminal range of motion achieved specifically through active muscle contraction. Within the osteopathic field all three concepts of flexibility are important, but 'static' flexibility and the latter definition of 'dynamic' flexibility can be objectively quantified and measured with the greatest ease.

Hamill and Knutzen (2003) define static flexibility as "the terminal range of motion of a segment" (p. 116) that is restricted not only by bony structure but also neurological feedback mechanisms and connective tissues, such as muscle, ligament, fascia, tendon and adipose tissue (Magee, 2008). Those factors that have the greatest capacity for modification are antagonist muscle length, and the neurological processes operating on muscle, and therefore these are the focus of most flexibility training regimens (Hamill & Knutzen, 2003).

The degree of flexibility found in one joint is specific to that joint, and therefore the range of motion found in one joint cannot be expected of any others in the body (Alter, 1996; Anderson & Burke, 1991; Magee, 2008; Phillips, 2007). Flexibility may be influenced by the activity and range of motion a joint goes through on a regular basis. Non-modifiable factors that contribute to flexibility restriction are age, gender, ethnicity, genetic makeup, side dominance, local or systemic pathology and history of tissue trauma (Hamill & Knutzen, 2003; Magee, 2008).

Population differences in flexibility

It is a common observation that females are more flexible than males (Anderson & Burke, 1991). Bell and Hoshizaki (1981) found that on average the flexibility of a select 17 joints were greater in females, with this trend continuing throughout life, despite both male and female flexibility continuing to decline with age. With respect to hamstring flexibility, Youdas, Krause, Hollman, Harmsen and Laskowski (2005) observed 106 men and 108 women of ages ranging between 20-79 years old, and concluded that men demonstrated poorer flexibility in comparison to women when passive straight leg raise and passive knee extension tests were performed. They demonstrated a mean 8° and 11° difference between genders for those respective measures. A later study by Davis, Quinn, Whiteman, Williams and Young (2008) found consistent results, reporting greater flexibility for women in both the passive knee extension test and straight leg raise test. Widely used musculoskeletal examination texts (Hamill & Knutzen, 2003; Kendall, McCreary, Provance, Rodgers, & Romani, 2005) do not account for such gender flexibility differences, which has been criticised by one study (Youdas et al., 2005) that argued that common hamstring flexibility standards should account for more specific gender ‘norms’.

Age may also be a strong factor influencing flexibility (Hamill & Knutzen, 2003). Generally, health practitioners may expect to observe a natural decline in flexibility with age, explained by changes in muscle and joint architecture over time, in combination with decline in physical activity (Gajdosik, 2001; Youdas et al., 2005). Although both sexes experience some decline in flexibility over the life span, some authors believe the change is only small (Allander, Bjornsson, Olafsson, Sigfusson, & Thornsteinsson, 1974; Bell & Hoshizaki, 1981). A more recent study by Youdas et al. (2005) found that in a healthy active population ranging from 20 to 79 years, age was not an influencing factor over hamstring length, reporting no statistically significant age effect. Further definitive research is required with regard to such findings, as the latter study recruited physically active participants from a fitness centre, which may not be generalisable to the greater population, especially with regard to a normal, inactive older subset of the population.

The clinical relevance of hamstring muscle group flexibility

The accepted orthopaedic ranges of motion about the healthy knee stated in popular musculoskeletal texts (Hamill & Knutzen, 2003; Magee, 1997) are 0-135° of flexion and 0-15° of hyperextension, along with various degrees of accessory movement. Knee flexion is performed by the biceps femoris, semitendinosis and semimembranosis muscles, which compose the hamstrings muscle group. Due to their attachment points they also act to extend the hip joint. Tension in the hamstrings may cause resistance to the action of the antagonist muscle group called the quadriceps that extends the knee. Flexion of a healthy hip joint is approximately 140° with a flexed knee, but such ranges are limited partly by the hamstrings when the knee is extended.

The ability of an individual to achieve normal range of movement may be affected by such pathophysiological states as muscle injury, pain in adjacent joints, and spinal cord injury (Youdas et al., 2005), however, such range limitations may also occur in healthy people. The term ‘tight hamstrings’ is regularly employed in clinical and athletic settings, however, the term is colloquial and lacks a definitive meaning (Kuilart, Woollam, Barling, & Lucas, 2005). Therefore the term is of little diagnostic use in such settings without an operational definition. Kuilart et al. defined tight hamstrings as "the subjective perception of reduced extensibility" (p. 89) in the muscle, whereas Gajdosik (1991b) defined the term anatomically as "muscles with decreased length, decreased extensibility and decreased passive compliance" (p. 239) observed in healthy individuals in the absence of intervertebral disc pathology or neuromuscular disease. Such anatomical 'tightness' may be of consequence to long-standing muscle or connective tissue shortening. While a shortened muscle group may cause an objective measurable reduction in range of motion of a joint, the subjective sensation of tightness is not necessarily an indicator of poor hamstring muscle extensibility. The 2005 study by Kuilart et al. found those participants who perceived tightness were unlikely to have reduced flexibility compared to the normal healthy population. Such sensations of discomfort in the posterior thigh and knee are commonly reported as hamstring pain, however, may not only arise from the hamstring muscles but also mechanically sensitive neuromeningeal structures such as the sciatic, posterior tibial and common peroneal nerves, and their connective tissues. Turl and George (1998) have even suggested that adverse neural tension is a clinical feature of repetitive hamstring strain.

On a regular basis osteopaths are presented with symptoms that are caused by or are of consequence to reduced flexibility of tissues local to the area, or in other regions (Kuchera, 2003). An example of such a presentation may be pain in the region of the lumbar spine, which is of consequence to poor lower limb mechanics contributed to by the hamstring muscle group (Youdas et al., 2005). Turl and George (1998) have described the hamstring muscle group as "one of the most functionally complex in the human body" (p. 16). The hamstrings have the potential to create alterations in posture, as well as the mechanics of locomotion (Gajdosik, 1991b). Full extension at the knee is favourable during the gait cycle (Hamill & Knutzen, 2003), however, Magee (1997) indicates that tight hamstrings increase the degree of flexion at the knee on "heel strike and in stance phase…[which may]…contribute to patellofemoral pathology" (p. 521). In addition, pelvic mechanics must compensate for changes in hamstring length, further altering mechanics of the lower extremity, as well as lumbar spine (Hamill & Knutzen, 2003). The length of time such alterations are present and how well the body can adapt and compensate will be factors in determining the degree of local and widespread complications, such as acute inflammation or chronic degenerative processes (Wells, 2003).

In the athletic population, lack of flexibility in hamstring musculature is speculated to be one of several possible etiological factors contributing to and increasing risk of hamstring strain injury in athletes (Corkery et al., 2007; Sullivan, DeJulia, & Worrell, 1992; Witvrouw, Mahieu, Danneels, & McNair, 2004). Furthermore, there are authors that believe that inflexibility is the primary characteristic responsible for strain injury (de Weijer et al., 2003), an opinion which is controversial. Therefore, while assessment of these muscles in the case of hamstring injury is essential (Youdas et al., 2005), flexibility should also be monitored as part of a training protocol. As anatomically tight hamstrings can have ongoing widespread and local effects in the body, potentially increase injury risk to competitive athletes and promote long-term changes in tissue structure and function, it is essential to diagnose with reliable testing procedures and create appropriate treatment regimen to protect, prevent and recover the patient to the degree of flexibility required for their given functional demands.

METHODS OF RANGE OF MOTION ASSESSMENT

Measurement devices and hamstring range of motion assessment

Within a clinical or athletic setting the range of motion of a joint may be measured through visual estimation, however, researchers and some clinicians have a variety of tools at their disposal to measure range more specifically. Such tools include manual goniometers, flexometers, inclinometers, motion analysis video equipment and electrogoniometers (Anderson & Burke, 1991; Phillips, 2007). Consistent placement of the device of choice is important in repeated measurement of one participant, as well as between participants in indirect hamstring muscle measurement. Such consistency will help to obtain accurate, consistently reliable measurements. Piriyaprasarth, Morris, Winter and Bialocerkowksi (2008) explain that although devices can be placed in different positions on limbs to record range, placement of such equipment as a two-armed manual goniometer measuring knee range of motion requires accurate determination of the joint line, and joint plane according to bony landmarks. Other devices such as inclinometers or electrogoniometers may not require such specific placement with regard to the plane of movement occurring at a joint, as the motion of the device attached to the lower leg is measured relative to the thigh. Gabbe, Bennell, Wajswelner and Finch (2004) secured a bubble inclinometer 15 cm below the midpoint of the tibial tuberosity on the anterior tibial border to record active knee extension, and demonstrated similar intratester reliability (r = 0.94 to 0.96) as Sullivan et al. (1992) and Worrell, Sullivan and Dejulia (1992) who positioned the inclinometer they used 1 inch (2.54 cm) inferior to the fibular head. With respect to electrogoniometers, the nature of the equipment permits use of a bony landmark such as the tibial tuberosity and measures it's own movement in space relative to a starting point, without the need to determine the specific joint line and axis of movement (Piriyaprasarth et al., 2008).

There are a number of orthopaedic tests used to indirectly measure the length of the hamstring muscles, but there remains no standardised method of assessment (Davis et al., 2008; Gabbe et al., 2004). Davis et al. suggest that professional background, personal preference and ease of test performance are factors that govern a tester's use of a procedure. The most commonly used methods are the straight leg raise test, and active and passive knee extension tests, all which can be performed actively by the participant, or passively by an operator such as a clinician or coach (Gajdosik, Rieck, Sullivan, & Wightman, 1993). Among other common flexibility measures described in the literature is the sit-and-reach test, which is used as a general measure for flexibility of posterior musculature of the lower limb, as well as the trunk and upper-extremities (Kendall et al., 2005). Kuilart et al. (2005) explain that range of motion testing procedures have a three-fold purpose, in that they test joint range of motion directly, extensibility of related tissues indirectly, and sensations perceived as a subjective measure. Therefore such methods have initial clinical diagnostic purposes, and may serve as a regular measure to gauge effectiveness and efficiency of hamstring flexibility treatment programs or progress in the treatment of hamstring injury (Worrell et al., 1992).

Perhaps the greatest shortcoming of hamstring measurement methods is that they do not clearly distinguish between tension created by hamstring musculature and the mobility and extensibility of lower limb neuromeningeal structures (Butler, 2000; Kuilart et al., 2005). It is believed that the straight leg raise test is limited to a greater extent by neurological tissue tensioning in comparison to the knee extension tests (Davis et al., 2008; de Weijer et al., 2003; Phillips, 2007; Sullivan et al., 1992). While the straight leg raise test and the active and passive knee extension tests are reported to measure hamstring tension, one study by Gajdosik et al. (1993) reported a significant negative correlation (r = 0.37 to 0.66) between the passive straight leg raise and the passive and active knee extension tests, suggesting that the two tests can only be performed along side each other and cannot be substituted in the clinical setting. Davis et al. (2008) supported this theory, reporting poor concurrent validity for the passive straight leg raise and passive knee extension test as a correlation of $r = 0.63$. It is thought that adverse neural tensioning, differences in testing positions, differences with pelvic positioning, and other non-contractile factors that accompany the straight leg raise test are confounding factors which make the two tests incomparable.

The active and passive knee extension tests

The active and passive knee extension tests have been referred to by Magee (2008) as the "90-90 straight leg raising test" (p. 697), where the participant lays supine on a plinth in the start position, with the leg being tested flexed to 90° at the hip and 90° at the knee. Both the active and passive tests are performed unilaterally, while the contralateral leg remains straight. The flexed hip is usually maintained in this position with reference to some kind of device such as a cross-bar, or board over the plinth. The foot is maintained in a neutral or plantar flexed position to reduce neuromeningeal tensioning (Butler, 2000). Hamstring flexibility is then tested through active or passive knee extension and the angle created measured by a goniometer, inclinometer, motion analysis software (Phillips, 2007) or electrogoniometry (Piriyaprasarth & Morris, 2007). This indirect measurement technique was originally defined by Gajdosik and Lusin (1983), and the early technique was replicated and mildly modified by other authors in subsequent studies and books (see Tables 1 and 2), with most differences occurring in its application by range of motion endpoint definition and the degree of strapping used in the protocol. The passive knee extension test has been labelled the 'gold standard' of hamstring tests (Davis et al., 2008), and it has been argued that the passive and active knee extension tests may be more valid than other indirect measurement techniques as adverse neuromeningeal tension is reduced, and influences from variable pelvic and hip joint positioning are eliminated through stabilisation against the crossbar or board (Gajdosik et al., 1993; Worrell et al., 1992). However, Kuilart et al. (2005) argue that to some extent the knee extension tests still implicate functionally related mechanosensitive neural structures.

Descriptions of the passive and active knee extension test ranges have been a source of difference between studies. The KEA or ‘knee extension angle’ has been defined as the “degree of knee flexion from terminal knee extension” (Davis et al., 2008, p. 583), which is the opposite to the PA or ‘Popliteal Angle’, defined as the “obtuse adjacent angle between femur and tibia” (Davis et al., 2008, p. 583). In a combined total the knee extension angle and the popliteal angle would summate to 180°. This conversion is not difficult for the reader, and aids them in converting the measures to a comparable angle when reviewing the literature. Additionally, some studies have stated only the range of motion starting from 90° knee flexion (Sullivan et al., 1992; Worrell et al., 1992). Worrell et al. and Sullivan et al. utilised a fluid filled inclinometer when measuring the active knee extension test. They determined 90° of knee flexion by use of a two-armed goniometer, and then set the fluid filled inclinometer to 0° at this position, proceeding to measure from this point. Although they expressed their results in degrees of movement from that zero position at 90° knee flexion, the reader could also determine the popliteal angle by adding 90° to angle achieved, or determine the knee extension angle by subtracting the measured angle from 90°.

There has been disagreement with regard to the need to secure the pelvis and opposite leg by strapping to ensure a high level of test reliability. The originators of the test (Gajdosik & Lusin, 1983; Gajdosik et al., 1993) have recommended strapping of the pelvis and opposite leg to that being tested, reporting intra-rater ICC values ranging from 0.86 to 0.99. In contrast, Worrell et al. (1992) investigated the reliability of the active knee extension test, and refrained from strapping the pelvis or the opposite leg. They also reported high intra and inter-rater reliability of $r = 0.96$ to 0.99 and $r = 0.93$ respectively (see Table 1), concluding that restraints were unnecessary. Although authors remain adamant regarding their preference for protocol, both methods have demonstrated an equally high degree of reliability. Therefore, the decision to employ either technique in the outcome measure may depend on the researcher’s preference and research conditions.

The defined ‘endpoint’ of knee range of motion for both the passive and active procedures have been identified as a source of inconsistency (Youdas et al., 2005), restricting comparability between studies using these techniques. In the literature, the endpoint of the active knee extension test was determined mostly by the participant’s perception. Instructions to those participants have included knee extension until initial stretch or discomfort was experienced in the hamstrings (Corkery et al., 2007; Gajdosik & Lusin, 1983; Kuilart et al., 2005), knee extension as far as was comfortably able (Turl & George, 1998), and knee extension to its absolute maximal without moving the hip from its 90° position (Decoster, Scanlon, Horn, & Cleland, 2004; Gabbe et al., 2004; Magee, 2008; Spernoga, Uhl, Arnold, & Gansneder, 2001). The end-point determination relies on the participant's ability to understand and follow instructions, as well as apply a degree of concentration to the task. Such instructions were problematic in a study by Gajdosik et al. (1993) in which they instructed their participants to extend the knee until they experienced myoclonus, and then flex the knee slightly until myoclonus ceased, at which point the angle was measured. According to participant reports, they had difficulty in determining the myoclonus cessation point or whether lower limb shaking was due to some other fatigue mechanism. In spite of such issues and differences in endpoint definition, the intra and inter-rater reliability of the active knee extension testing procedure have proved to be high, ranging from intra-rater ICC values of 0.86 to 0.99, and inter-rater reliability of 0.79 to 0.93 (see Table 1). Although inter-rater reliability is high, Worrell et al. (1992) has criticised this procedure, reporting large inter-tester standard error of measurement (SEM) of 4.81° and 95% confidence interval of ± 9.42° between the two clinicians they used. On the other hand, they found excellent results for the intra-tester reliability, of SEM = 1.82°, recommending that where possible it is better to have a single examiner undertaking the measurement. The reliability of this test procedure is further discussed later in Chapter 4.

While the participant's perception of endpoint has been valued in the passive knee extension test for some studies, many depended more on the perception of the operator applying the force to the limb. Studies defined endpoint as the operator's perception of slight (Davis et al., 2008) or, firm resistance to stretch or further range of motion (Bandy, Irion, & Briggler, 1997, 1998; Nelson & Bandy, 2004; Youdas et al., 2005). The participant's feeling of discomfort or tightness (Bandy et al., 1997), or strong but tolerable hamstring stretch (Davis, Ashby, McCale, McQuain, & Wine, 2005; Davis et al., 2008) was also used. The passive test has high intra-rater reliability like the active test procedure, with comparable reliability reports of ICC = 0.90 to 0.98 (see Table 2), however, such high levels of reliability are dependent on the operator applying the same degree of force each time the test is performed. There is little information on the inter-

Table 1.Summary of Studies Reporting Active Knee Extension Test Reliability.

Author	Measurement Device	Intra-tester ICC value	SEM (°)	CV (%)	Inter-tester ICC value	SEM (°)
Cronin, Nash and Whatman (2007) and Nash (2005)	Video and Silicon Coach computer software	0.89	-	>2.1	-	-
Decoster et al. (2004)	18-inch ‘standard’ goniometer	0.90	2.7-2.9	-	-	-
DePino, Webright and Arnold (2000)	Gravity-assisted protractor	0.96	2.29	-	-	-
Gabbe et al. (2004)	Bubble inclinometer	0.94-0.96	3	-	0.93	-
Gajdosik and Lusin (1983)	Pendulum goniometer	0.99	-	-	-	-
Gajdosik et al. (1993)	Pendulum goniometer	0.86	-	-	-	-
Kuilart et al. (2005)	Digital photography and goniometer	0.99	-	-	-	-
Rakos et al. (2001)	Blinded goniometer	-	-	-	0.79	-
Sullivan et al. (1992)	Inclinometer	0.99	1.75-1.80		0.93	4.81
Webright, Randolph and Perrin (1997)	Video Analysis	0.98	1.7	-	-	-
Worrell et al. (1992)	Fluid-filled goniometer	0.96-0.99	1.75-1.82	-	0.93	4.81

Note: SEM = Standard error of measurement, CV = Coefficient of variance. Intra-rater intraclass correlation coefficient relates to single tester and inter-class correlation coefficient denotes reliability based on performance of the test by more than one tester.

Table 2. Summary of Studies Reporting Passive Knee Extension Test Reliability.

Author	Measurement Device	Intra-rater ICC value
Bandy et al. (1997)	Double-armed full circle protractor	0.97
Bandy et al. (1998)	Double-armed full circle protractor	0.97
Davis et al. (2008)	Gravity inclinometer	0.94
Gajdosik et al. (1993)	Pendulum goniometer	0.90
Nelson and Bandy (2004)	Double-armed full circle protractor	0.96
Youdas et al. (2005)	Hand-held universal goniometer	0.97-0.98

Note: The SEM for intra-tester reliability, coefficient of variance and inter-tester reliability data were not provided in this table, as no data was reported in these studies.

rater reliability of the passive test. One can only speculate that inter-rater reliability may be poorer than that of the active test due to the nature of different operators exerting varying degrees of forces on the limb to obtain end point and having a different perception of end-feel.

According to Hamill and Knutzen (2003) hamstrings are best isolated and have the greatest action on knee flexion in this 90°-90° position, which would suggest this position ideal for active range of motion hamstring testing. Some authors (Nash, 2005; Phillips, 2007) have discussed the active knee extension test as a measure of ‘functional’ range, that the participant would be able to achieve in normal activities, in contrast to the passive knee extension test which would be unachievable without the aid of an operator applying an external force to the limb (Nash, 2005). Additionally, Worrell et al. (1992) explains that an advantage of the active testing that the active test eliminates any inconsistency that may arise from varying degrees of force that an operator or different operators may exert on the limb when trying to passively reach hamstring muscle endpoint, improving intra- and inter-rater reliability.

The physiological difference between the ranges observed in the passive and active knee extension tests has been investigated and discussed by one study by Gajdosik et al. (1993) who reported an 11.9° mean difference ($p<0.001$) in the achieved range of motion, with passive range exceeding active. In that study the defined end point for active range of motion was immediately before myoclonus onset, and the passive endpoint as a firm resistance to further motion perceived by the operator applying force. Gajdosik et al. propose that the difference in range of motion was because the tests placed the muscle in two different states of muscle lengthening. Active knee extension is not a measure of the maximal achievable range, as it represents the 'initial length' of muscle, perceived by the participant as the initial resistance to stretch before myoclonus occurs. Exceeding the 'initial length' in the active test produces myoclonus; however, this point is still regarded as within the muscle's range of extensibility. In comparison, the passive knee extension test elongates muscle to its 'maximal length', achieved at the point of maximal resistance to stretch, which can be identified by onset of electromyographic activity (Gajdosik, 1991b). Therefore, it can be assumed that the different endpoint instructions used not only between the passive and active tests, but also within these tests are not entirely comparable as they test the muscle at varying degrees of stretch. Further investigation into these conditions has been recommended (Kuilart et al., 2005).

The loss of range that an individual must have to qualify as having 'tight hamstrings' appears to vary slightly in different sources of literature for both active and passive testing. Various studies (Bandy & Irion, 1994; Bandy et al., 1997, 1998; Davis et al., 2005; DePino et al., 2000; Nelson & Bandy, 2004; Youdas et al., 2005) have used an operational definition of greater than 150-160° passive knee extension (measured by popliteal angle) as normal hamstring flexibility, where as a loss of greater than 20° to 30° extension would be deemed as hamstring inflexibility. In contrast to the passive test, authors utilising the active knee extension test have defined a loss ranging from 15° (de Weijer et al., 2003; Webright et al., 1997) to 25° (Decoster et al., 2004; DePino et al., 2000; Spernoga et al., 2001) as a reduction in hamstring flexibility beyond that of normal. In a further disparity, Magee (2008) defined ‘tight hamstrings’ as a popliteal angle less than 125°, while noting ‘normal’ flexibility as 155° to160° knee extension. These values for ‘normal’ flexibility do not appear to be referenced from literature, rather determined by clinical experience.

The accepted ‘standards’ for tight hamstrings do not account for gender variation (Youdas et al., 2005). Corkery et al. (2007) attempted to investigate normative range values for hamstring length in 72 ‘college-age’ male and female participants of average fitness ranging from 18 to 22 years of age, in an attempt to define what was normal. They defined the endpoint of the active knee extension test as the onset of initial resistance to stretch, and found the average female range of motion ranged from 154.1° to 157.5° extension (measured by popliteal angle), while males achieved less with ranges from 142.9° to 145° extension. The differences in range of motion between the sexes were comparable to that found in a 2005 passive knee extension study by Youdas et al. (2005), who reported a significant difference in range between genders. The mean (±SD) passive knee extension angle was 154.8° ± 12.0° and 142.3° ±7.7° for 23 women and 20 men respectively, between the ages of 20-29. Such studies suggest that, when using the active and passive knee extension test, a loss of full knee extension ranging from approximately 26° for women, and 38° may be normal for an untrained young adult population, which for the normal male population is a far greater loss than the defined 15° to 30° for the literature stated above.

The passive straight leg raise test

The passive straight leg raise has been described as the most widely used method of indirect hamstring measurement used by clinicians and athletic personnel (Gajdosik, 1991a). It is a tool that has diagnostic value and may indicate effectiveness and participant response to clinical treatments and athletic performance and flexibility regimens (Gajdosik, 1991b). However, the validity of this test as a hamstring measure has been criticised, due to confounding factors such as body positioning, strapping and neural tension that impact on the test procedure (Davis et al., 2008; Worrell et al., 1992).

The straight leg raise test is performed with the participant supine on a plinth, with legs extended. Unilaterally, an operator passively elevates the leg maintaining the knee in extension and flexing the hip. The angle the hip makes with the plinth is then measured with goniometry or video analysis. The straight leg raise can be performed both actively and passively, however, for safety and ease the passive test is more popular. End-points for the passive straight leg raise test in the literature have varied, using either the participant's or practitioner's perception to conclude end range. Such definitions include the participant's first point of stretch or discomfort (Gabbe et al., 2004), the instance both practitioner and participant experienced a firm resistance (Gajdosik, LeVeau, & Bohannon, 1985; Youdas et al., 2005), observations of when the knee began to flex (Stewart & Sleivert, 1998) or the very end of available range of motion (Davis et al., 2008; Phillips, 2007). Gajdosik et al. (1991b) explain that the straight leg raise test is not only limited by hamstring tension, but also by "deep fascia of the lower limb and pelvic soft tissues" (p. 240), hip joint capsule tightness and contralateral hip flexor tightness (Davis et al., 2008). Additionally existing fascial connections between the gastrocnemius and hamstring muscles may further tension the hamstring when the ankle is placed in dorsiflexion. Therefore, tension through the posterior myofascial system of the leg will determine the range achievable (Gajdosik et al., 1985).

The validity of this test procedure as an indirect hamstring measure has been questioned (Davis et al., 2008; Worrell et al., 1992), as the test not only tensions the muscle but provides a "concurrent sciatic nerve stretch" (Phillips, 2007, p. 90). The straight leg raise test is commonly used to observe neuro-meningeal mobility and sensitivity, to determine such pathology as intervertebral disc prolapse, sciatica and nerve root irritation (Butler, 2000; Gajdosik et al., 1985). Butler refers to such tests as 'neurodynamic' testing procedures. According to Gajdosik et al. as the hip moves into flexion the sciatic nerve becomes less mobile, and past 70° of hip flexion nerve mobility ceases. At that point tension along the nerve is generated at a greater degree, resulting in nociceptive impulses perceived as stretch or pain. Such effects may be enhanced through 'sensitising manoeuvres'. These manoeuvres are body positions that place a greater amount of tension along the neuromeningeal system, and include flexion of the cervical spine, abducted limb positioning (Butler, 2000), and dorsiflexion at the ankle joint (Gajdosik et al., 1985). It is thought that such movements in combination with the straight leg raise further tension the neural complex, consequently limiting the range of movement achievable before the onset of symptoms (Butler, 2000). Therefore for the purpose of hamstring measurement it is essential that all sensitising manoeuvres be avoided by maintaining a neutral cervical spine, limbs in a relaxed naturally adducted position and the ankle relaxed or in slight plantar flexion.

With respect to specific components of the test protocol, the greatest issue for debate (Phillips, 2007) remains whether the pelvis and contralateral leg should be strapped for stabilisation (Gajdosik, 1991b; Gajdosik et al., 1993), or whether specific pelvic rotation, lumbar positioning and thigh flexion is required (Kendall et al., 2005) to specifically diagnose ‘tight hamstrings’ as well as obtain reliable repeated measurements. Other studies (for example Youdas et al., 2005) have used methods specified by Kendall et al. (2005) in which the test must be performed with the lumbar spine and sacrum flat on the plinth. Should the participant have short hip flexors, then the contralateral leg should be slightly flexed. In contrast, other studies have used strapping instead, to restrain movement occurring at the pelvis and/or from the contralateral thigh (Davis et al., 2008; Gajdosik et al., 1985). For the purpose of comparing the two variations on the procedure, Gajdosik et al. (1993) compared the differences between strapping and Kendall et al.’s technique. Results showed no significant differences ($p>0.05$) between the two methodologies, reporting similar reliability (see Table 3). Gajdosik et al. (1993) considered that strapping the pelvis at the anterior iliac spines might have had a similar effect as tilting the pelvis to flatten the lumbar spine and sacrum. Additionally they noted that flexing the thigh to release tension on the hip flexors may have no different effect to strapping down the thigh. They concluded that further research was required to investigate these differences. Of interest is that the performance of Kendall et al.’s (2005) technique was reported to require more effort, with the examiner and participant expressing difficulty in maintaining the flat lumbar spine. Therefore, the strapping procedure may be of greater ease and comfort for the participant and examiner, and for that reason is a more preferable procedure to those undertaking research.

Both Kendall et al. (2005) and Davis et al. (2008) have defined 80° of hip flexion as ‘normal’. However, Kendall et al. has been criticised by Youdas et al. (2005) who claimed that their range estimate was based “on clinical observations rather than data gathered from a cohort of healthy persons” (p. 249), and failed to recognise the impact of gender variation on the passive straight leg raise. In their 2005 study, Youdas et al. explored ‘norms’ of range for the passive straight leg raise technique. Their sample of men achieved a passive straight leg raise test mean of 68.5° ± 6.8° which was far less than the estimated 80° by Kendall et al. (2005). Kendall et al.’s estimation was closer to that observed in their population of women 76.3° ± 9.5°. They went on to state that standards should account for gender discrepancies. Gajdosik (1991b) used an operational definition of ≤65° for hamstring tightness in healthy men between the age of 18 and 34 years of age, which comparable for the males in the study by Youdas et al. (2005).

Although the passive straight leg raise is such a common measure, there are few studies that have investigated the intra-rater reliability of its performance, and even fewer that have reported inter-rater reliability. Intra-rater reliability has ranged from r = 0.69 to 0.98. The study (Stewart & Sleivert, 1998) that reported the lower range of reliability employed the technology of electrogoniometry. The details of the studies identified in the literature are found in Table 3, and discussed further in Chapter 4.

Table 3. Summary of Studies Reporting Passive Straight Leg Raise Test Reliability.

Authors	Measurement Device	Intra-rater ICC value	SEM (°)	Inter-rater ICC value
Davis et al. (2008)	Gravity inclinometer	0.92	-	-
Gabbe et al. (2004)	Bubble inclinometer	0.91	4	0.93
Gajdosik et al. (1993)	Pendulum goniometer	0.83-0.88	-	-
Stewart and Sleivert (1998)	Electrogoniometer	0.69	-	-
Youdas et al. (2005)	Hand-held universal goniometer	0.98	-	-

Note: SEM = standard error of measurement

The sit-and-reach test

The sit-and-reach test is also described in some texts as the ‘forward bending test’ for length of the posterior muscles (Kendall et al., 2005). Rakos et al. (2001) indicate that in past literature the test has been used to measure hamstring length, however, the test is not valid for that purpose as movement that occurs simultaneously in other muscles and joints of the body. The test observes flexibility as a complex of structures, including myofascial structures of the posterior lower limb and back muscles, pelvic mobility, lumbar and thoracic vertebral mobility, and mobility of the upper extremities (Kendall et al., 2005). While it is not a joint specific flexibility test, it remains a commonly used general flexibility measure in range of motion studies (Cochrane & Stannard, 2005; Issurin et al., 1994).

Performance of the test requires the participant to reach forward with fingertips as far as possible, while seated with extended legs in front. This process tilts the pelvis anteriorly, flattening the lumbar lordosis, increasing the thoracic kyphosis and tensions posterior leg musculature. The distance between the outstretched fingers and base of the hallux determines the result. According to Kendall et al. (2005) adults who exhibit ‘normal’ flexibility of the lower-limb and trunk should be able to touch finger-tips to toes creating an 80° angle between the sacrum and the table as the pelvis tilts forward.

As a clinical diagnostic tool, the sit-and reach test does not determine exactly where flexibility limitations arise from, or if there is excessive movement in an area of the bony-ligamentous-myofascial complex that is compensating for another area. For example, excessive flexion arising from the back may compensate for short hamstrings in this test, and therefore will be observed as ‘normal’ flexibility in a participant (Kendall et al., 2005). The greatest disadvantage of such a method within the scope of scientific research where pre and post measures are investigated is that when change in sit-and-reach flexibility is observed, the specific degree of flexibility change at the individual sites of the complex cannot be isolated (Anderson & Burke, 1991). Additionally, this test is not valid when there is a difference in hamstring lengths between the right and left lower extremities (Kendall et al., 2005). Therefore, in studies that observe a specific area of the body such as the hamstring muscles, other flexibility measures like the straight leg raise or knee extension tests may be more appropriate.

CONCLUSION

Flexibility can be described as either static or dynamic, indicating either passive or active range of motion about a joint, as well as the resistance to movement throughout range. There are a number of factors limiting joint range of motion, some of which are non-modifiable such as gender and biological tissue age. The greatest modifiable factors that are exploited by flexibility interventions are muscle length and neurological processes acting on those muscles.

The flexibility of the hamstring muscles may be important with regard to particular clinical presentations involving local or widespread symptoms in an individual. Additionally, research suggests that poor flexibility may be a factor contributing to repetitive hamstring strain in sportspeople.

There are a number of commonly used active and passive clinical testing procedures that measure hamstring flexibility, including the active and passive knee extension tests and passive straight leg raise test. These have demonstrated high reliability when traditional goniometers and inclinometers were employed. However, studies investigating reliability of such tests measured by electrogoniometry equipment are rare, and have demonstrated mixed reliability. The passive and active knee extension tests are thought to be more valid indirect measures of hamstring flexibility than the passive straight leg raise test, as they are influenced to a lesser degree by mechanosensitive tensioning in lower limb nerves and their connective tissues.

CHAPTER 3: METHODS USED TO CHANGE FLEXIBILITY AND THE EFFECT OF THESE ON PERFORMANCE

INTRODUCTION

For healthy individuals who experience objective limitations in joint range of motion current popular methods used to improve flexibility include various styles of stretching exercises, heat, and massage. However, there is no common consensus regarding the most effective method (Cronin et al., 2008) due to mixed flexibility responses and simultaneous attenuation of other performance factors such as power and strength (Nelson & Bandy, 2005). Recently, vibration has been suggested as a potential tool to augment flexibility, which may also prove beneficial to performance factors such as jump height, strength and power (Kinser et al., 2008). This chapter discusses the methods commonly employed to improve joint range of motion, and then goes on to discuss vibration as a potential tool to enhance flexibility.

STRETCHING TECHNIQUES

Introduction

Although there is little consensus with respect to the most effective method of flexibility enhancement, stretching is one of the most common techniques recommended by coaches, and clinicians alike (DePino et al., 2000; Witvrouw et al., 2004). It is usually used as a technique on its own or as part of a warm-up. While there is overwhelming evidence towards significant augmentation of flexibility via stretching methods, one review of the literature has illustrated deficiencies in the body of knowledge thus far with regard to optimal stretching parameters, and the other consequences of stretching (Nelson & Bandy, 2005). Witvrouw et al. (2004) have surmised that “no scientifically based prescription for stretching exercises exists”(p. 443), which is a disadvantage to its practical use. Limitations to research, and significant differences in protocol parameters have made studies difficult to compare. Although stretching is commonly used as a means to relax muscle, reduce muscle soreness, prevent injury and improve performance, there is mounting evidence to suggest that stretching methods may in fact be detrimental to particular performance factors and may have little effect in reducing injury risk in some sporting activities (Nelson & Bandy, 2005; Whatman et al., 2006; Witvrouw et al., 2004).

The ‘static stretch’ is the most popular stretching procedure and involves maintaining a muscle in a lengthened state to induce relaxation (de Weijer et al., 2003). Nelson and Bandy (2004) have labelled static stretch as the ‘gold standard’ stretching procedure due to its ease of instruction and performance. Although static stretch holds popularity with such authors, it remains unclear which stretching methods are more effective (Spernoga et al., 2001). Other stretching techniques include proprioceptive neuromuscular facilitation (PNF), muscle energy technique (MET), dynamic, active, passive, isometric and ballistic stretching (Bandy et al., 1997; Nelson & Bandy, 2004; Stone et al., 2006; Whatman et al., 2006).

Stretching protocol

Few studies have elaborated on the scientific basis informing the stretch duration and regularity of the stretching program used (Booth, 2008). With respect to static stretching regimens, stretching routines ranging from one to four repetitions of ten to 60 seconds before and/or after activity are frequently used in clinical, athletic and research settings (de Weijer et al., 2003; DePino et al., 2000; Magnusson, Aagaard, & Nielson, 2000; Spernoga et al., 2001). Studies by Bandy and Irion (1994) and Bandy et al. (1997) have explored optimal time periods for stretch performance in order to produce significant changes in range of motion. There was evidence to suggest that a single static stretch sustained for 30-seconds daily over six weeks was sufficient to improve passive knee extension flexibility by approximately 11.5º to 12.5°. Additional repetitions or prolonged hold time demonstrated little advantage. A review of literature regarding PNF stretching has revealed a single repetition is adequate to induce change in range of motion (Sharman, Cresswell, & Riek, 2006). As these studies were performed on young healthy individuals, Nash (2005) has expressed concern with respect to the generalisability of such studies to an older population. A 2008 review of warm-up methods by Booth suggested that as individual muscle groups have variable response to stretch and heat, the optimal time to hold a stretch for a specific group is variable.

The physiological mechanisms of stretch

Magnusson, Aagaard, Larsson and Nielson (2000) have explained that static stretch is composed of two different phases, involving elongation of a muscle towards a desired length known as the ‘dynamic phase’, then maintenance at that length which is the ‘static phase’. When a muscle is taken beyond an initial onset of resistance, a greater degree of passive resistance develops in the muscle (Gajdosik, 2001). Within the ‘static phase’ creep deformation and stress relaxation processes occur. Spernoga et al. (2001) has described the process of ‘creep’ as tissue lengthening due to loading on the muscle, where as stress relaxation occurs due to a decrease of force over time in relation to a tissue maintained at a particular length. Such processes result in temporary viscoelastic changes in the muscle-tendon unit and decreased passive energy absorption (Gajdosik, 2001; Magnusson, Aagaard, Larsson, & Kjaer, 2000; Whatman et al., 2006). The muscle-tendon unit has shown decreases in stiffness from 22.9 to 20.6 N/mm and reductions in hysteresis from 20.6% to 13.5% following a 10-minute stretching session (Kubo, Kanehisa, Kawakami, & Fukunaga, 2001). The subsequent decrease in stiffness of the muscle-tendon unit is thought to be responsible for flexibility improvements seen in maximal range of joint motion and may exist from 10 to 20 minutes post stretch. Interestingly, Magnusson, Aagaard and Nielson (2000) identified that changes in viscoelastic properties may not occur beyond the first repetition of stretching performed in series. They studied the short-term effects on the viscoelastic properties of the hamstrings when three consecutive 45-second static stretches were performed. Although a 20% viscoelastic stress relaxation was observed and maximal joint flexibility improved in successive stretch repetitions, the resistance in the muscle to successive stretches did not reduce. The authors remarked that an increased tolerance to stretch was more likely responsible for successive joint range of motion changes, rather than further alterations in the viscoelastic properties of the muscle-tendon unit.

Heat has also been shown to enhance effects of stretch, as elevated tissue temperature permits further elongation of tissue. Knight, Rutledge, Cox, Acosta and Hall (2001) demonstrated that application of both superficial moist heat and ultrasound prior to stretch delivered slightly greater active and passive range of motion than stretching, and warm-up alone. The seven minutes of ultrasound producing deep heat produced an increase of 6.2° and 7.35° for active and passive ankle dorsiflexion, respectively.

Stretching methodologies such as PNF and MET are also thought to entail a neural-mediated component, involving either 'reciprocal inhibition' or 'autogenic inhibition'. These processes involve inhibition of the homonymous muscle via golgi tendon organs, and inhibition of alpha motoneurons in that muscle (Sharman et al., 2006), causing relaxation in the muscle. Motor pool excitability has been shown to diminish, improving muscle compliance and increasing length of muscle (Spernoga et al., 2001). Additionally, Mitchell et al. (2007) observed changes in subjective perception of stretch that increased the pain threshold and allowed for a greater degree of stretch before onset of discomfort.

Acute and long-term effects of stretch on flexibility

There is little evidence regarding the effectiveness of single session stretching and effect duration (Whatman et al., 2006). Immediate effects studies using static stretching parameters ranging from three to four repetitions of 20 to 30 seconds have reported significant improvements in passive and active range of 3 to 13° (Cronin et al., 2008; de Weijer et al., 2003; DePino et al., 2000; Whatman et al., 2006). However, studies have demonstrated only short and variable durations of effect for single stretching sessions. Whatman et al. investigated the effects of four 20-second static stretches of the hamstring muscle group. A small 4 to 5° increase in knee range of motion was noted, with a concurrent clinically significant change in passive musculotendinous stiffness. They noted that it was unclear whether these improvements lasted beyond five minutes. Spernoga et al. (2001) found a similar transient effect duration of six minutes in their modified hold-relax stretch program. DePino et al. (2000) observed a 6.8° increase in active knee extension one minute post stretch, that was maintained at minute three, but observed a return to baseline by six minutes post intervention. In contrast to those studies, de Weijer et al.(2003) reported changes in range immediately post-stretch of 13° that only began to decline 15 minutes post stretch. They noted that 24 hours post intervention there remained a residual increase of 7.7° in flexibility. These contrasting findings call for further investigation into the effects of acute stretching. The studies further highlight viscoelastic changes of such procedures are not permanent and remain in the elastic range of tissue deformation. Cronin et al. (2008) suggested that single-bout stretching prior to physical activity may have little benefit to performance due to its length of effect. Their participants rested for 10 minutes before the final measure, however, it is possible that individuals undertaking stretching as part of a warm-up could potentially experience longer-lasting benefits. Without maintained warm-up, to reap any benefits in flexibility, subsequent exercise would need to be within the brief window of flexibility increase, which appears to be between three and 15 minutes.

Long term-flexibility programs involving regular stretching regimens have proven beneficial in range of motion enhancement. Decoster et al. (2004) observed a three-week long hamstring stretching regimen, involving three repetitions of 30-second static stretches, in either standing or supine that resulted in range increases of 9.4° and 8.1° respectively measured by active knee extension test. Furthermore, a six week program of twice daily 30-second static hamstring stretches demonstrated similar improvements with an 8.9° improvement in active knee extension test angle (Webright et al., 1997), a result similar to that of Nelson and Bandy (2004) who found approximately a 12° improvement in the passive knee extension test. The long-term physiological explanation for such range changes is conflicting. While some believe viscoelastic changes are still principally responsible, Magnusson (1998) has presented evidence to suggest long-term stretching regimens do not significantly change the viscoelastic properties of the musculotendinous unit. Their study involving 20 days of five 45-second static stretches found no change in stiffness, energy or torque after this time. They proposed that range of motion changes over this time are in fact due to increased stretch tolerance.

The effect of stretching on performance

There have been mixed reports regarding the effect of stretching procedures on performance factors such as strength, power, and jump height, with some condemning stretch as a method of attenuation for such factors. Some studies have demonstrated such changes as reduction in maximal voluntary contraction of the quadriceps of 9.5% lasting up to 120 minutes (Behm et al., 2004; Power et al., 2004), countermovement jump-height reduction of 7.4% (Cornwell et al., 2002) and decreases in balance scores of 9.2% (Behm et al., 2004). In light of these results, many studies have also observed no change in such factors as vertical jump height (Unick, Keiffer, Cheesman, & Feeney, 2005), maximal voluntary contraction (MVC) for active knee extension (Behm et al., 2004) or MVC active dorsiflexion (Kubo et al., 2001) following acute stretch. A recent study (Ogura, Miyahara, Naito, Katamoto, & Aoki, 2007) suggested that detrimental effects of static stretching on maximal voluntary contraction may be time dependent, as a single 60-second stretch significantly decreased maximal voluntary contraction of the hamstring muscles, in comparison with a 30-second stretch group. The effects on performance remain unclear, and the mechanisms behind losses in performance not easily understood (Stone et al., 2006). Compliant muscle-tendon units have been shown to generate less power and force production, as consequence to less efficient energy transfer through the muscle-tendon unit, where greater degrees of stiffness in the musculotendinous demonstrates better transmission of forces, to move joints in explosive movements (Witvrouw et al., 2004). Reduced muscle stiffness has a role in down-regulating of nervous system responses, thereby altering stretch-reflex characteristics leading to less efficient force transmission, accompanied by decreases in performance such as power output and force development (Stone et al., 2006).

The relationship of stretching and injury prevention

Up until the last decade, there was little doubt with regard to the importance of stretching before exercise to reduce the risk of skeletal muscle injury. However, in recent years research has been contradictory, inconsistent and controversial regarding this area (Decoster et al., 2004; Nelson & Bandy, 2005; Whatman et al., 2006). With respect to this conflict, Witvrouw et al. (2004) stated that “no conclusive statements can be made about the relationship of stretching and athletic injuries” (p. 443). Nelson and Bandy (2004) argue that the hamstrings are the most frequently stretched muscles, yet they are also the most often strained. Witvrouw et al. (2004) held the opinion that stretching may only be effective in injury prophylaxis in sports requiring particular biodynamic movements. Explosive physical activities like jumping or bouncing, require greater muscle-tendon unit compliancy to meet demands of elastic energy absorption and release throughout stretch-shortening cycles. Less compliant tissues are at greater risk of approaching plastic range, and failure if forces exceed their capacity, resulting in injury. It is thought that stretching may be beneficial in risk reduction in such activities, due to scientific clinical evidence that stretching has an effect on tendon compliance by increasing tendon viscosity, and decreasing the degree of force generated in the muscle while it is under stretch. However, the case of such occurrences it is unclear whether any positive effects of acute stretching before intense exercise remain long enough to provide injury prophylaxis (Whatman et al., 2006). Other activities that operate through power generation by muscle work (using a positive work-loop) for locomotion such as running or cycling may not require such compliance, and therefore stretching prior to exercise may have little benefit with regard to injury prevention (Witvrouw et al., 2004).

WARM-UP TECHNIQUES

The aim of warm-up is much the same as that of stretching, to improve performance, range of motion and reduce the incidence of injury (Stewart & Sleivert, 1998). Anderson and Burke (1991) defined warm-up as “an activity that raises the total body temperature, as well as temperature of the muscles, to prepare the body for vigorous exercise” (p. 65). Examples of commonly used warm-up may include heat application, stair-climbing, stretching, light jogging, short sprints, and callisthenics (Booth, 2008; de Weijer et al., 2003; Woods, Bishop, & Jones, 2007). Such activities may directly relate to the succeeding activity, or may be completely unrelated, but all serve the purpose of sub-maximal exertion to increase muscle temperature, blood flow, range of motion, increase oxygen uptake, improve proprioception and balance, and excite neuromuscular tissues to increase the speed of neuromuscular response (Subasi, Gelecek, & Aksakoglu, 2008; Woods et al., 2007). Warm-up is strongly advocated by coaches and those in the sport-medicine field (Whatman et al., 2006), and should be specific to the athlete’s activity (Booth, 2008). According to Subasi et al. (2008) a period of 5 to 15 minutes of both related and unrelated warm-up activities is standard prior to vigorous exercise. Woods et al. (2007) indicate that warm-up should be performed within 15 minutes of the activity. Although warm-up is a very popular tool, there remain very few studies demonstrating the effects of warm-up to support anecdotal evidence (Stewart & Sleivert, 1998). Unlike other authors (de Weijer et al., 2003; Woods et al., 2007) who recommend stretching as part of a warm-up routine, Booth (2008) believes that the warm-up period should not be a time to attempt to elongate tissues to their maximal range, and disagrees that static stretch should be used within a warm-up protocol as it may result in muscle soreness, along with attenuation of strength.

The physiological mechanisms of warm-up

The physiological changes that occur with sub-maximal exertion in warm-up are thought to be due to increases in peripheral circulation to skin and muscle, as well as elevation in core temperature (de Weijer et al., 2003; Stewart & Sleivert, 1998; Woods et al., 2007). Increases in intramuscular temperature decreases muscle stiffness, and improves range of motion by permitting further elongation in the tissue (Knight et al., 2001). In contrast to this theory, Magnusson, Aagaard, Larsson and Kjaer (2000) found that a 10-minute warm-up of running on a treadmill elevated intramuscular temperature, but did not effect the passive viscoelasticity of the musculotendinous unit.

Factors contributing to warm-up effectiveness

Many warm-up protocols employ a combination of sub-maximal cardiovascular exercise with some form of stretching technique. Such combinations are thought to increase intramuscular temperature, and therefore potentiate effects of the stretching protocol (Stewart & Sleivert, 1998). De Weijer et al. (2003) reported the enhancing effects of 10 minutes of stair climbing at a 70% maximal heart rate on static stretches compared with only the cardiovascular component. A 14° increase in active knee extension range of motion was observed, while a non-significant increase of 1.2° resulted in the group undertaking only stair climbing. Such effects suggest that intramuscular temperature elevation plays a significant role in the effects of warm-up.

The intensity of a warm-up may not be a principal factor determining warm-up effects. Beedle and Mann (2007) sought to compare the effects of a challenging warm-up, in comparison to a less demanding stimulus in thirty healthy and active young adults. They compared a five-minute treadmill run at 70% of their maximal heart rate and six minutes of ballistic stretching, with a run at 60% max heart rate and six minutes of static stretching. No significant differences were apparent between the two groups when lower-back, active knee extension and plantar flexion flexibility were compared, suggesting that warm-up intensity and stretch type may have little impact on change in range of motion that occur in warm-up. Such observations are consistent with that found by Stewart and Sleivert (1998), who observed the acute effects of a warm-up routine in nine senior rugby union players, consisting of a 15-minute treadmill run at 60 to 80% VO_{2max}, followed by PNF stretching of the major lower-limb muscle groups. There was no relationship between the level of cardiovascular intensity to range of motion achieved post warm-up, as range achieved at the intensities of 60, 70 and 80% VO_{2max} were equivalent. Woods et al. (2007) suggests that it is ideal that warm-up intensity remain within 40-60% of VO_{2max} to ensure that warm-up does not fatigue the individual and cause detrimental effects to subsequent performance.

VIBRATION

Introduction to vibration training

The adverse effects observed from prolonged exposure to very high or low frequency is well documented in the literature (Griffin, 1990; Kerschan-Schindl et al., 2001; Lohman III, Petrofsky, Maloney-Hinds, Betts-Schwab, & Thorpe, 2007). However, safer use of such modalities has been the focus of vibration research, and has revealed a number of channels for its use ranging from treatment of neuromuscular spasticity conditions (Hagbarth & Eklund, 1968), balance and gait improvement in people with Parkinsons disease (Ebersbach, Edler, Kaufhold, & Wissel, 2008), and preservation of mobility in the elderly (Rees, Murphy, & Watsford, 2007). Low-frequency (less than 80Hz) vibration training is fast becoming a popular training method employed in recreational exercise as well as competitive athletics training (de Ruiter, van der Linden, van der Zijden, Hollander, & de Haan, 2003) as it is thought to improve muscular strength (Delecluse, Roelants, & Verschueren, 2003) and improve metabolism (Rittweger, Schiessl, & Felsenberg, 2001). Additionally, vibration may be a potential tool in recovery and rehabilitation from muscular injury (Fagnani et al., 2006), although this field is yet to be investigated.

There has been recent interest in the field of sport science with regard to the enhancement of strength and flexibility by both segmental (locally applied) and whole-body vibration (Cronin et al., 2008), with some promising results in both acute and long-term studies (Fagnani et al., 2006; Issurin et al., 1994). Unlike popular flexibility exercises such as stretching, vibration may improve range of motion without forgoing other neuromuscular performance factors (Kinser et al., 2008). Therefore, such vibration studies indicate a potential new method for warm-up, flexibility, and strength training that could preserve and enhance overall physical performance, beyond that that can be achieved by warm-up and stretching alone.

Vibration training parameters and equipment

In the field of sport science research, as well as recreational exercise, low-frequency low-amplitude segmental and whole-body vibration has been used to stimulate effects in target muscles or muscle groups. Involved in both kinds of vibration are numerous vibratory parameters that determine the kind of vibration a participant receives. These parameters include frequency, amplitude intensity, loading (Mester, Kleinoder, & Yue, 2006) and waveform (Cronin et al., 2007). Frequency has been defined as “the repetition rate of cycles of oscillation” (Cardinale & Wakeling, 2005, p. 585) while amplitude defined as the magnitude of oscillatory movement from peak to peak. Mester et al. (2006) has indicated that the “duration of the training session and inter-training resting phase, the length of the entire training period and the body position with respect to the vibration facility” (p. 1057) are equally important factors that may determine the degree of response in an individual.

A participant’s response to vibration is individual, variable at different frequencies and variable in the same person at different times. Additionally, responses may be different between different people (Griffin, 1990). Griffin summarised a number of key factors contributing to variability within and across participants responses as differences in “body dynamics, dimensions, masses, posture, age, gender, health, experience and training, attitude and motivation, as well as sensitivity and susceptibility” (p. 23). Such physical factors determine the degree of ‘resonance’ the vibration stimulus has with tissues of the body. Cronin et al. (2007) described the principle of ‘resonance’ as “when the movement frequency of the stimulus is matched by the natural frequency of the musculotendinous unit” (p. 34), and therefore as natural frequency is dependent on tissue composition the response is individual for each person.

As a whole, the body of literature remains inconsistent with regard to study design, placebo and control groups, and vibration parameters such as frequency, amplitude, loading, duration of exposure and rest periods between exposures (Cochrane & Stannard, 2005). The absence of a standardised approach is problematic, as while mainstream vibration training is becoming more popular there is little research on the positive and negative effects of different frequencies on neuromuscular performance (Cardinale & Lim, 2003). Authors (Cronin et al., 2007; Griffin, 1990; Nash, 2005) agree that a person’s response to vibration is individual, and that the response may differ between participants. Furthermore, there is yet to be development of technology or protocol that can determine an individual’s response or that individual’s ideal vibration load (Cardinale & Lim, 2003). Review of the literature shows that short durations from 20 to 60-seconds of whole-body sinusoidal vibration, ranging from 25 to 45 Hz, at an amplitude of 1 to 10 mm and accelerations of 3 to 17*g* are most frequently used, however, there is little evidence to support that such parameters are optimal for training programs or safe for the participant (Cronin, Oliver, & McNair, 2004; Jordan, Norris, Smith, & Herzog, 2005).

The only studies identified that attempted to investigate optimal parameters of vibration with respect to vibration's effects on flexibility enhancement, were performed on relaxed muscle. Cronin et al. (2007) and Nash (2005) investigated the acute effect of four different segmental vibration parameters on dynamic hamstring range of motion, when random waveform vibration was delivered for 30 seconds to a relaxed muscle. Parameters ranging from 33.2 to 49.4 Hz, with amplitudes of 3 to 5mm yielded the greatest improvement in the active knee extension test, with range of motion increases of 1.6 to 2.1% (mean increase of 2.4° to 2.9°), and effect sizes ranging from 1.15 to 1.77. However, these improvements were considered small, and not beyond the potential measurement error. Although it was unclear to what extent, if at all, waveform type contributed to neuromuscular response, the applicability of such studies to other sinusoidal vibration programs in which muscles are under stretch or in a state of contraction may be limited.

Posture is an additional factor that may determine the degree to which different muscles are affected by vibration. A study by Rohmert, Wos, Norlander and Helbig (1989) investigated the effects of a handheld drill, with vibration parameters of 30 Hz, 40 ms^{-2} acceleration for five minutes on EMG readings in muscles of the upper limb and cervico-thoracic region, in three different postures. They found that different postures changed the degree of vibration transmitted to those muscles under observation. They stated that "prime movers and muscles with increased muscle length or increased degree of contraction are most affected by vibration" (p. 248), as these muscles exhibited greater EMG levels. Additionally greater tonic vibration reflex responses have been noted in muscles on stretch during vibration exposure. It is for this reason that many vibration studies choose to place the participants in positions of muscle contraction, such as the squat (for example Cochrane & Stannard, 2005; Fagnani et al., 2006), or positions in which muscles are on stretch such as the forward split (Kinser et al., 2008; Sands et al., 2006), to enhance any effects beyond that which would be seen if the muscle was within a natural resting length. However, it must be considered that muscles at their resting length may also be affected by vibration, albeit to a lesser degree. While these studies appear promising in groups of semi-trained to highly trained athletes, the response of other populations is less certain. Issurin and Tenenbaum (1999) found that there was a greater change observed in an elite group of athletes in comparison to an amateur group, which they suspected was as a result of the more highly tuned nature of the elite athlete's peripheral and central nervous system which was more susceptible to additional stimulation. Kinser et al. (2008) found greater flexibility change in their population of gymnasts in comparison to a less trained group (Nash, 2005), which may indicate that highly trained athletes may be more susceptible and responsive to the effects of vibration interventions. Additionally, there has only been minimal exploration of the how such vibration-flexibility regimens would affect a normal, healthy untrained but recreationally active population (Nash, 2005) which warrants further investigation.

There are a range of vibration devices available commercially and designed for use in the research setting, including pulley machines (Issurin et al., 1994; Issurin & Tenenbaum, 1999), whole-body vibration platforms (Cochrane & Stannard, 2005) and localised 'segmental' vibration devices (Cronin et al., 2007; Kinser et al., 2008; Nash, 2005; Sands et al., 2006). The most popular machine commercially is the whole-body vibration platform, in which most participants stand in a squat position without any additional loading (Cochrane & Stannard, 2005; de Ruiter, van Raak, Schilperoort, Hollander, & de Haan, 2003). Many researchers who employ whole-body platform equipment in their studies do so with the aim to justify use of popular fitness programs by replicating such programs in the research setting (Delecluse et al., 2003). However, Jordan et al. (2005) have highlighted potential issues of using commercially developed equipment in the experimental setting as should machine calibration not be monitored it may deviate from factory specifications. Authors (for example Cronin et al., 2007; Sands et al., 2006) who have employed segmental vibration have not been as forthcoming with the rationale behind their decision to use local vibration over whole-body vibration. Although it could be assumed that such local vibration devices are of convenience to the specific postural position required of the participant for the protocol. Additionally, local vibration may be viewed as advantageous with regard to safety, as only the muscle area of interest is exposed to the vibration, minimising risk of transmission to undesirable areas of the body such as the head or low-back (Griffin, 1990).

The relationship between vibration and injury

The potential for injury from low-frequency vibration training remains unclear, and for the most part not discussed in whole-body or segmental vibration studies investigating performance and flexibility. Although the body of knowledge derived from the occupational health and safety field regarding the numerous dangers associated with prolonged, frequent exposure very high or low frequencies and amplitudes of vibration is large (Griffin, 1990; Lohman III et al., 2007), little comment has been made with regard to recreational exposure. The 2004 study by Cronin et al. reported whole-body vibration induced injury lasting seven to ten days, following a program consisting of five 60-second exposures of 26 Hz frequency, 6 mm amplitude and 15 *g* acceleration with rest periods of 60-seconds between. The untrained participants experienced pain in the jaw, neck, and muscles of the lower extremity in response to vibration, which required physical therapy treatment. Cronin et al. noted that no adverse effects from vibration training have been reported in other similar studies, however, most studies have focused on highly trained athletes and the degree of muscular conditioning is far greater in such populations. Cronin et al. are among other authors (Cardinale & Bosco, 2003; Cardinale & Wakeling, 2005; Jordan et al., 2005; Mester et al., 2006) that have identified a significant need for further research regarding dose-response relationships to ensure safe prescription of vibration training methods.

Studies investigating performance-enhancing effects of vibration

Vibration exercises for performance enhancement are becoming more popular in recreational exercise and for competitive athletics. Likewise, there are increasingly more studies attempting to find scientific evidence to verify anecdotal effects (Cronin et al., 2004). However, there remains little research in this field to support the large commercial claims for the use of vibration training equipment (Cardinale & Wakeling, 2005). Delecluse et al. (2003) are also very critical of the studies that are not placebo controlled and therefore do not adequately differentiate the degree that vibration contributed to the effects observed.

A range of performance outcome measures has been investigated with respect to local and whole-body vibration, some with very contrasting results. Significant improvement in maximal dynamic leg press scores ($p<0.05$ to 0.005) at different loadings, with an alteration of the force-velocity and power-force curves has been reported (Bosco, Colli et al., 1999). Additionally increases of dynamic knee extensor strength of 16.6%, 9% ($p<0.001$) (Delecluse et al., 2003) and 11.2% (Fagnani et al., 2006) were reported subsequent to long-term whole body vibration training. In contrast to these findings, de Ruiter, van der Linden et al. (2003) reported that an acute five-minute exposure of whole-body vibration decreased maximal voluntary knee extension force by 7% ($p<0.05$) and took three hours to return to baseline. Jackson and Turner (2003) found that prolonged vibratory stimulation of the quadriceps femoris muscle at 30 Hz and 120 Hz continuously for 30 minutes reduced neural activation measured by EMG, and also significantly reduced the maximal knee extension force and rate of force generation in the quadriceps ($p<0.05$). One long-term whole-body vibration study (de Ruiter, van Raak et al., 2003) lasting 11 weeks found no change in knee extension force.

Such inconsistencies extend to explosive strength performance measures such as jump height. Cronin et al. (2008), Kinser et al. (2008) and de Ruiter, van Raak et al. (2003) reported no significant change in counter movement jump in their immediate effects studies, however, other studies have observed improvements in counter movement jump height ranging from acute changes of 8.7% ($p<0.05$) (Fagnani et al., 2006) to long term study changes of 7.6% when the test was performed without arm-swing (Delecluse et al., 2003) and 8.1% ($p<0.001$) performed with arm-swing (Cochrane & Stannard, 2005).

Upper limb performance has also been investigated, with findings demonstrating significant increases in maximal elbow flexion strength in elite boxers ($p<0.001$) (Bosco, Cardinale, & Tsarpela, 1999). Additionally, both elite and amateur athletes have shown improvements in maximal bicep curl strength of 10.4% and 9.7% respectively following a single session of local vibration superimposed with strength exercises (Issurin & Tenenbaum, 1999). A three-week trial involving male athletes produced increases as large as 49.8% in maximal isotonic strength (Issurin et al., 1994).

It remains unclear to what extent vibration training can enhance performance. The conflicting evidence found in the literature emphasises that response to vibration can be variable. Differences in vibration protocol and parameters may be a strong contributing factor (Jordan et al., 2005; Mester et al., 2006). Cardinale and Wakeling (2005) propose that failure to stimulate muscles at their resonant frequencies may be a factor owing to the poor response in some studies. Also, Issurin (2005) suggested that variable results may be due to differences the length of vibration exposure and also the sample populations. The author noted that positive effects were observed following 10 minutes of vibration performed on athletes, while those studies of smaller duration (four minutes) had little response. The majority of research that has been conducted has included club level to elite athletes, and therefore may not be applicable to the untrained population (Cronin et al., 2004).

Studies investigating the effects of vibration on enhancement of flexibility

Until now much of the sport science research on the neuromuscular effects of vibration has focused on performance factors such as maximal strength, power and total work (Cronin et al., 2008; Nash, 2005). More recently vibration for flexibility enhancement has become increasingly popular in this field. While there have been relatively few studies undertaken to date, those identified in the literature appear to demonstrate either clinically insignificant effects (Nash, 2005) or positive results (Fagnani et al., 2006; Issurin et al., 1994; Kinser et al., 2008; Sands et al., 2006; van den Tillaar, 2006). Cochrane and Stannard (2005) indicate that lack of a consistent experimental approach in employing comparable interventions combined with the dearth of literature may be a factor contributing to such mixed results. Study designs are similar in some respects (refer to Tables 4 and 5), but vary in choice of vibration equipment, vibration parameters, exposure length and study durations, ranging from single-session to four-week training regimens. In addition, either whole-body vibration or local vibration programs have been employed, which place the participant in different positions and therefore affect muscles in different states of contraction, stretch and resting length (Rohmert et al., 1989; Subashi, Matsumoto, & Griffin, 2008). While most of this type of research appears promising, a lack of continuity in study design has expanded the breadth of knowledge, but not the depth, and therefore demands more thorough investigation.

Of the small number of local and whole-body vibration studies performed, the studies have focused upon vibration exposure mostly applied to the lower limb (see Tables 4 and 5). Studies can be categorised by the degree of stretch and contraction, or lack thereof, of the muscle exposed to vibration, which may have contributed to the mixed results observed (Issurin & Tenenbaum, 1999).

Vibration applied to muscle in a relaxed state

Only a small number of studies (Cronin et al., 2007, 2008; Kinser et al., 2008; Nash, 2005) were identified in the literature that observed the flexibility effects of low-frequency vibration applied to muscle within its resting length, and all involved locally applied vibration (see Table 5). Of those, all have been single session vibration studies, observing immediate effects on range of motion post intervention. The literature reports varied responses to vibration of this kind, ranging from no significant effect to moderate effect sizes. Positive results include small increases in hamstring range of motion of 1.6 to 2.1% (ES = 1.15 to 1.77) in a small sample of active males (Cronin et al., 2007; Nash, 2005) and large increases in right, left and favoured leg forward split flexibility of 9.1% to 10% (ES = 0.25 and 0.30 respectively) in trained gymnasts (Kinser et al., 2008). The positive results observed by Kinser et al. contrast those reported by Nash (2005) and Cronin et al. (2008) who found under similar parameters and exposure time no significant change in hamstring range of motion in a smaller, less trained population. Although these studies used similar vibration parameters of 30 to 34 Hz and 2 to 3 mm amplitude, participants received different oscillatory waveforms (sinusoidal and random). It appears that sinusoidal waveform vibration had better results, and although Nash (2005) and Cronin et al. (2007) did not postulate the reasons for different effects of waveforms, they acknowledge this difference as a possible factor contributing to the poor results they found. Additionally it cannot be ruled out that elite athletes such as the gymnasts may have been more susceptible to the stimulation than the less trained group, due to the highly tuned nature of their neuromuscular system (Issurin & Tenenbaum, 1999). Overall, the insignificant to moderate effect sizes seen in literature as a whole may be of consequence to sub-optimal vibration exposure times, different oscillatory waveforms (Cronin et al., 2007), small sample sizes that are under-powered and the resting state of the muscle at the time of vibration (Kinser et al., 2008). Vibration applied to resting muscle length requires more research to provide a baseline effect measure by which to compare other studies involving some degree of stretch or contraction.

Vibration applied to muscle on stretch

As muscle under some degree of stretch or contraction is more affected by vibration (Rohmert et al., 1989; Subashi et al., 2008), there is growing interest in ‘segmental’ vibration applied concomitantly to muscle in a lengthened state to enhance flexibility.

Thus far such vibration-stretch studies have yielded far greater results than local vibration as a stand-alone intervention, with some authors concluding that "superimposed vibrations applied for short periods allow for increased gains" (Issurin et al., 1994, p. 561) in flexibility. Reported results from single session vibration studies include 17.6% to 19.5% (ES = 0.65 and 0.78 respectively) increases in forward split flexibility in young female gymnasts (Kinser et al., 2008) and effect sizes of 1.67 to 2.19 in young male gymnasts (Sands et al., 2006). Kinser et al. reported that the forward split flexibility increases observed in their study were almost twice that of the group that received vibration to relaxed muscle under the same conditions, suggesting that simultaneous vibration and stretch improve flexibility to a greater degree than vibration alone (see Table 5). In a more long-term study (Issurin et al., 1994), a three-week simultaneous vibration-stretch program using an oscillating ring produced an 8.7% increase in a 'two-leg split across' exercise, and 43% increase in sit-and-reach test. This result exceeded a group undertaking only contract-and-release stretch by 6.3% and 24.4% respectively. Sands et al. (2006) conducted a four week study, in which they reported effect sizes of 1.4 and 0.84 for right and left legs respectively in the forward split position. Such results indicate that concomitant stretch and vibration may enhance flexibility to a greater degree than vibration and stretch alone.

While simultaneous vibration-stretch programs appear promising, research that involved vibration immediately followed by stretch provided more contrasting results. Nash (2005) conducted an acute study, in which participants alternated between static stretch and then vibration to a relaxed muscle. The author found no significant change in range of motion post intervention. No other immediate-effects studies of this kind were identified in the literature, and therefore no comparison can be made, however, again the random waveform vibration oscillation and resting state of muscle used in this study may have contributed to the poor results. In contrast, van den Tillaar (2006) observed more beneficial results in a long-term study investigating the effect of whole-body vibration followed by the contract-and-release method of stretching over a four week period. Whole-body vibration alternating with contract-and-release stretch proved more effective than stretch alone in increasing hamstring flexibility, demonstrating a 30% (mean increase 26.8°) improvement in the straight leg-raise test, which surpassed the 14% (mean increase 12.4°) achieved by the stretch group ($p = 0.002$). Van den Tillaar suggested that whole-body vibration may have the potential to significantly enhance the effects of conventional stretching protocols on hamstring flexibility, however, in light of the acute results found by Nash (2005) further research is required.

Vibration applied to contracted muscle

All identified whole-body vibration studies applied vibration to muscles in a contracted state, for example, in an upright squat position. Participants were positioned upright in isometric squats with knees at angles varying from 90° to 120° while vibration was applied from a vibrating plate beneath the feet (Cochrane & Stannard, 2005; Fagnani et al., 2006; van den Tillaar, 2006). In this squat posture many muscle groups would be contracted in the lower limb and torso (Subashi et al., 2008). Muscle that is under a state of contraction or stretch is believed to be more susceptible to the effects of vibration, and therefore researchers believe any effects would be enhanced by such positioning (Rohmert et al., 1989; Subashi et al., 2008).

Due to the nature of the wide-spread body vibration transmission that occurs with whole-body vibration, two of the three whole-body vibration flexibility studies identified (Cochrane & Stannard, 2005; Fagnani et al., 2006; van den Tillaar, 2006) utilised the sit-and-reach test as the flexibility measure, which as a test would measure the impact of vibration on not just the posterior musculature of the lower limb, but also the back. Cochrane and Stannard (2005) measured the immediate effects of a single session whole-body vibration protocol on vertical jump height and flexibility in 18 female elite level hockey players (21.8 ± 5.9 years). After a single five-minute vibration session at 26 Hz and 6 mm amplitude, in six sustained standing and squatting postures they reported an 8.2% increase ($p<0.05$) in sit-and-reach flexibility, beyond that achieved by a cycling and control group that both improved by approximately 5.3 ± 5.0%. Improvement seen in the control group may be attributed to and highlight the absence of a warm-up in this study, which due to effects of repeated stretch on muscle may distort the degree by which the vibration group improved. In a long-term graduated vibration training program over eight-weeks, Fagnani et al. (2006) observed greater sit-and-reach test flexibility gains than Cochrane and Stannard, yielding a 13% increase ($p<0.05$) in sit-and-reach flexibility, with no significant improvement in the control group. Although positive, these two results are far less than that reported by Issurin et al. (1994) who found an 43.6% increase in sit-and-reach test when local vibration was applied simultaneously with stretching, which may suggest that local vibration with

Table 4. Summary of Range of Motion Studies Using Whole Body Vibration Interventions

Authors	Participants	Duration	Intervention	Vibration Type	Outcome Measure	Mean ROM Change	Effect Size or p-value
Cochrane and Stannard (2005)	18 female highly trained 21.8 ± 5.9 yrs	Acute pre-post	No warm-up **1) Vibration: 5mins WBV in 6 positions** 2) Control: No intervention 3) Cycling: 50rpm 50W x 5mins	WBV vertical sinusoidal 26Hz 6mm	Sit & Reach test	**Vibration group = ↑ 8.2 ± 5.4%** vs. control ↓ 5.3 ± 5.1% and cycling ↓ 5.3 ± 4.9%	$p<0.05$
Fagnani et al. (2006)	24 female highly trained 21-27 yrs	Long term 8 weeks	10-minute warm-up **1) Vibration: Sport training and graduated WBV squatting of 30-60secs, 1min rests x variable sets x 3 sessions x 8 weeks** 2) Control: sport training only x 8 weeks	WBV vertical sinusoidal 35Hz 4mm 17*g*	Sit & Reach test	**Vibration group = ↑ 13%** vs. control group = no significant change ($p=0.2$)	$p<0.001$
van den Tillaar (2006)	18 male & female trained sport students 21.5 ± 2.0 yrs	Long term 4 weeks	5-minute warm-up **1) WBV & stretching: WBV 30secs x 6 reps squatting alternating with contract and release stretching x 3 sessions x 4 weeks.** 2) Stretch: contract and release stretching as above, no WBV	WBV vertical sinusoidal 28Hz 10mm	Passive straight leg raise test	**WBV & stretch = ↑ 26.8°** Stretch = ↑12.4°	$p=0.002$

Note: WBV = Whole body vibration, used in variation of squat position, trained = physically active sport science students, highly trained = elite sports people/athletes competing at a high level, Exp = experimental vibration group. Items in bold represent a vibration intervention.

Table 5. Summary of Range of Motion Studies Using Segmental (Local) Vibration Intervention

	Participants	Duration	Intervention	Vibration Type	Outcome Measure	Mean ROM Change	Effect Size or p-value
Cronin et al. (2007)	10 male trained athletes 22.7 ± 3.6 yrs	Acute pre-post	5-minute jogging warm-up **Each participant was exposed to 30 secs at four settings, with a 15 min rests on relaxed muscle**	Local random waveform 14 - 44Hz 3 - 5 mm 19.3–49.4 ms^{-2}	Dynamic active knee extension test	↑1.6 - 2.1% overall Greatest increase in ROM setting 4 at 44Hz 5mm* = 3.1° (↑2.1%) *Not significantly different to 24 and 34Hz	≥ 1.2 (from 1.15 to 1.77)
Issurin et al. (1994)	28 male trained 19-25 yrs	Long term 3 weeks	7-10 minute warm-up **1) Group A: leg flexibility stretch with superimposed vibration, normal arm strength exercises.** 2) Group B: arm strength exercise with superimposed vibration, normal leg stretch exercises. 3) Control: Irrelevant training All had 3 sessions x 3 weeks	Local sinusoidal 44Hz 3mm 22 ms^{-2}	Two-leg split across Sit & Reach test	Group A = ↑ 8.7% vs. group B ↑ 2.4% and control ↑ 1.2% Group A = ↑43.6% vs. Group B ↑19.3% and control ↑5.8%	**p<0.001**
Kinser et al. (2008)	22 female highly trained gymnasts 11.3 ± 2.6 yrs	Acute pre-post	No warm-up specified **1) Vibration alone: 4 x 10 sec, 5 sec rests in 4 positions for x 3 reps on relaxed muscle** **2)Vibration & stretching: as above, with muscle on stretch.** 3)Stretch alone: Stretching over device, with no vibration.	Local 30Hz 2mm	Forward split flexibility	**Vibration alone (leg)** **Right = ↑9.1 ± 6.9%** **Left = ↑10 ± 11.4%** **Favoured = ↑9.8 ± 11.7%** **Vibration & stretch (leg)** **Right = ↑18.6 ± 10.4%,** **Left = ↑18.5 ± 7.8%** **Favoured = ↑19.5 ± 9.5%** Stretch alone (leg) Right = ↑2.0 ± 4.8% Left = ↓1.9 ± 8.2% Favoured = ↑0.2 ± 7.8%	**R: 0.25** **L: 0.30** F: 0.26 **R: 0.67** **L: 0.72** F: 0.78 R: 0.08 L: 0.05 F: 0.01

Note: Small effect sizes are ≤ 0.2, moderate 0.2 < ES < 0.8, and ≥ 0.8 large. Items in bold indicate vibration intervention

Contd. Table 5. Summary of Range of Motion Studies Using Segmental (Local) Vibration Intervention

	Participants	Duration	Intervention	Vibration Type	Outcome Measure	Mean ROM Change	Effect Size (d) or p-value
Cronin et al. (2008)	10 male recreationally-active 22.7 ± 3.6 yrs	Acute pre-post	**1) Vibration: 3 x 30 secs, 30 sec rests on relaxed muscle** **2) Vibration alternating stretch: vibration as above, alternating with 3 x 30secs static hamstring stretches on device** 3) Stretching: 3 x 30 secs hamstring stretches on device	Local random waveform 34Hz 3mm 42.2ms^{-2}	Dynamic active knee extension test	**Vibration alone: no significant change ↑0.02° at 10 mins post**	**p>0.05**
						Vibration and stretch: no significant change. ↑1.9° at 10 mins post	**p>0.05**
						Stretch: significant ↑2% (3.0°) at 10 mins post	0.4 p<0.05
Sands et al. (2006)	10 male highly trained gymnasts 10.1 ± 1.5 yrs	Acute pre-post	Warm-up of walking, jogging, light stretch, tumbling **Vibration: 4 x 10secs, 5 sec rests, in 4 positions (total of 4 mins) right and left legs** Control: 4 mins total in 4 positions without vibration right and left legs	Local sinusoidal 30Hz 2mm	Forward split flexibility	**Vibration group** **Right rear split d = 2.19** **Left rear split d = 1.67**	**p<0.01** **p<0.05**
						* control not reported	**-**
		Long term 4 weeks	**Vibration: as above 5 sessions x 4 weeks** Control: as above, no vibration	As above	Forward split flexibility	**Vibration group** **Right rear split**	**1.37** **p<0.05**
						Left rear split	**0.84** **p>0.05**
						Control	**p > 0.05**

Note: Small effect sizes are ≤ 0.2, moderate 0.2 < ES < 0.8, and ≥ 0.8 large. Items in bold indicate vibration intervention.

simultaneous stretch may be a more effective method of flexibility enhancement over whole body vibration to contracted muscle.

The physiological mechanisms of vibration on muscle

The physiological mechanisms underpinning any changes in flexibility or performance as a result of segmental or whole-body vibration are poorly understood and remain speculative at best (Cronin et al., 2004). Optimal frequencies for muscle stimulation have been investigated to an small extent. Cardinale and Lim (2003) investigated the effect of whole-body vibration on EMG at frequencies of 30, 40 and 50 Hz. The vibration stimulus was applied to the vastus lateralis muscle when the participant was positioned in a half-squat position on the platform. The 30 Hz frequency stimulus evoked the greatest EMG activity. Another study (Bosco, Cardinale, & Tsarpela, 1999) has demonstrated similar findings upon stimulation of the biceps brachii, however, other authors (Issurin et al., 1994; Issurin & Tenenbaum, 1999) considered 40 to 50 Hz to be optimal, based on an assumption that at that frequency motoneurons have greater capacity to synchronise for more efficient force production.

The theoretical physiological mechanism of vibration on flexibility

The exact mechanism of the effect of vibration on muscle flexibility remains unclear, but there are a number of hypothesised mechanisms that underlie flexibility enhancement by vibration. Issurin (2005) identified these mechanisms as “neural, circulatory and thermoregulatory factors” (p. 326). Vibratory stimulation of Ia neural components and the proprioceptive loop is thought to provoke analgesic effects in muscle entailing increases in pain threshold thereby increasing the degree of stretch achievable before onset of discomfort or pain (Cochrane & Stannard, 2005; Sands et al., 2006), which van den Tillaar (2006) described as “the proprioceptive feedback potentiation of inhibition of pain” (p. 195). In support of pain threshold increases post vibration, Sands et al. (2006) reported anecdotal evidence of participants having greater ease in stretch, and therefore surpassing their normal range, as consequence to the intervention. However, Lundegburg, Nordemar and Ottoson (1984) noted little to no reduction in pain perception at frequencies below 50 Hz, while Panteleo, Duranti and Bellini (1986) found that low frequency vibration of 30 Hz did not increase muscular pain threshold.

Short-term vibration conducted at low frequencies has been demonstrated to induce vasodilation of peripheral vessels, thereby improving blood flow to tissues, without creating significant changes in heart-rate or blood pressure (Kerschan-Schindl et al., 2001; Lohman III et al., 2007). Such increases in circulation, along with tissue friction generated during vibration, are said to contribute to elevation of intramuscular temperature (Fagnani et al., 2006; Issurin, 2005; Kerschan-Schindl et al., 2001). A study by Cochrane, Stannard, Sargeant and Rittweger (2008) found the rate of temperature increase during whole-body vibration to be greater than that achieved by an active warm-up involving cycling or by passive warm-up in a hot bath. Intramuscular temperature rises have been associated with reduced viscous resistance in the musculotendinous unit (Cronin et al., 2004), and therefore it could be presumed that an increase in heat would facilitate better flexibility (Fagnani et al., 2006; Issurin, 2005; Nash, 2005).

The nervous system is suspected of playing a large role in the changes in flexibility following whole-body and segmental vibration. During vibration, some authors believe that vibration stimulus excites the golgi tendon organ, that causes monosynaptic reflex suppression (Jordan et al., 2005). The resultant inhibition and relaxation of the agonist is then exploited to improve flexibility (Bishop, 1974; Fagnani et al., 2006; Issurin, 2005). However, vibration is assumed to create greater degrees of excitatory response in the muscle spindles, surpassing that of the golgi tendon organ (Cardinale & Bosco, 2003). In the post vibratory period 'reciprocal inhibition' is one of the proposed neurophysiological methods by which vibration is said to improve flexibility, as vibration has been shown to inhibit antagonist muscle afferents via the corticospinal tract (Bishop, 1974; Kossev, Siggelkow, Kapels, Dengler, & Rollnik, 2001; Lundeberg et al., 1984). Cochrane and Stannard (2005) believe that whole-body vibration may create neural potentiation of the stretch reflex loop and inhibit the antagonist muscle via Ia interneurones. They theorised intramuscular co-ordination would change, and decrease breaking force about joints to facilitate greater stretch. Cochrane and Stannard go on to explain that stretch loading at the time may dictate which reflexes dominate and therefore spindle response may over-ride and suppress golgi tendon organ firing. Nash (2005) and Cronin et al. (2008) have discussed such neurological processes with respect to flexibility enhancement and highlighted that increases in stretch-reflex loop activity and increases in the number of motor units recruited may very well heighten sensitivity and resistance to stretching. The authors queried whether range of motion improvements would be based upon increased temperature and pain threshold that surpass the reflexes that dominate.

The theoretical physiological mechanism of vibration on performance

Most vibration programs and studies with the aim of enhancing performance factors other than flexibility have generally used whole-body vibration protocols. Both stretching and vibration exercise techniques are thought to target similar tissues, and therefore may have a degree of similarity in their effects on flexibility of the muscle tendon unit (Nash, 2005). It is for this reason that vibration training has been paralleled to resistance training by some authors (Bosco, Colli et al., 1999; Fagnani et al., 2006), who believe that short durations of whole-body vibration at 26 Hz may have the equivalent effects of intense resistance training sessions over several weeks. Issurin and Tenenbaum (1999) have indicated that motor pool activation, frequency of stimulation and initial length of the stimulated muscle are determining factors dictating responses to vibration. Neuromuscular performance is enhanced by way of “recruitment, synchronisation, inter- and intramuscular coordination and also proprioceptors responses” (Cardinale & Lim, 2003, p. 621).

Regardless of slight discrepancies in frequency, the resultant neural activation caused by vibration been described as a “dramatic enhancement of the neural traffic regulating neuromuscular behaviour” (Bosco, Colli et al., 1999, p. 186). In simple terms vibration induces rapid changes in muscle length, which facilitates excitability in spinal reflexes (Cardinale & Bosco, 2003). Neural activation begins at the level of the primary afferent endings, which stimulate excitatory flow through Ia muscle spindles. The stimulation of alpha motoneurons are then up-regulated, and result in increased motor pool recruitment, and initiate concentric-eccentric contractions in muscle, similar to the tonic vibration reflex (Bosco, Colli et al., 1999; Cochrane & Stannard, 2005; Delecluse et al., 2003; Issurin & Tenenbaum, 1999). The resultant neural potentiation or ‘adaptation’ has been shown to improve neuromuscular efficiency by better synchronisation of units and neural drive, while increasing muscle tension. The ensuing augmentation of muscular power occurs simultaneously with decrease in the EMG/power ratio (Bosco, Cardinale, Tsarpela, & Locatelli, 1999). Input from gamma motoneurones is thought to further enhance this mechanism by increasing sensitivity of primary endings (Cochrane & Stannard, 2005). Central motor command is altered by vibration. The supplementary motor area of the brain becomes activated, and combined with the heightened excitation in the peripheral the nervous system contribute to the level of force generated in movement. Although evidence is building with respect to the neurophysiological mechanism behind vibration, the extent to which reflexes are evoked remains uncertain (de Ruiter, van der Linden et al., 2003).

The tonic vibration reflex is the involuntary reflexive muscle contraction that may occur as a result of mechanical vibration stimulus applied to skeletal muscle. This reflexive activity results in involuntary muscle contraction and additional motor unit recruitment (Hagbarth & Eklund, 1968). It is believed that subsequent reflexive activity operates through reciprocal inhibition and relaxation of antagonist muscles (de Ruiter, van der Linden et al., 2003) while increasing recruitment and activating polysynaptic pathways (Cochrane & Stannard, 2005). Vibration applied at approximately 30 Hz can evoke a tonic vibration response in muscle. Its elicitation is said to be dependent on the muscle length and degree of contract that muscle is under at the time of vibration (Rohmert et al., 1989). It remains unclear which parameters have the ability to provoke an optimal tonic vibration reflex in muscle (Jackson & Turner, 2003). One benefit to performance is that the nature of the concentric-eccentric contractions that occur may have the potential to improve metabolic power in tissues, with improved oxygen uptake (Rittweger et al., 2001).

While residual effects from acute bouts of whole-body vibration are thought to come about due to improved peripheral blood flow, intramuscular temperature increases and augmented sensitivity of receptors (Issurin & Tenenbaum, 1999), the long term effects that come as a result of regular vibration application are considered much like the process that occurs in resistance training called ‘neural adaptation’ (Bosco, Cardinale, Tsarpela et al., 1999; Delecluse et al., 2003). Like resistance training, the first changes to be seen in response to vibration training are neurological changes, before any changes in the morphological structure of muscle itself occur (Bosco, Colli et al., 1999). Ongoing regular intermittent stimulation of the nervous system creating fatigue is thought to produce a biological adaptation as response to neural potentiation that results in permanent enhanced activation and co-ordination of muscles, creating improvements in strength (Delecluse et al., 2003). One study (Bosco, Colli et al., 1999) indicated that such a process may even begin following a short 10-minute single exposure to low frequency vibration, however, Delecluse et al. disagree that the degree of fatigue required to produce neural adaptation can be achieved in normal durations of whole-body vibration, and furthermore only moderate fatigue has been observed in single training sessions (de Ruiter, van Raak et al., 2003).

Some changes observed in performance have been attributed to changes in viscoelasticity of muscle, in that alterations in musculotendinous stiffness may contribute to increases in strength, power and other performance measures. For the most part this assumption was based upon theory rather than actual evidence. A 2004 study by Cronin et al. observed insignificant alterations in muscle stiffness post vibration. Further investigation regarding proposed changes in muscle-tendon unit stiffness post vibration is required.

Perhaps one of the more important findings to emerge from research is that prolonged vibration exposure is detrimental to motor performance, as such stimulation depresses spinal reflexes through “localised cortical effects” or “reduction in peripheral transduction of central drive to motoneurons” (Jackson & Turner, 2003, p. 384). Jackson and Turner observed a reduction in maximal knee extensor force following continual stimulation for 30 minutes by either 30 Hz or 120 Hz of vibration. Although both frequencies resulted in pronounced loss of force, the 30 Hz parameter resulted in the greatest attenuation of maximal knee extensor force, emphasising the influence that this particular frequency has on the neuromuscular system.

Crossed effects

All of the vibration-flexibility studies (whole body or segmental) identified in the literature have delivered vibration to both sides of the body or else only observed same-side effects of stimulation in a unilateral limb. Stimulation of both sides may avoid potential issues related to possible neurological crossed effects that could occur in a contralateral limb in response to ipsilateral muscular stimulation. ‘Crossed effects’ have been described by Jackson and Turner (2003) as “a phenomenon where exercise of one limb can produce beneficial effects in the contralateral limb” (p. 380). There has been little investigation with regard to crossed effects of muscular vibration on contralateral non-vibrated musculature (Kossev et al., 2001) and there is conflicting evidence as to the existence of this effect. In their 2003 study, Jackson and Turner observed effects to suggest that prolonged vibratory stimulation might have such an effect. Unilateral rectus femoris muscles were persistently stimulated for 30 minutes at either 30 Hz or 120 Hz. Although no neuromuscular activation (EMG change) was observed in the contralateral limb in response, there were significant reductions in maximal force and maximal force generation in both legs. The authors suggested that the contralateral effects may be due to “an effect on heteronymous motoneuron pools or an effect acting on central descending drive to contralateral muscles” (p. 380). As muscle vibration is thought to induce increased cortical activation, crossed effects may be of consequence to interhemispheric inhibition of outputs to the contralateral side governed by transcollosal pathways (Kossev et al., 2001). Kossev et al. demonstrated this theory, with vibration of the extensor carpi radialis muscle at 80 Hz amplitude 0.5mm for 4-seconds followed by transcranial magnetic stimulation, demonstrating a significant reduction of motor-evoked potentials to contralateral homonymous antagonistic muscles of the forearm, remaining one-second post vibration. Jackson and Turner suggested such results indicate a cross extension reflex in which stimulation of an agonist on an ipsilateral side causes an effect in an antagonist in the other limb. It should be highlighted that the duration of stimulation used by Jackson and Turner would induce fatigue in the muscle and is not consistent with common vibration training regimens. Likewise, the frequency at which Kossev et al. conducted their study is greater than the frequency used in vibration training programs.

There are a few studies (Bosco, Cardinale, & Tsarpela, 1999; Bosco, Cardinale, Tsarpela et al., 1999; Bosco, Colli et al., 1999; Cronin et al., 2004) that have investigated vibration’s effect on strength, applied from five to 10 minutes of vibration with rest intervals, to unilateral upper extremity and lower extremity limbs, while the contralateral limbs acted as the control. Although improvements in strength in the ipsilateral vibrated limbs were observed in some studies, they identified no changes in the contralateral limbs in the performance measures used. These authors did not discuss the possibility of crossed effects in their study. It is uncertain to what extent the crossed effects observed by Kossev et al. and Jackson and Turner can be applied to exercise vibration studies which apply vibration at either different frequencies, or for shorter durations with rest periods. Although evidence is minimal, consideration of such possibilities is important in interpreting studies using the contralateral limb as a control when vibration is delivered unilaterally, for a short period.

CONCLUSION

There are numerous techniques for flexibility enhancement that have been employed for decades and remain advocated by coaches, sport science researchers and sports medicine practitioners. Two of the most common methods used are static stretch and warm-up. Although they are employed with great confidence, there remains little finite scientific research with respect to optimal parameters for their use and which are most effective with respect to improvement of range of motion and duration of effects. Additionally, methods like static stretch appear to produce significant range of motion changes potentially at the expense of performance factors like power and strength. The underlying mechanisms behind stretch and warm-up are yet to be fully understood and require further in-depth analysis to provide substantial evidence to support their continued use.

Vibration training is a relatively new exercise method that has quickly risen to popularity with little clinical evidence of its effects and the underlying mechanisms involved. Results have been promising in this field, in terms of fast and significant performance changes that may preserve and improve both strength and flexibility, unlike other flexibility techniques such as static stretch. However, this field of research is still young and similar gaps in the literature exist with regard to optimal training parameters, as for stretching and warm-up. There remains no conclusive evidence to validate the use of vibration strength and flexibility training, although the body of knowledge is rapidly growing. Vibration applied from 24 to 44Hz and 3 to 5mm amplitude may be effective in creating significant improvements in hamstring flexibility when random waveform is used, although it is unclear what duration of exposure is ideal. There appears to be little evidence to support the existence of 'cross-over' effects in a contralateral limb subsequent to prolonged or high frequency vibration exposure. Furthermore, it is uncertain whether such an effect would occur at the low frequencies and short durations commonly used in vibration training protocols. Further investigation is required across the scope of the field, especially with regard to validating anecdotal claims, and understanding the effects of different vibration parameters on the various subsets of the population.

CHAPTER 4: RELIABILITY OF THE PASSIVE STRAIGHT LEG RAISE AND THE ACTIVE KNEE EXTENSION TEST

INTRODUCTION

When change is observed in participants over the course of a study, it cannot be assumed that the change is primarily of consequence to the given intervention (Kropmans, Dijkstra, Stegenga, Stewart, & de Bont, 1999). Interpretation of results must consider the influence of within-subject natural variation, the natural history of disease when it is present and any discrepancy in the reliability of the measurement procedure itself (Bland & Altman, 1996b; Kropmans et al., 1999).

Hopkins (2000) defined retest reliability as "the reproducibility of the observed value when the measurement is repeated" (p. 1). Therefore, the purpose of reliability statistical analysis is to assess the consistency of measurements, and determine to what extent any change observed can be attributed to the intervention, beyond that caused by measurement or biological error. Measurement error can arise from numerous concomitant sources such as the rater/s, measurement devices, study design, biological variation, participant motivation and other random error sources (Bland & Altman, 1996a; Hopkins, 2000; Roebroeck, Harlaar, & Lankhorst, 1993). The reliability of a measurement device or method of measurement is an important factor that can minimise total measurement error, in order to determine if there was a statistical and clinically significant effect (Piriyaprasarth et al., 2008; Roebroeck et al., 1993).

The passive straight leg raise, passive knee extension and active knee extension tests are all commonly performed in clinical settings to estimate hamstring flexibility (Gajdosik et al., 1993). The passive knee extension test has been described by Davis et al. (2008) as the 'gold standard' procedure due to its high intra-rater reliability (see Table 2, Chapter 2). Although the test is highly reliable, the 'gold standard' label is unsubstantiated as the active testing procedure is equally as reliable (see Table 1, Chapter 2) with respect to intra-rater reliability (Worrell et al., 1992) and also demonstrates good inter-rater reliability (Gabbe et al., 2004). Numerous studies (for example see Decoster et al., 2004; DePino et al., 2000; Gabbe et al., 2004; Gajdosik & Lusin, 1983; Gajdosik et al., 1993; Kuilart et al., 2005; Nash, 2005; Webright et al., 1997; Worrell et al., 1992) have estimated the reliability of manual goniometry and video analysis methods for the active knee extension test. These authors have reported excellent intra-class correlation coefficients (ICC) ranging from 0.86 to 0.99, with variable standard error of measurement (SEM) values ranging from 1.67º to 3º. Research utilising the passive knee extension test measured with manual goniometry have also reported similar ICC values ranging from 0.90 to 0.97 (Bandy & Irion, 1994; Bandy et al., 1997, 1998; Davis et al., 2008; Gajdosik et al., 1993; Nelson & Bandy, 2004; Youdas et al., 2005) suggesting that the reliability of both the passive and active test procedures are comparable. Unfortunately, of the studies identified no calculation of standard error of measurement (SEM) was reported for the passive knee extension test. Likewise, calculation of the smallest detectable difference (SDD) for both active and passive procedures were not reported.

The validity of the passive straight leg raise as an indirect measure of hamstring flexibility remains unclear. Only two studies (Davis et al., 2008; Gajdosik et al., 1993) identified in the literature have investigated the test's validity in comparison with the active and passive knee extension tests. The straight leg raise test is thought to place additional 'mechanical forces' upon the sciatic nerve (Butler, 2000) beyond that occurring simultaneously in the hamstring muscles. For that reason it has been suggested that the straight leg raise test is not interchangeable with the passive and active knee extension tests. This assumption has been supported by concurrent validity studies, reporting poor Pearson product moment correlation coefficients ranging from $r = 0.37$ to 0.63 between the knee extension tests and the passive straight leg raise test (Davis et al., 2008; Gajdosik et al., 1993). While the passive and active knee extension tests may potentially be more valid indirect measures of hamstring range of motion, the passive straight leg raise is still a useful tool, providing a different kind of information combining both hamstring and nervous system tensioning. Like the knee extension measures, the passive straight leg raise test measured manual goniometry has also demonstrated high reliability (see Table 3) with ICC values ranging from 0.83 to 0.98 (Davis et al., 2008; Gabbe et al., 2004; Gajdosik et al., 1993; Youdas et al., 2005).

Development of technology in the field of electrogoniometry and digital, gravity and fluid inclinometer devices has lead to greater utilisation of this equipment in studies investigating extremity range of motion (Rowe, Myles, Hillmann, & Hazlewood, 2001; Soper, Reid, & Hume, 2004). The reliability of electrogoniometer studies however have been mixed, with ICC values ranging from 0.69 for the passive straight leg raise and from 0.94 (Stewart & Sleivert, 1998) to 0.95 for knee joint angle measurement, with an estimated standard error of measurement (SEM) of ≤3° across studies (Piriyaprasarth & Morris, 2007; Rowe et al., 2001).

Both the active knee extension test and the passive straight leg raise test have been reported as highly reliable testing procedures in the literature. The decision to use these two different tests in the reliability study was based upon the high reliability reported in the literature and the kind of information they provided to the subsequent vibration study (see Chapter 5), regarding the affect of vibration on muscular flexibility, and to some degree neurodynamic tensioning. The study aimed to investigate the reliability of these two testing procedures, when measured by electrogoniometry and one tester. Results of statistical analysis from the reliability study directly informed statistical analysis in the intervention study reported in Chapter 5.

METHODS

Participants

Ten healthy recreationally-active male participants aged 25.1 (± 5.2) years, weight 81.8 (± 11.6) kg and height 180.6 (± 4.7) cm volunteered to take part in the study. Participants were recruited through information posters on Mount Albert Unitec student notice boards, and by word of mouth. They initially met with the researcher to determine whether they fit the inclusion/exclusion criteria prior to testing. This criteria required healthy males between the age of 18 and 35, who a) participated in physical exercise at a recreational level no more than three times per week and b) were unable to fully extend the knee joint at 90° of hip flexion due to inflexibility of the hamstrings. Exclusion criteria included a) recreational physical exercise more than three times per week b) competition-level athletes (training and/or competing in the last three months),

c) recent macro-trauma to hamstrings or immobilization of lower limbs, d) known musculoskeletal or neurological disorders or injury, e) medication that could affect the musculoskeletal system and f) any other major health concerns. All participants were required to sign a consent form (Appendix 5) before the study commenced, which had been approved by the Unitec Research Ethics Committee (refer to Appendix 1).

Equipment

A triaxial electrogoniometer (Model: 3DM, MicroStrain Inc., Williston VT, USA) was the measurement device used for both the passive straight leg raise and the active knee extension testing procedures (see Figure 1). The device is capable of detecting deviation from a designated starting position in the anatomical planes of flexion/extension, side-bending and rotation, denoted as ‘pitch’, ‘yaw’ and ‘roll’ with respect to the device. Flexion and extension were the planes of movement of interest and therefore the ‘roll’ axis was used. According to factory specifications the ‘roll’ component displays ± 0.7 degrees of accuracy at a constant ambient temperature (MicroStrain Inc., 2008b). The electrogoniometer was connected to a laptop computer running custom written ROM software (LabView, National Instruments Corp., Austin, TX) logging the movement of the electrogoniometer in absolute degrees against time. Raw data were saved in a format that could be viewed on a Microsoft Excel spreadsheet.

Figure 1. 3DM triaxial electrogoniometer (MicroStrain Inc., 2008a)

Procedure

The tester was a final year Master of Osteopathy student, who performed the measurement procedure on all participants in one session, on different days. The participant was blinded to the output display on the ROM software while testing was underway, in an attempt to reduce systematic bias. The tester could view the output display as they were required to reset the electrogoniometer to zero, commence recording, and stop to save the results. Once reset to 0° and recording, any displacement of the device was recorded with reference to the start position.

Participants wore loose fitting shorts for ease of movement, and to expose the lower legs for strap attachment. They undertook a five-minute warm-up on an exercise bike with a standardised resistance of 1 kg, at a speed at which they found challenging, yet could continue to hold no more than a light conversation. Immediately after, the participant was advised to remove their footwear and lay supine on the plinth. The plinth had been modified through the attachment of a frame to support a detachable board that would maintain the hip at 90° during the active knee extension test measure (see Figure 2). The cervical spine was maintained in a neutral plane with a flat pillow, reducing the likelihood of sensitisation of the nervous system that may occur in cervical flexion positioning (Butler, 2000).

Figure 2. Plinth with frame modification and detachable cross-board.

An elastic strap was then velcroed onto each leg at a mark made three centimetres distal to the mid-point of tibial tuberosity (see Figure 3). The straps were the attachment point for the electrogoniometer by velcro and were removed only when testing was complete. If strap slippage was visible at any stage, the strap was immediately realigned with the marker. The leg not being tested was strapped to the plinth proximal to the knee joint to limit contralateral leg lift and pelvic rotation, in accordance with the procedures specified by Gajdosik and Lusin (1983) and Gajdosik et al. (1993). The participant was given a set of written instructions to read (see Appendix 6), which were then explained immediately after by the tester.

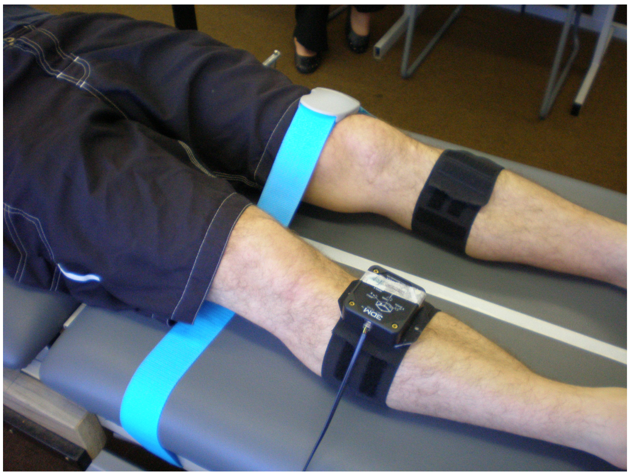

Figure 3. Electrogoniometer attached to tibia by elasticated strap and restrictive strapping on contralateral thigh.

Initially a set of familiarisation exercises involving two passive straight leg raise and two active knee extension tests were performed on both legs to lessen the lengthening affect of repeated measures on muscle (Kropmans et al., 1999) as well as familiarise the participant with the testing procedure and expected end-feel. Such familiarisation would act to reduce or negate any learning or training effects that could introduce systematic error in subsequent testing trials (Hopkins, 2000). In the study three trials were completed at 10-minute intervals. The reliability study was similar in time structure to the planned vibration study, which Hopkins (2000) indicates is an important factor when later applying the reliability data of a measure to a subsequent intervention study. Before each test, the electrogoniometer was reattached, and reset to zero when the leg was in the test start position. Each trial consisted of three consecutive repetitions of passive straight leg raise and active knee extension tests on both legs. Between trials participants were able to move to a seated position.

For the passive straight leg raise test the participant lay supine in the start position, arms by their sides and legs extended. They were advised to relax and let the tester flex their right hip by slowly lifting the extended leg (pictured in Figure 4). The ankle was left in a natural position of slight plantar flexion to avoid sensitising or tensioning nervous tissues (Butler, 2000). The participant used a clicker to indicate the first onset of a firm resistance or stretch. The tester ceased lifting immediately when the clicker was heard and lowered the leg to the starting position. The test was repeated two more times, giving a total of three repetitions. The test was then performed on the left leg.

Figure 4. Passive straight leg raise test position.

For the active knee extension test a board was secured to the frame on the plinth that helped maintain the hip at 90° of flexion. The supine participant was positioned so that this degree of flexion could be achieved, with the right thigh loosely strapped to the board. The strap was relaxed, and only served to cue the participant if the thigh began to move away from the board, as the strap would then tighten. This form of strapping is not conventional, and was added to the design in response to poor participant compliance to verbal instructions identified in the pilot-testing phase. The possibility that such a strap may introduce systematic error by reducing hamstring function was considered, however, was regarded as minimal when the active technique was performed correctly. The opposite thigh was strapped to the plinth proximal to the knee joint. The right knee was passively positioned to the start position of 90° by the tester. This angle was determined through the use of a small spirit level. Once in the start position the electrogoniometer was set to zero degrees. The participant was then verbally instructed to actively extend the knee slowly as far as they could without losing contact with the board (see Figure 5). The tester monitored thigh contact with the board. The participant held this position for one second and then when verbally cued by the tester relaxed and returned to a comfortable flexed position before two further repetitions. The left leg was then tested.

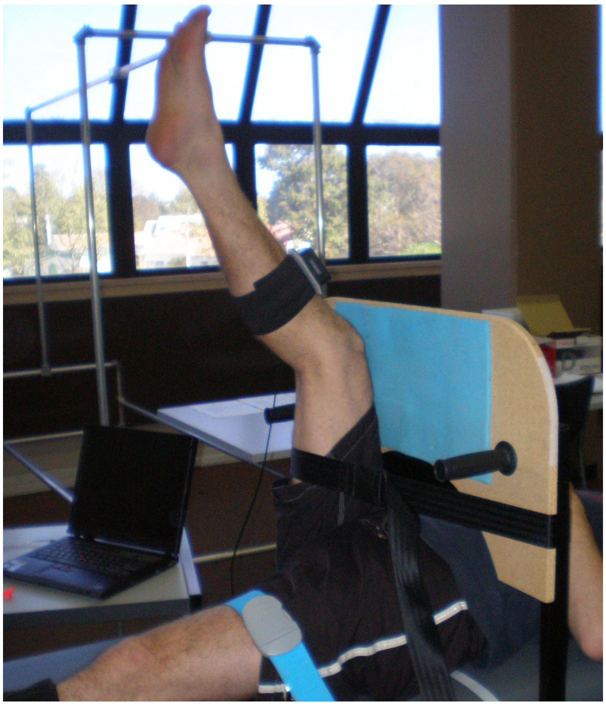

Figure 5. Active knee extension test position.

Statistical analysis

Statistical analysis was performed in both Microsoft Excel and SPSS 12.0.1 (SPSS Inc., Chicago, Illinois) computer programs. The three maximal excursions for each leg were averaged to find the mean value in absolute degrees for each measure for each trial. Averaging the repetitions was done to minimise the magnitude of differences in measurements and reduce error (Piriyaprasarth & Morris, 2007). The means for both right and left legs were pooled to give a sample size of n=20, and standard deviations calculated. The intra-class correlation coefficient was determined in the SPSS program using the ICC (3,3) two-way mixed effects model, using average measures and 95% confidence intervals calculated. Hopkins (2000) indicates that the ICC model that was used is unbiased with respect to sample size. The standard error of measurement (SEM) was calculated using the formula: $SEMp = SD*\sqrt{(1-r)}$, where 'SD' represented the calculated standard deviation, and 'r' represented the reliability coefficient (Kropmans et al., 1999; Worrell et al., 1992). The 95% confidence interval for the SEM was calculated as ± 1.96*SEMp. The smallest detectable difference (SDD) was calculated as $SDD = 1.96*\sqrt{2}$ *SEMp (Kropmans et al., 1999; Roebroeck et al., 1993). Using a single factor analysis of variance (ANOVA) the mean within-subject variance was calculated, then within-subject standard deviation (SW) was calculated with the formula: SW = √mean within-subject variance (Bland & Altman, 1996a).

RESULTS

The mean range of motion and standard deviations for the active knee extension measure ranged from 47.1º ± 9.2 to 49.1º ± 10.0 and the passive straight leg raise ranged from 66.6° ± 8.0 to 67.7° ± 7.8 over the three trials (detailed in Table 6). For individual mean values refer to Appendix 7. The intra-class correlation coefficients for the active knee extension test and passive straight leg raise were r = 0.98 and 0.96 respectively, suggesting that the test-retest reliability of these two procedures were high. The SEM and SDD for both tests were similar between the two measures. However, the within-subject standard deviation (SW) was much greater in the active knee extension measure, with an SW= 5.2° in comparison to that seen in the passive straight leg raise (SW=2.3°), suggesting there was far greater variation in individuals for the active knee extension test.

Table 6. Reliability of the Passive Straight Leg Raise Test and Active Knee Extension Test Over Three Trials.

	Trial 1 Mean (°) ± SD	Trial 2 Mean (°) ± SD	Trial 3 Mean (°) ± SD	ICC (3,3) (95% CI)	SEM (°) (95% CI)	SDD (°)	SW (°)
PSLR	66.6 ± 8.0	67.2 ± 8.2	67.7 ± 7.8	0.96 (0.91 to 0.98)	1.7 (± 3.3)	4.6	2.3
AKE	49.1 ± 10.0	47.1 ± 9.9	47.1 ± 9.2	0.98 (0.96 to 0.99)	1.4 (± 2.7)	3.7	5.2

Note: PSLR = passive straight leg raise test, AKE = active knee extension test.

DISCUSSION

The pilot study aimed to investigate the reliability of the active knee extension and passive straight leg raise tests when measured with an electrogoniometer by a sole tester. The testing was undertaken to demonstrate that these two indirect measures of hamstring flexibility were reliable in the current testing conditions. Additionally, pilot testing determined the degree of measurement error (SEM) that existed in the protocol to inform the results of the subsequent intervention study in the following chapter (Chapter 5).

Intra-class correlation coefficients (ICC) analyse the consistency of repeated measurements (Eliasziw, Young, Woodbury, & Fryday-Field, 1994) by comparing how well the values of one trial match that in others, as well as the degree to which values maintain their rank order (Hopkins, 2000). There is currently no consensus on a standard interpretation of ICC value magnitude (Nash, 2005), although it is acknowledged that the closer to one the value is the greater the reliability, and the closer to zero the less consistency between tests (Hicks, 1999; Hopkins, 2000).One interpretation framework detailed by Meyers and Blesh (as cited in Nash, 2005, p. 52) is to bracket ICC values: less than 0.70 is poor reliability; 0.70 to 0.79 fair reliability; 0.80 to 0.89 good reliability; 0.90 to 0.99 high reliability. By the Meyers and Blesh standards the ICC of the active knee extension test in this study may be regarded as highly reliable, and is similar to ICC values seen in other studies using manual goniometers (Gajdosik & Lusin, 1983; Kuilart et al., 2005; Webright et al., 1997; Worrell et al., 1992). Additionally, the ICC value for the passive straight leg raise test was high, and more reliable in comparison with that reported by another electrogoniometer study by Stewart and Sleivert (1998) of $r = 0.69$. While bracketed interpretation of ICC values may make reliability analysis interpretation more straightforward, Hopkins (2000) has criticised such frameworks as they do not account for the utility of magnitudes of retest correlations with regard to specific test protocols and populations. Eliasziw et al. (1994) indicate that reliability coefficients are based upon variability of measurements within that study sample, which can only be applicable to other populations similar to that sample. Therefore, generic bracketing frameworks may not always be appropriate for interpretation of ICC values.

The standard error of measurement (SEM) was reported by only several of the studies reviewed (see Table 1). The SEM can be a key analytical tool in determining whether change observed in a group is as a result of error or a real change related to the intervention, as it accounts for variability in the rater's measurements (Eliasziw et al., 1994; Kropmans et al., 1999). In the present study the SEM for each test was calculated on a mean of three trials, which were based on a mean of three repetitions at each trial for each individual (refer to Appendix 7). The active knee extension test procedure had a low degree of error, with similar intra-tester ICC and SEM values to those reported by Worrell et al. (1992), Sullivan et al. (1992) and Webright et al. (1997) and less standard error than indicated in other comparable studies (Decoster et al., 2004; DePino et al., 2000; Gabbe et al., 2004). The SEM for the passive straight leg raise test was smaller in comparison to the 4° of error reported by the one other study that used this analysis (Gabbe et al., 2004). Manual goniometry requires the tester to accurately place the device measuring the angle along axes of joint rotation, as well as read the angle measured, which are two factors that may introduce error. Electrogoniometry, on the other hand, measured the deviation of the goniometer itself in space in relation to a starting point. Therefore, the nature of the electronic logging of results in electrogoniometry may have been a factor in reducing tester error, and subsequently the standard error of measurement.

Interpretation of intervention results should consider that a statistically significant result might not always be an indicator of a clinically significant effect (Hopkins, 2001b). The result must exceed the level of error and achieve at least the smallest detectable difference to suggest a clinically significant effect (Kropmans et al., 1999). In other words, the smallest detectable difference (SDD) represents the smallest change required between pre and post measures to no longer be considered error. The SDD was not reported in any of the studies reviewed, however, can be calculated based upon those that reported SEM, by a simple equation [SDD= $1.96*\sqrt{2}$ *SEMp]. For the active knee extension test procedure SEMs in the literature ranging from 1.7° to 3° indicated SDD values from 4.7° to 8.3° (Gabbe et al., 2004; Webright et al., 1997). Those values were either slightly larger or over twice the size calculated for the electrogoniometry method used in this study. The SEM value of 4° reported by Gabbe et al. for the passive straight leg raise test resulted in an SDD of 11°, which was also over twice the size of that calculated in this study. The SDD results imply that the current study's measurement procedures had a higher degree of precision in comparison to those applied in the literature and, therefore, may have the power to detect smaller changes in range of motion.

According to Hopkins (2000) within-subject variation or standard deviation (SW) represents the random variation that occurred when an individual was repeatedly tested. The author explains that a smaller variation in measurements for that participant would make it easier to see change in that participant's performance. Performance can be affected by the degree of participant motivation and level interest, and therefore participant effort may have an impact on the consistency of results that are achieved (Piriyaprasarth & Morris, 2007). The mean of several repetitions in an individual for each trial was used and may have reduced the impact of measurement variation to an extent. However, both the active and passive outcome measures entailed participant motivation and concentration that may have resulted in performance inconsistency in apathetic or overzealous participants. A sense of competition to surpass previous maximal active knee extension range was noted in some participants, despite instruction to perform consistently, which may account for the large within-subject standard deviation (SW) observed in the active knee extension measure.

Although both procedures appear to have a high degree of reliability and low SEM, possible error sources should be considered. Piriyaprasarth et al. (2008) and Rowe et al. (2001) utilised flexible electrogoniometers which were very different in design and attachment to the 3DM electrogoniometer used in this study. However, their difficulties have highlighted potential errors that may be applicable to the current testing procedure. Such error sources include slippage of the device at its attachment, irregular limb contour altering position between participants, and inconsistent repositioning caused through detachment and reattachment required by the method. To the researcher's knowledge only one study has investigated the error associated with repeated repositioning of an electrogoniometer, applied to the knee of supine, sitting and standing participants by multiple examiners (Piriyaprasarth et al., 2008). This study used a flexible electrogoniometer, and observed angles of less than 90° knee extension. The study reported an inter-tester SEM of 0.5° to 3.3°, and an intra-tester SEM of less than 2.3°. The intra-tester SEM was smaller in comparison to the current study, but comparability may be limited due to the use of a different electrogoniometer model, and measurement of knee flexion rather than extension. The authors recommended single examiner testing, to minimise measurement error, reasoning that a sole examiner may be able to reposition the equipment more accurately and consistently each time. In the current study not only was the goniometer removed repeatedly, but also the participant was allowed to change from the supine position to a seated position during intervals between trials. The repositioning of the participant and goniometer may have contributed to error. The examiner regularly checked the positioning of the elastic strap to check for slippage and tibial alignment, however, there may have been some degree of unnoticed error.

The existence of systematic error cannot be ruled out with respect to strapping of the active leg in the active knee extension test procedure. The tester attempted to prevent loss of hip flexion primarily through verbal instruction, when it appeared board-thigh contact was diminishing. The leg was loosely strapped with purpose of providing further feedback to the participant only in the even that contact was lost. However, any tightening of the strap caused by loss of hip flexion could potentially have impaired hamstring lengthening and reduced the validity of the active knee extension test. With regard to these comments, the extent to which strapping may have introduced systematic error and compromised validity is considered minimal as strapping was only used a precaution and no participant depended on the strap to support hip flexion. Experimenter bias cannot be ruled out, as the tester was the researcher (Hicks, 1999). The tester gave all participants the same written instructions (see Appendix 6) to refer to throughout the testing, and gave specific verbal instructions and equal encouragement to all participants.

CONCLUSION

The active knee extension and passive straight leg raise test procedures measured with the 3DM electrogoniometer have demonstrated high reliability across the three trials taken at 10-minute intervals in this sample group. Reliability and SEM for both outcome measures recorded with electrogoniometry was on a par, if not better, when compared with more traditional measurement equipment such as manual goniometers. There were numerous sources of potential error in the protocol, such as device repositioning, consistency of patient positioning, experimenter bias, and participant motivation. Diligence by the tester in controlling variables in future use of these outcome measures will aid in maintaining the high level of reliability of testing procedures.

CHAPTER 5: THE EFFECT OF SEGMENTAL VIBRATION ON RANGE OF MOTION OF THE HAMSTRINGS

INTRODUCTION

There are a number of common methods used to improve flexibility, the most common of which is the static stretch. However, Nelson and Bandy (2005), among other authors (Stone et al., 2006; Whatman et al., 2006; Witvrouw et al., 2004), have voiced concern regarding inconsistencies and lack of sound scientific evidence demonstrating the effects of stretch on performance and injury prevention. As evidence remains deficient and conflicting, Nelson and Bandy place the commentary:

> The search continues for an activity that will increase flexibility as well as static stretch does. If an activity is found that will accomplish this task, other avenues of research will be open to determine if gains are made in strength, injury reduction and performance improvement. (p. 14)

Low-frequency vibration training is an activity that might have fewer limitations than stretch (Kinser et al., 2008), but more scientific critique is required before it can be promoted as a performance enhancement tool (Cronin et al., 2007).

There is a growing body of knowledge with regard to the neuromuscular effects of vibration on performance factors. Of recent popularity in this field is exploration of the effects of vibration in flexibility enhancement (Cronin et al., 2007, 2008; Nash, 2005). Although little is known regarding the mechanisms of effect responsible for the changes observed, there is evidence of a number of factors contributing to greater responses in individuals. Firstly, the length of the muscle at the time of vibration may augment effects of vibration (Rohmert et al., 1989), as vibration applied to muscle in a state of stretch or voluntary contraction has demonstrated greater range of motion changes than muscle in a relaxed state (Kinser et al., 2008). Range of motion improvements have included 8 to 43% improvement in sit-and-reach test flexibility (Cochrane & Stannard, 2005; Issurin et al., 1994), 18% increase in forward split flexibility (Kinser et al., 2008) and 27% increase in range of motion measured by the passive straight leg raise test (van den Tillaar, 2006). Although research for such conditions is indicated, only a few studies (Cronin et al., 2007, 2008; Kinser et al., 2008; Nash, 2005) have provided evidence of the baseline effects of vibration on muscle in a relaxed state for comparison. Secondly, research suggests that individuals of higher neuromuscular tuning, such as elite athletes, may be more susceptible to the affect of vibration (Issurin & Tenenbaum, 1999) and for this reason much of the research has concentrated on athletes participating in some degree of competitive sport, from club level to more trained individuals (Cronin et al., 2004). It is unclear to what extent vibration may have an effect on relaxed muscles in a healthy population who are not involved in heavy physical activity. Such baseline information may help to deepen the understanding of the effects of vibration and provide a comparative measure to future studies investigating optimal vibration parameters.

In consideration of the previous factors, this within-subject repeated measures trial aimed to investigate the extent to which low-frequency random-waveform segmental vibration applied to muscle in a relaxed state produced immediate and short-term changes in hamstring flexibility, in healthy recreationally-active male adults. The study also intended to identify trends seen in any effects that were observed.

METHODS

Sample size

The sample size for this study was determined by using a statistical computer software program called Gpower (http://www.psycho.uni-duesseldorf.de/aap/projects/gpower/). Studies in the field of vibration flexibility research such as Sands et al. (2006) and Cronin et al. (2007) previously found effect sizes of close to 2.0, however, many of these studies used small sample sizes of 10 to 20 participants. A moderate effect size of 0.5 was chosen for this study, and a Type II error of 80%. With these figures, the Gpower software derived a sample size of 34 participants. The final number recruited and that participated was 31.

Participants

Thirty-one healthy male participants (age 25.5 ± 4.9 years, height 180.5 ± 6.5cm, weight 80.5 ± 10.7kg) volunteered to participate in the study. Ten of these participants had participated in the reliability study in Chapter 4. They all signed a consent form (Appendix 5) that had been previously approved by the Unitec Research Ethics Committee (refer to Appendix 1). All were recruited by convenience sampling through advertisements on Unitec notice boards (see Appendix 3), as well as by word of mouth.

Participants were only recreationally-active, and exercised no more than three times per week. Exclusion criteria for participation in the study was consistent with that specified by the BS 7085 (British Standards Institution, 1989, as cited in Griffin, 1990) for contraindication for participation in a whole body vibration experimental study. The criteria included recent or ongoing pain, trauma or immobilisation of the lower limbs or back, history of lower limb surgery, known musculoskeletal or neurological disorders, major health conditions, or consumption of medication affecting the neuromuscular system.

Most participants held occupations that ranged from moderate to particularly physically demanding, with only a small number involved in sedentary desk jobs. The group participated in a broad spectrum of physical activities outside of work hours. The occupations and physical exercise activities are detailed in Tables 7 and 8. The number of hours spent participating in physical activity on average per week ranged from 1 to10 hours, over one to three days. Approximately one third participated in only one type of activity weekly (n =10), whereas 12 participated in two activities, eight participated in three forms of exercise, and one participated in four activities regularly. Only nine participants regularly stretched their hamstring muscles (‘regularly’ was defined as most occasions when participating in physical activity) and 24 of the 31 regularly experienced a sensation of tightness in their hamstring muscles. All were unable to fully extend the knee joint in the active knee extension testing position.

Equipment

A 3DM triaxial electrogoniometer (Model: 3DM, MicroStrain Inc., Williston VT, USA) recorded range of motion data in absolute degrees to a laptop computer running custom

Table 7. Participant Occupations

Occupation	Number of Participants
Student: osteopathy	17
Managers: desk	3
Chemical technician	1
Drain layer	1
Electrical engineer	1
IT technician	1
Instrument craftsman	1
Media editor	1
Shop assistant	1
Student: communications	1
Student: construction	1
Student: fabrication	1
Welder	1
Total	31

Table 8. Participant Physical Activities

Physical Activity	Number of Participants
Cycling	9
Running	7
Soccer	5
Walking	4
Surfing	4
Squash	4
Swimming	4
Non-specific gym work	4
Weight training	3
Tennis	3
Power walking	2
Golf	2
Mountain biking	1
Cricket	1
Rowing	1
Rugby refereeing	1
Trampolining	1
Street acrobatics	1
Capoeira	1
Waka ama	1
Boxing sparring	1
Basketball	1
Taichi	1

Note: Some individuals participated in more than one activity.

written ROM software (LabView, National Instruments Corp., Austin TX). Outputs could be viewed on a Microsoft Excel spreadsheet.

The device that delivered the local vibration was sourced from the School of Sport, Institute of Sport & Recreation Research New Zealand, Faculty of Health and Environmental Sciences of AUT University. It had been used in previous studies by several authors such as Nash (2005) and Cronin et al. (2007, 2008). It consisted of an oscillating platform vibrated by a motor enclosed in a solid casing (see Figure 6).

Figure 6. Front and side views of the segmental vibration device.

Nash (2005) and Cronin et al. (2007) investigated the vibration parameters of this specific device using an accelerometer and computer analysis program. They stated that the vibration device produced a random waveform (see Figure 7) and that each of the six settings had different frequency, amplitude and acceleration parameters.

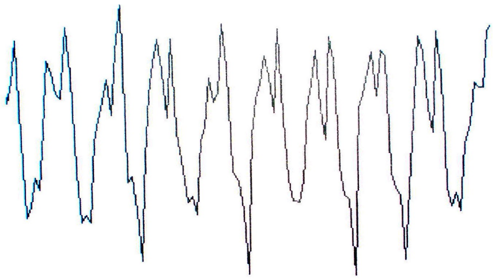

Figure 7. Typical waveform produced by vibration device (Nash, 2005, p. 57)

These authors investigated the effects of the device's six frequency settings on range of motion of the hamstrings. That investigation determined that machine settings three, four and five produced mean increases of ROM of 1.6% (2.4° dynamic ROM change) to 2.1% (3.1° ROM change), with statistically significant effect sizes ranging from 1.15 to 1.77 (Nash, 2005, p. 61). Based upon this research and in accordance with Nash's subsequent vibration flexibility study that used setting four, it was decided that machine setting four would be used in this study. That setting had a frequency of 34 Hz, amplitude of 3 mm and peak acceleration of 42.2 ms^{-2}. Cronin et al. exposed their subjects to a very short period of vibration involving a single 30-second period of vibration. In comparison to some studies (Fagnani et al., 2006; Cochrane & Stannard, 2005) that dose may be considered minimal, as others delivered several 30 to 60-second doses with rest intervals. Therefore it was decided that five 60-second vibration exposures would be delivered, with 60-second rest intervals between.

Procedure

Study design (see Figure 8)

The study consisted of a within-subject repeated measures experimental design, where one of the participant's legs was the control leg, and the one leg that received vibration was the experimental leg. Although it has been proposed that 'crossed effects' may occur in a contralateral limb in response to high frequency vibration or prolonged exposure to vibration, evidence remains inconclusive as to the existence of such an effect. Furthermore, it is uncertain whether crossed effects would occur with respect to short duration, low frequency vibration.

Data collection was performed solely by the researcher, who had completed the clinical component of osteopathic training and had been formally educated on performance of the passive straight leg raise and active knee extension tests that were used in this study. The researcher had also performed and recorded the measurements in the reliability study (Chapter 4), which demonstrated high intra-rater reliability for both the passive straight leg raise test and active knee extension test measures tested (ICC = 0.96 and 0.98 respectively).

All measurements were recorded in one experimental session for each participant. Research was conducted in the same location, with the same equipment each time, and only the researcher and participant were present at the time. Participants' weight was measured by a standard weight-scale and height measure. All participants wore shorts for freedom of movement and to expose the lower leg for attachment of the electrogoniometer strapping.

The experimental design (see Figure 8) began with an initial warm-up involving cycling for five minutes on a bicycle ergometer. Following the warm-up, a series of outcome measure familiarisation exercises were performed to instruct and expose the participant to the measurement protocol, while helping to precondition the hamstrings. Baseline measurements were then taken for the passive straight leg raise and active knee extension test three times on each leg using an electrogoniometer. The three readings were averaged to find the individual participant's mean range to be used in later statistical analysis (Phillips, 2007). The least flexible leg according to the active knee extension test results received the vibration intervention. Immediately after vibration (P1) measurements were recorded on both legs, for both outcome measures, according to the same protocol as the baseline measurements. Measurements were recorded again 10 minutes post cessation of vibration (P2). The measurement protocol took approximately four and a half minutes to complete by the researcher at Baseline, P1 and P2. Three measurements were taken for each outcome measure on each leg, at each measurement time. For all measurements the right leg was recorded first. The passive straight leg raise was always performed on both legs before the active knee extension testing commenced. The layout of the experimental design is illustrated in Figure 8.

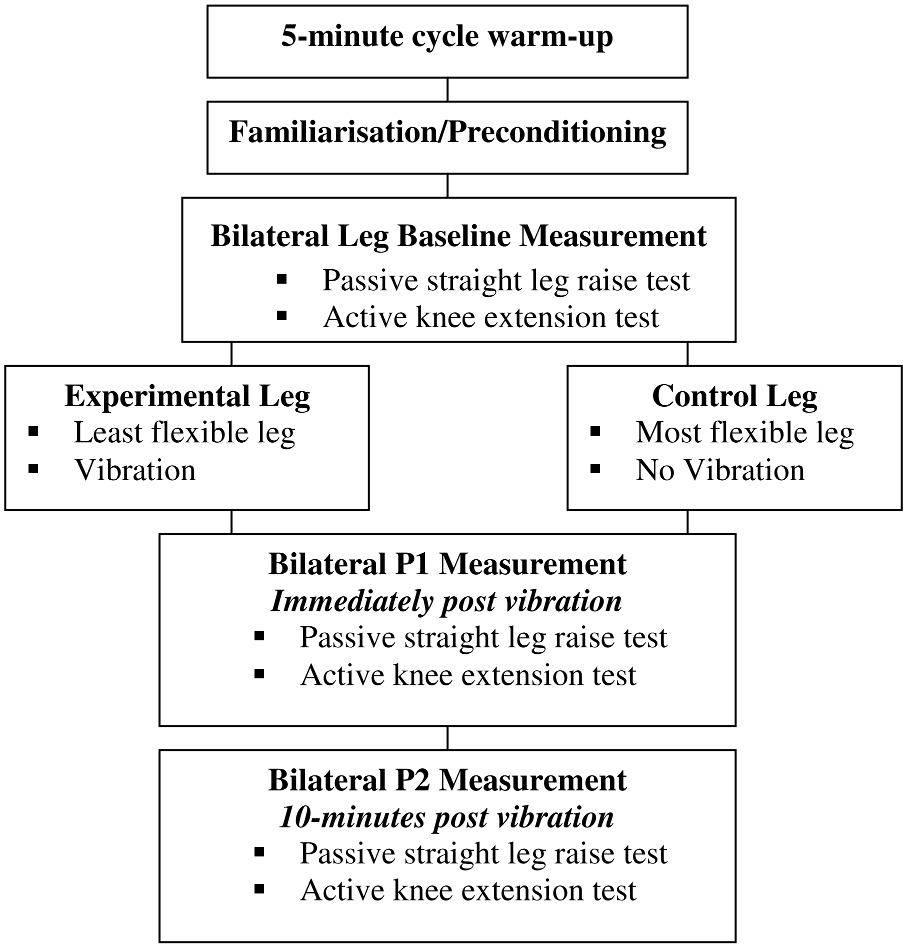

Figure 8. Study design.

Warm-up and familiarisation protocol

Participants performed a five-minute warm-up cycle on a bicycle ergometer with a resistance of 1 kg. They were instructed to cycle at a rate they found vigorous, yet they could continue to hold light conversation for five minutes. The participant then lay supine (without shoes) on a plinth that had been modified for attachment of a removable cross-board. The cervical spine was kept in a neutral plane to avoid the neurodynamic tensioning effects of cervical flexion (Butler, 2000). A mark was made approximately 3cm distal to the mid point of the tibial tuberosity on both legs, and elastic straps were velcroed firmly at this mark. The electrogoniometer attached to the elastic straps by velcro. The straps were checked continually throughout the experimental session for any sign of slippage, and tightened if necessary.

The participant received written instruction of the protocol (refer to Appendix 6), followed by verbal instruction by the researcher. Familiarisation exercises were based on the outcome measures, which ensured that the participant understood the instructions. The exercises also acted to precondition the hamstrings and reduce any impact of learned effects (Hopkins, 2000). The exercises consisted of two passive straight leg raises and two active knee extension tests on both legs. For the straight leg raise test participants were advised to let the researcher lift their leg, and used a clicker to indicate the point where the first onset of a stretch sensation in the hamstring muscle was experienced. The endpoint of the active knee extension test was defined as the point to which the participant could maximally actively extend the knee joint when in the active knee extension position. They were asked to hold this for one second each time. After the familiarisation exercises the baseline straight leg raise and active knee extension test measurements were recorded.

Measurement protocol: passive straight leg raise test

The electrogoniometer was velcroed to the elastic strap on the right tibia. The left thigh was strapped to the plinth proximal to the knee joint. The goniometer was reset to zero and began recording once the leg was extended in the starting position. The foot was left in a neutral, relaxed position to avoid tensioning neuromeningeal and posterior myofascial structures (Gajdosik et al., 1985). The researcher slowly and passively raised the straight leg (see Figure 9) until the participant used the clicker to indicate the initial point of stretch in the hamstring muscles. At that time the researcher stopped elevation and slowly replaced the leg into the start position on the plinth. If the straight leg began to bend at the knee before the participant clicked then that point was regarded as end of range. However, knee flexion did not occur for any of the participants. The electrogoniometer was not reset to zero and continued recording until a total of three measurements had been made. A mean of the three measurements was used in further statistical analysis. The left side was then measured three times in the same way.

Figure 9. Performance of the straight leg raise test on a participant.

Measurement protocol: active knee extension test

Immediately after the straight leg raise measurements the active knee extension test was performed on the right and left leg. The vertical cross-board was attached to the frame modification on the plinth. This cross-board limited hip flexion to 90° when the participant lay at a specific position on the plinth. The leg not being measured was strapped to the plinth proximal to the knee joint. The leg being measured was passively flexed to contact the board, and the thigh strapped loosely onto it to provide feedback to the participant if the leg was going to come away from the board. The electrogoniometer was velcroed to the tibial strap, and a small spirit level was used to determine when the electrogoniometer was horizontal, at 90° of knee flexion (Figure 10).

The electrogoniometer was then zeroed and began recording. The participant was instructed to actively maximally extend the knee slowly, maintaining a relaxed ankle, and hold for one second before slowly returning to a flexed knee position (see Figure 11). The goniometer was not reset at this stage, and the participant repeated the test two more times under the researcher's instruction. The researcher monitored the testing leg to ensure that the thigh did not lose contact with the board, and that the hip did not slip into abduction.

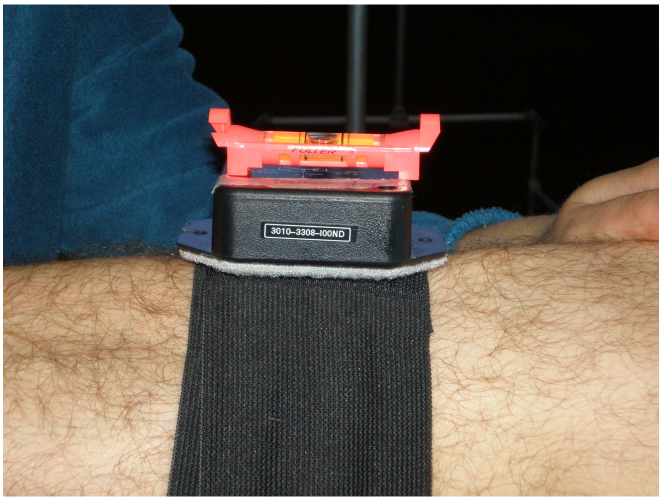

Figure 10. Spirit level placed on top of electrogoniometer to estimate 90° knee flexion for the active knee extension test.

Figure 11. Active knee extension test start position (left) and performance of test (right).

The baseline active knee extension test results determined which leg would be vibrated. The three maximal readings for each knee extension test were averaged for both legs to determine which was least flexible. Additionally these means were used in further analysis. The least flexible leg then received the vibration ('experimental' leg). The other leg did not receive vibration and acted as the control.

Intervention: vibration

The participant sat on the edge of the plinth and rested the hamstring muscle bellies of the experimental leg on the vibration device (see Figure 12). The participants were positioned with a straight back and sat on their ischial tuberosities. The upright-seated position was used as leaning forward might have resulted in vibration transmission to the trunk or head, whereas leaning backwards would have reduced vibration to the target muscles. Participants were instructed to apply adequate leg pressure onto the machine by resting the thigh on the machine without actively pushing it down. This position ensured that they received a deep vibration rather than skin rub. The control leg rested to the side of the machine on the ground. Participants were asked to advise if they experienced any vibration in the lower back, however, none reported such feelings. Both the researcher and the participant wore protective earmuffs as a safety precaution to reduce any potential risk from noise. Additionally, one author has suggested that noise has a subjective impact on perceived discomfort due to vibration, and therefore minimising noise would impact on participant perception (Griffin, 1990). The vibration device was set to deliver vibration at 34 Hz, with an amplitude of 3 mm and acceleration of 42.2 ms^{-2}. Participants received five one-minute exposures of vibration to the experimental leg each separated by one-minute rest intervals.

Figure 12. Participant seated on the plinth with the experimental leg resting on the vibration device.

Post 1 (P1) and Post 2 (P2) Measurement

Immediately after vibration the participant lay supine on the plinth. P1 hamstring range of motion of the control and experimental leg was then measured in the same way as the baseline measures. After this measurement, the participant remained supine. Ten minutes after the vibration had ceased the P2 measurements were recorded.

Statistical analysis

Data analysis was performed using the statistical programming options within Microsoft Excel. For each testing period, the three maximal excursions for each participant's legs (experimental and control) measured by straight leg raise and active knee extension tests were averaged to find the mean value in absolute degrees, to be used in subsequent analysis for that individual. Analysis involved calculating the group means and standard deviations for the experimental and control groups, at baseline, Post 1 (P1) and Post 2 (P2) for each outcome measure. Multiple pair-wise t-tests were performed between the relevant variables to determine whether the vibration produced any meaningful change in range of motion of the hamstrings within groups, and between groups.

The smallest detectable difference had been calculated previously in the reliability study (see Chapter 4), which resulted in a smallest detectable difference (SDD) of 4.6° for the passive straight leg raise and 3.7° for the active knee extension test. An excel spreadsheet designed by Hopkins (2001a) was used to calculate clinical likelihood probabilities for true values, using calculated p-values, difference in group means and the smallest detectable difference. The author states that clinical likelihood probabilities "are more meaningful than the traditional p value" (Hopkins, 2002, p. 1), as he is critical of the fact that statistical significance does not indicate clinically useful effects and is often misinterpreted (Hopkins, 2001b). In this study the clinical likelihood probabilities are expressed as a percentage that the true value of the statistic is 'less than/equivalent to (trivial)/greater than' the measured value.

RESULTS

The mean range of motion recorded for the experimental and control groups at each time point are shown in Table 9. Individual mean scores for the passive straight leg raise and active knee extension test for both groups can be viewed in Appendix 8 and 9 respectively.

Table 9. Baseline, Post 1 and Post 2 Group Means for Range of Motion Measures.

Group	passive straight leg raise test			active knee extension test		
	Baseline (°)	P1 (°)	P2 (°)	Baseline (°)	P1 (°)	P2 (°)
Experimental	62.7 ± 7.4	64.3 ± 8.1	63.9 ± 6.3	45.6 ± 8.6	45.2 ± 8.3	45.7 ± 8.8
Control	63.8 ± 8.6	63.4 ± 9.3	64.2 ± 8.9	48.8 ± 9.7	45.8 ± 10.5	45.3 ± 11

Note: Data represent mean ± standard deviation

Passive straight leg raise test results

Within the experimental group, individual mean change scores for the passive straight leg raise at the first post intervention measurement (P1) ranged from –4.4° to 12.4°, and at the second post intervention measurement (P2 v P1) from –6.5° to 11.2°. The control group mean individual change scores ranged from –15.5° to 9.7° and -12.5° to 11.5° for the respective time points. Results of statistical analysis for the passive straight leg raise test are reported in Tables 10 and 11. Table 10 illustrates the mean change in range of motion for experimental and control groups between time points, including mean range of motion change for P1 v baseline, P2 v P1, and P2 v baseline time points, with the latter time bracket representing overall change. A positive value represents a larger mean value at the latter time point relative to the earlier. The smallest detectable difference of 4.6° for this outcome measure was determined in the Chapter 4 reliability study and used to calculate the clinical likelihood probability that the measured difference was less than, trivial, or greater than the true difference of the statistic. The experimental group had an overall (P2 v baseline) mean change of 1.2° in the passive straight leg raise, however, the change was not clinically significant. This trivial clinical significance was illustrated by probability values (less than/ trivial/greater than) of 0/92/8%, 2/97/1%, and 0/96/3% for P1 v baseline, P2 v P1 and P2 v baseline respectively. The control group demonstrated similar clinically trivial results, with probabilities indicating that chances of the true value being less than/equivalent or trivial/greater than that measured was 6/91/3% for P1 v baseline, 1/93/5% for P2 v P1, and overall change (P2 v Baseline) of 1/97/2%.

The smallest detectable difference (SDD) of 4.6° for the passive straight leg raise test was also used to analyse and express the response rate of individuals in Table 11. The table illustrates the number of participants that had a change in range of motion less than, greater than, or within smallest detectable difference. The change in range is reported in the table as 1) 'decrease', indicated by a loss in range of motion equal to or greater than 4.6°, 2) 'no change' as in the change in range of motion is less than ± 4.6° and 3) 'increase', indicating the range of motion change was equal to or greater than 4.6°. A large number of participants (n =21 to 25) in both groups exhibited no change detectable by the passive straight leg raise.

Table 10. Changes in Mean Straight Leg Raise Range of Motion and Clinical Likelihood Probabilities.

Group	Time Period	Change in ROM (°)	p-value	90% CI	Clinical Probability (%)		
					-ve	trivial	+ve
Experimental	P1 v baseline	1.6	0.44	-2.6 to 5.8	0	92	8
	P1 v P2	-0.4	0.84	-4.4 to 3.6	2	97	1
	P2 v baseline	1.2	0.51	-2.5 to 4.9	0	96	3
Control	P1 v baseline	-0.4	0.88	-5.8 to 5.0	6	91	3
	P2 v P1	0.8	0.73	-3.9 to 5.5	1	93	5
	P2 v baseline	0.4	0.84	-3.6 to 4.4	1	97	2

Note: +ve = positive, -ve = negative, CI = confidence interval. Difference in mean is the change in flexibility in degrees over a time period, calculated as latter test result minus the earlier, for example: Post 1 - Baseline. A positive score for the difference in mean represents a larger mean value for the latter time period relative to the earlier. Clinical likelihood probability was calculated based upon a SDD of 4.6°.

Table 11. Change in Range of Motion Based Upon the Smallest Detectable Difference for the Passive Straight Leg Raise Test.

Group	Time Period	Number of participants with detectable ROM change		
		ROM Decrease	No Change	ROM Increase
Experimental	P1 v baseline	0	24	7
	P2 v P1	3	25	3
Control	P1 v baseline	4	21	6
	P2 v P1	3	24	4

Note: Based upon a SDD of 4.6°

Active knee extension test results

With respect to individual mean change scores, responses in the experimental group ranged from –13.2° to 11.4° at P1, and -11.7° to 9.1° P2 v P1. The control group ranged from –11.1° to 3.3° at P1 and –15.9° to 6.9° at P2 v P1. Tables 12 and 13 detail the results of statistical analysis for the active knee extension test, for both the experimental and control group. Table 12 shows the change in range of motion at different time points, along with the clinical likelihood probabilities that the change values represented a true change. There appears to be a trend where immediately post vibration (P1), both groups experienced a mean decrease in range, however, there was a far greater reduction observed in the control group, which decreased by 3°. At the P2 time point experimental group flexibility had recovered, while the control group had continued to decrease. The experimental group had a very small overall (P2 v baseline) mean increase in range of increase of 0.1°, in comparison with the control group that had an overall mean decrease of 3.5°. The clinical likelihood was calculated based upon a smallest detectable difference value for the active knee extension test of 3.7°. For the experimental group the clinical likelihood probability that the true value was less than/trivial/greater than the measured value was 6/91/3% for P1 v baseline, 4/87/9% for P2 v P1 and 17/64/19% for P2 v baseline respectively. Considered in combination with the small 0.1° increase in range overall, it is probable that the effect seen in the experimental group overall was trivial, rather than clinically positive or negative. In contrast, for the control group analysis the likelihood values (less than/equivalent/greater than) were 39/60/1%, 15/76/9% and 47/53/0% for P1 v baseline, P2 v P1 and P2 v baseline respectively.

Table 13 shows the individual response in relation to the smallest detectable difference of 3.7° of the active knee extension test. The table shows that at the first post measure approximately 45% of the control group had a clinically significant (detectable) reduction in range, while the other 55% had no detectable change. No individuals demonstrated a detectable increase in flexibility. The distribution of results seen in the smallest detectable difference table at P1 is fairly representative of the clinical likelihood probability values for that group shown in Table 12. Both tables demonstrate a degree of improvement in range for some participants in the control group at the second post measurement (P2), which was 10 minutes post vibration.

Table 12. Changes in Mean Active Knee Extension Test Range of Motion and Clinical Likelihood Probabilities.

Group	Time Period	Change in ROM (°)	p-value	90% CI	Clinical probability (%)		
					-ve	trivial	+ve
Experimental	P1 v baseline	-0.4	0.85	-4.7 to 3.9	6	91	3
	P2 v P1	0.5	0.83	-4.2 to 5.2	4	87	9
	P2 v baseline	0.1	0.98	-8.0 to 8.2	17	64	19
Control	P1 v baseline	-3.0	0.24	-8.2 to 2.1	39	60	1
	P2 v P1	-0.5	0.87	-6.7 to 5.7	15	76	9
	P2 v baseline	-3.5	0.19	-8.8 to 1.8	47	53	0

Note: +ve = positive, -ve = negative, CI = confidence interval. Difference in mean is the change in flexibility in degrees over a time period, calculated as latter test result minus the earlier, for example: Post 1 - Baseline. A positive score for the difference in mean represents a larger mean value for the latter time period relative to the earlier. Clinical probability was calculated based upon a SDD of 3.7°.

Table 13. Change in Range of Motion Based Upon the Smallest Detectable Difference for the Active Knee Extension Test.

Group	Time Period	Number of participants with detectable ROM change		
		Decrease	No Change	Increase
Experimental	P1 v baseline	7	19	5
	P2 v P1	6	16	9
Control	P1 v baseline	14	17	0
	P2 v P1	4	23	4

Note: Based upon a SDD of 3.7°.

Between group comparisons for the passive straight leg raise and active knee extension tests

When change in range of motion was compared between the experimental and control groups for the passive straight leg raise test (see Table 14) the difference was 2° and 0.8° at the P1 v baseline and P2 v P1 time points respectively, where a positive difference indicated a greater experimental group value. The probability that those differences were less than, trivial or greater than the true value was 0/98/2% at the first post measure and 0/100/0% overall (P2 v baseline) respectively.

The difference in mean change of range of motion for the active knee extension test is detailed in Table 14 also. At the first post intervention measurement, the difference in mean change scores between groups was 2.6°, and at the second post intervention measurement (P2 v baseline) the difference was 3.6°. The likelihood that the true value of the difference between the experimental and control group was less than/equivalent (trivial)/greater than the measured difference, was 0/85/15% and 0/53/47% for the respective time points.

Table 14. Comparison Between Experimental and Control Group Range of Motion Changes and Clinical Likelihood Probabilities.

Outcome Measure	Time Period	Difference in Change in ROM (°)	p-value	90% CI	Clinical probability (%)		
					-ve	trivial	+ve
PSLR	P1 v baseline	2.0	0.12	-0.5 to 4.5	0	98	2
	P2 v baseline	0.8	0.55	-1.9 to 3.5	0	100	0
AKE	P1 v baseline	2.6	0.02	0.5 to 4.7	0	85	15
	P2 v baseline	3.6	0.004	1.2 to 6.0	0	53	47

Note: A positive difference in mean represents a larger experimental group mean value relative to the control group mean value.

DISCUSSION

This study aimed to investigate the effects of low frequency segmental vibration on flexibility, when applied to muscle in a relaxed state. It also sought to provide a baseline comparison for other related research involving vibration to muscle in either a contracted or significantly lengthened state.

The baseline flexibility of the sample population measured by the active knee extension test was up to 7° less than other normative data for males in the same age group reported by Youdas et al. (2005) However, they did not have categorically ‘shortened’ hamstrings as defined by Magee (2008), whose definition included less than 125° of knee extension. The use of different goniometric measurement techniques and active range of motion end-point definition may have been partial contributors to the observed difference.

Individual participant responses to vibration were considerably varied, ranging from losses in range of approximately 15° to increases of approximately 11° in both groups. The distribution of individual responses is illustrated in the smallest detectable difference tables (refer to Tables 11 and 13) and demonstrates that some individuals responded more than others. For example, 19 of the experimental group participants did not have a measurable change in range at the first post intervention time-point when measured by the active knee extension test, while seven participants demonstrated a measurable reduction in range, and five showed an increase. Such varied responses were consistent with that observed by other authors (Cronin et al., 2007; Griffin, 1990; Nash, 2005). Nash and Cronin et al. performed acute testing on individuals using the same vibration device as this study, at a range of different vibratory parameters, and reported variability between and within individual responses at different vibratory loadings. The authors have indicated that such individual variability may be of consequence to resonance, dictated by the unique tissue composition in each individual. Resonance mediates the degree of transmission of vibration through the body and responses of the tissues, owing to the increased susceptibility and response seen in some participants (Griffin, 1990).

Trends in the group response were explored by clinical likelihood probabilities. Hopkins (2002) developed a schema for describing the ranges of likelihood probabilities in linguistic terms that indicate how likely a result is. For example, values of less than 1% are regarded as “most certainly not” likely, 1-5% “very unlikely”, 5-25% “unlikely and probably not”, 25-75% “possibly (not) or may (not) be”, 75-95% “likely and probably”, 95-99% “very likely” and finally, greater than 99% “almost certain” (p. 1). Based upon this schema, results indicate that the small changes in range of motion observed in the passive straight leg raise test in both the experimental and control group were very likely to be of clinically trivial significance. The between group comparison for this measure was also clinically insignificant, with an overall (P2 v baseline) clinical likelihood probability of 100% triviality. Although the smallest detectable difference analysis suggests that there were some individuals who responded either with increased or decreased flexibility measured by the passive straight leg raise, the group range of motion means and standard deviations detailed in Table 9 for both groups at the two post vibration time points were not largely dissimilar to baseline. It appears that segmental vibration applied to the hamstrings at the specified parameters had no clinically significant affect on flexibility according to the passive straight leg raise test. Only one other vibration-flexibility study (van den Tillaar, 2006) was identified in the literature that used this outcome measure. That study demonstrated large increases in range, however, had observed the results of a long-term whole-body vibration regimen and no acute effects were recorded.

The lack of a measurable response by the passive straight leg raise test may have been due to other factors beyond the assumption that the vibration delivered was an ineffective stimulus or that most participants were unresponsive. The passive straight leg raise is commonly used as a neurodynamic testing procedure, and the validity of this test as an indirect measure of hamstring flexibility has been questioned (Davis et al., 2008; Sullivan et al., 1992). The end-point used for testing was the participant's perception of the first onset of stretch or firm resistance. The origin of the end-feel sensations is unclear and although care was taken to avoid sensitising manoeuvres throughout the testing procedure, it is uncertain whether the test was sensitive enough to detect changes in hamstring length beyond discomfort created by mechanically sensitive neuromeningeal tissues. The mean range of motion for the control and experimental group spanned from approximately 63° to 65° (refer to Table 9), which is relatively close to the 70° of hip flexion at which the sciatic nerve is thought to come onto tension (Gajdosik et al., 1985). An osteopathic study by Kuilart et al. (2005) found that sensations of hamstring tightness were experienced in individuals with 'normal' range of motion, and that the discomfort experienced in stretching the hamstrings may in fact be due to tension in neural structures. The authors advocated the use of a neurodynamic testing procedure such as the 'slump test' to help differentiate possible origins of sensations. Of the 31 participants who undertook the present study, 24 reported regularly experiencing 'tightness' in their hamstring muscles. Unfortunately, as no other neurodynamic procedure was performed prior to testing, the possibility of the end-feel determined due to poor neuromeningeal mobility cannot be excluded. However, if it were assumed that the observed results of the passive straight leg raise were due to neural tension, then it could be said that vibration delivered at the specified parameters had little impact on neuromeningeal mobility or sensitivity.

The active knee extension test clinical likelihood probabilities revealed that vibration of the experimental leg produced an almost negligible mean change in range of motion overall (P2 v baseline), that was unlikely to be clinically positive or negative. The control group, on the other hand, had demonstrated a mean reduction (- 3.5°) in flexibility 10 minutes post vibration, which may have been equally of trivial or negative clinical significance, but was almost certainly not a positive effect. It appears that both groups decreased in range of motion immediately post vibration, although the experimental group loss was minimal and was recovered within 10 minutes. With regard to the between group comparison for the active knee extension test (Table 14), care must be taken in the interpretation of the difference between the experimental and control group 10 minutes post vibration (P2 v baseline). At first glance it may appear that there was a positive effect in the vibrated leg. However, interpretation must take into account the trend seen in the control group over the course of the experiment, as control group flexibility worsened, while the experimental group had minimal change from baseline. It is likely that immediately post vibration the control leg decreased in flexibility, in comparison to the vibrated leg. Ten minutes post vibration, it is likely that the differences between the legs was clinically negative. Therefore, there is evidence to suggest that there was a clinically negative effect on hamstring flexibility in the control leg subsequent to contralateral leg vibration, as measured by the active knee extension test.

As a consequence of loosely strapping the active leg during the active knee extension test, it is possible that some degree of systematic error may have been introduced to the testing procedure through impairment of hamstring extensibility. Although the author assumed that the loose nature of the strapping did not restrict hamstring lengthening, interpretation of the active knee extension results should be considered in light of such potential error.

No clear explanation can be given for the active knee extension flexibility attenuation observed in the control group, although the contribution of diminishing effects of warm-up, as well as crossed neurological effects were considered. De Pino et al. (2000) observed a similar decrease of 2.9° in control leg range of motion three minutes post warm-up, which continued to decline over the next 30 minutes. The control group was exposed to six active knee extension familiarisation exercises as a warm-up before baseline measures were taken, and then lay supine for three minutes before the next measurements. Although the authors could not provide a definitive cause for this phenomenon, they speculated that it was due to decline in the intramuscular heat generated by the warm-up over time, causing an increase in muscle tendon unit viscosity and diminished flexibility. This argument may explain the effects observed in the present study to an extent. However, range changes as large as –13.2° were observed in some individuals, which seem far too sizeable to be explained in this manner. The potential involvement of a neural-mediated crossed effect, resulting in reduction in control leg flexibility immediately and up to 10 minutes after contralateral leg vibration, cannot be ruled out. These results were unexpected, and highlight the inherent flaw of the study design that was used. Although other studies (Bosco, Cardinale, & Tsarpela, 1999; Bosco, Colli et al., 1999; Cronin et al., 2004) investigating the effects of vibration on strength performance factors have used the contralateral limb as a control, those authors reported no significant changes in the control following unilateral vibration of the experimental limb. While crossed effects are naturally occurring events in the human body (Martini, 1998), the existence of such crossed effects in response to vibration remains unclear and relatively unexplored (Kossev et al., 2001). If crossed effects were implicated in this circumstance, the neural processes responsible may include inter-hemispheric modulation of descending output to particular muscles in the control limb (Jackson & Turner, 2003; Kossev et al., 2001). Kossev et al. demonstrated a reduction in motor-evoked potentials to the opposite limb following vibration, while Jackson and Turner observed a loss of maximal power in the contralateral quadriceps following prolonged vibration, in the absence of EMG changes. The active knee extension test is determined not only by hamstring extensibility, but is also dependent upon the ability of the quadriceps muscle group to actively extend the knee joint. With respect to the contralateral agonists and antagonists, reflexive crossed effects affecting either functional muscle groups cannot be ruled out.

It is evident from the results gathered in this study that vibration delivered at 34 Hz, 3 mm amplitude and 42.2 ms^{-2} acceleration locally to the hamstrings was not a sufficient stimulus in producing mean range of motion increases in either test in the sample population studied. These results may have been due to a number of factors. The vibration device that was used produced random waveform oscillations, which differs from the sinusoidal waveform used in many recreational exercise and research settings. It is unclear to what extent waveform contributes to the responses observed in participants (Cronin et al., 2007, 2008; Nash, 2005). The same random waveform device used was also used with similar vibration parameters in other acute studies that found varied responses ranging from no significant change in range of motion (Cronin et al., 2008; Nash, 2005) to moderate effect sizes and small increases in range of ES ≥ 1.21 and 1.6 to 2.1% (3.1° increase) respectively (Cronin et al., 2007), immediately and 10 minutes post vibration exposure. Therefore, the response seen in the experimental group in the present study is not entirely uncharacteristic of what can be expected from these vibratory parameters applied locally to muscle in a relaxed position. An explanation for the lack of measurable response in this study can only be speculated, but may involve heightened neural excitability resulting in reflexive resistance to stretch. Cronin et al. (2007) explain that augmentation of the stretch-reflex loop and increased motor unit recruitment may increase sensitivity to stretch and therefore, limit range of motion. Nash (2005) suggested that the lack of response that they observed was due to "altered neural activation of muscles controlling the knee, most likely through enhanced reflex contraction of the hamstrings" (p. 77). Reflexive factors are not the only mechanisms proposed to contribute to vibration-induced changes in flexibility. Increases in intramuscular temperature as a result of friction and vasodilation, and increased stretch tolerance due to increases in pain threshold are thought to contribute to the effects observed by studies that have found significantly large increases in flexibility (Issurin et al., 1994; Kinser et al., 2008; Sands et al., 2006). In consideration of the present study, the lack of range improvement may suggest a neurological dominance over any beneficial effects of temperature and pain tolerance in the musculotendinous unit.

In comparison to the other vibration studies that were identified in the literature, the results observed in this study compare poorly with the large range of motion changes reported (see Chapter 3: Tables 4 and 5). However, many of those studies have applied vibration to muscle either on substantial stretch, or to contracted muscle, which are states known to augment vibration transmission (Subashi et al., 2008), and neuromuscular responses (Rohmert et al., 1989). Nash (2005) proposed that the combined effects of stretch and vibration may decrease neural sensitisation. The only other comparable acute local vibration study (Kinser et al., 2008) that involved vibration applied to muscle that was relaxed investigated these effects in young elite gymnasts. Kinser et al. conducted an acute pre-post measure study, applying vibration at a frequency of 30Hz and 2mm amplitude to the lower extremity over a total of four minutes. They found increases of up to 10% in forward split flexibility, which are considerable improvements in this class of athlete, as generally further improvements in range would be expected to be trivial or small (Sands et al., 2006). Aside from the different range of motion measures used, a primary difference in the Kinser et al. study was that highly trained athletes were studied. It is thought that such individuals may be more susceptible to vibration stimulus, due to enhanced nervous system acuity from higher muscle receptor sensitivity and muscle conditioning (Cronin et al., 2004; Issurin & Tenenbaum, 1999). Nash (2005) investigated recreationally-active males with similar effects to this study. Recreationally-active males may be less susceptible to neural stimulation by vibration under these conditions. A less homogenous sample may have improved the chances of observing a different response from vibration.

Very few vibration-flexibility intervention studies have reported the subjective sensations experienced by the participants who undergo the vibration protocol, although Nash (2005) and Cronin et al. (2004) have identified and forewarned of potential translation injury lasting up to ten days post intervention. Many of the participants in the present study reported numerous sensations during and immediately post vibration exposure. Such sensations included ipsilateral lower extremity discomfort, skin itch, warmth, involuntary muscle contraction, partial-numbness of the posterior thigh and tingling from the thigh to the plantar aspect of the foot. Although no participants reported pain, all reported discomfort or unpleasant sensations in the vibrated leg, at variable stages of the five-minute exposure. Five participants reported a sensation of slow continuous movement of the limb from right to left of the thigh as it rested on the vibration device, although these movements were not visible to the researcher. During the subsequent range of motion testing some participants reported that they felt their range of motion had increased post vibration, although the individual change scores did not necessarily support the perception of increased flexibility. Such reports are similar to that described in the literature (Griffin, 1990) coined ‘illusions of limb position’, where participant reports are inconsistent with limb positioning or movement at the time. The illusions are thought to be due to excitation of afferents in the limb as a response to tendon vibration (Kito, Hashimoto, Yoneda, Katamoto, & Naito, 2006), and stimulation of the “supplementary motor area, caudal cingulated motor area and area 4a of the brain" (Cardinale & Bosco, 2003, p. 5). All participants noted that all sensory abnormalities had resolved within 10 minutes post vibration, and no permanent adverse effects were noted.

With respect to other common techniques used to improve flexibility, the ongoing use of methods such as static stretching and warm-up prior to exercise or for general flexibility are advocated. Increases of range of motion ranging from 14° in acute combined warm-up and stretch programs (de Weijer et al., 2003) and 12° for stretch alone (Nelson & Bandy, 2004), surpass the results seen in this and similar studies in a normal recreationally-active population. Use of such methods are recommended until further evidence can be put forward to suggest that local or whole-body vibration is an effective and safe stimulus to enhance flexibility.

CONCLUSION AND RECOMMENDATIONS

In conclusion, the results indicate that five one-minute exposures of vibration applied locally to the hamstrings, at 34 Hz frequency, 3 mm amplitude, and 42.2 $m.s^{-2}$ acceleration, had little impact on hamstring flexibility as measured by the passive straight leg raise test up to 10 minutes post vibration. Additionally no clinically significant change was observed in experimental leg flexibility when measured by active knee extension, up to 10 minutes post vibration. Factors that may have contributed to the observed results include insensitivity of the outcome measure, ineffective stimulus strength, unresponsive sample population, vibration waveform, the state of muscle at the time of vibration and dominance of neural reflexes preventing muscle elongation. There was evidence to suggest that there was possibly a negative clinical effect in the control leg, indicated by a reduction in range by the active knee extension test. The mechanism responsible for the attenuation of flexibility remains unclear, but may be of consequence to a reduction in intramuscular temperature due to diminishing warm-up effects, or from crossed neurological effects from vibratory stimulation of the contralateral leg. Individual responses were unique and variable, and perhaps if a more diverse group of participants were observed, other trends may have been apparent.

With respect to the clinically insignificant changes observed for the most part in this study, there was no evidence to support the practical use of vibration under these conditions for enhancement of hamstring flexibility in healthy recreationally-active males. Additionally, a tentative comment could be made, that vibration may have little effect on neuromeningeal mobility. Although vibration is becoming a more popular exercise tool, there remains little in-depth knowledge with regard to the effects of vibration. Until further is known about this intervention, it should not be recommended in the clinical setting as potential tool for flexibility enhancement. Therefore, further investigation is warranted regarding all areas of vibration's effects, including physiological mechanisms involved, exercise safety, optimal vibratory parameters related to performance goals, and effects on different population subsets.

STUDY LIMITATIONS

The sample population consisted of healthy, recreationally-active male participants between 18 to 35 years of age. The changes identified in this group may not be representative of effects that may occur in other population subsets.

The sample size used in this vibration intervention study (Chapter 5) is considered small, and therefore may not be generalisable to a larger population. Individual participant responses to the vibration intervention were variable, and had there been a greater number of participants then perhaps clearer trends in responses may have become apparent.

The hamstring muscles were the target tissues to which the vibration was applied. Results observed in this study may not be typical of effects that may occur in other muscle groups of the body. Additionally, the vibration was applied to muscle in a relaxed state within its normal resting length, and therefore may not be indicative of responses in muscles on stretch or in a state of contraction.

Participants were exposed to random waveform vibration in this study, which differs to the sinusoidal waveform used in the more popular whole-body vibration programs in use recreationally, and some research studies. This difference may have produced effects that are not typically characteristic of other vibration programs using sinusoidal waveform oscillations and therefore limit the applicability of the results to those conditions.

The vibration intervention showed acute response to vibration applied at specific vibration parameters. As the study was based on immediate changes following a single session of vibration exposure, observations of effects may not be representative of long-term exposure, or those that occur with different vibratory parameters. Additionally potential disparity in results may extend to the use of different vibration devices and settings such as clinical, research and recreational settings.

The additional strapping of the active leg in the active knee extension test may have introduced some degree of systematic error, threatening validity, if any of the participants had moved out of the 90° of hip flexion. In any instance that this occurred, the extensibility of the hamstring might have been compromised by tightening of the strap.

The choice of a within-subject repeated measures study design, which employed the contralateral leg as the control group, was not as effective as expected due to unexpected results in the control leg. Those results highlighted the possibility of crossed neurological effects in the contralateral control leg as a result of unilateral vibration of the experimental leg.

CHAPTER 6: SUMMARY AND PRACTICAL IMPLICATIONS FOR FUTURE RESEARCH

SUMMARY

This dissertation was composed of two studies. One involved evaluation of the reliability of indirect hamstring outcome measures measured by electrogoniometry. The other investigated the effects of low-frequency segmental vibration on hamstring flexibility, when applied to the hamstring muscle in a relaxed state.

Numerous studies have reported high reliability of indirect measures of hamstring flexibility, when measured by such equipment as manual goniometers, inclinometers and video analysis. However, studies reporting the reliability electrogoniometry to assess hamstring range of motion are rare. The reliability study investigated the reliability of the passive straight leg raise test and the active knee extension test, using electrogoniometry and a single tester. Both outcome measures were found to be highly reliable (ICC = 0.96 and 0.98 respectively), with a fairly low standard error of measurement (SEM = 1.7° and 1.4°, respectively). The smallest detectable difference, of 4.6° for the passive straight leg raise test and 3.7° for the active knee extension test compared favourably with that calculated from other similar reliability studies using more traditional methods of goniometry. Overall, it was established that the outcome measures performed using the electrogoniometry device were sufficiently reliable to be used in the subsequent intervention study.

Vibration training is rapidly becoming a popular exercise recreationally, however, there is little scientific or clinical evidence to support the commercial and anecdotal claims regarding its effectiveness in improving strength and joint range of motion. Of the few studies that have investigated the effects of vibration on flexibility, in most cases vibration was applied to muscle in either contracted or lengthened states, in competitive athletes. Such studies boasted impressive results in comparison to more conventional methods such as static stretching. However, little is known about the effects of vibration in the untrained population. The intervention study observed the effect of segmental vibration on the flexibility of the hamstring muscles in a sample of 31 healthy recreationally-active male participants. They received vibratory stimulation to relaxed muscle at similar parameters to other vibration studies, although random waveform was employed. No clinically significant improvements were observed in either group, for either the passive straight leg raise test or active knee extension test. Non-significant results may have been due to the vibration protocol employed, the relaxed state of muscle at the time of vibration, the susceptibility of the sample population to vibration effects and sensitivity of outcome measures to detect changes. Furthermore, inhibitory nervous excitation may have been a contributing factor.

The study showed an unexpected potentially negative effect in the contralateral leg, which could not be explained. There is a possibility that the reduction in range was due to warm-down effects or neurologically mediated crossed effects. There is little scientific proof with respect to existence of crossed effects and the underlying mechanisms involved, and therefore further investigation of this field may be warranted.

The vibration parameters used in this study did not demonstrate any clinically significant improvements in range of motion, which suggests that vibration alone as a stimulus, applied under these conditions, is ineffective with respect to improving flexibility in this population subset. Other than the control leg response, the general trend observed is paralleled by a small number of segmental vibration studies. Therefore, there is evidence to indicate that the baseline effects of vibration applied to relaxed muscle in untrained individuals are negligible. The use of this particular exercise cannot be advocated for use by patients in the clinical setting until further definitive results can be demonstrated.

PRACTICAL IMPLICATIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

Electrogoniometry is a relatively new method of range of motion assessment. When used in conjunction with reliable outcome measures it appears to be a highly reliable tool that may reduce the degree of error introduced by the rater. As electrogoniometry may have a higher degree of accuracy than more traditional goniometric methods, further investigation of reliability in assessment of other, more multi-axial joints is recommended.

Future research investigating the effects of any intervention on the hamstring muscles should consider integration of a neurodynamic testing procedure such as the ‘slump test’. Such a procedure would determine to what extent the observed results might be due to mechanosensitive neuromeningeal structures. Additionally, such research would provide a greater understanding of the relationship between hamstring ‘tightness’ and neuromeningeal hypomobility.

The current study does not support the use of vibration as a lone stimulus for flexibility enhancement. The results may not necessarily be generalisable to a larger heteronymous population, but in combination with the findings of Nash (2005) and Cronin et al. (2008) provides a baseline indication of what may be expected when vibration at parameters of 34 Hz, 3 mm amplitude and 42.2 ms^{-2} acceleration is applied for five one-minute exposures. Such baseline results may be an informative comparison with respect to other research involving different parameters, for muscle on stretch or contraction. At the current time there remains little research to support the use of such interventions in other subsets of the population on an acute or long-term basis, other than in athletes. Until further research gives evidence to suggest a positive effect on flexibility, such interventions should not be recommended in a clinical setting to individuals who require treatment of inflexibility.

Future study designs should take into consideration potential crossed effects of vibration. Additionally future research should further focus on crossed effects of acute vibration exposure, as well as long-term studies.

The scope of the current body of knowledge is sparse, and more in-depth investigation is required to inform safer vibration training practices for all population subsets that choose this mode of exercise to achieve their physical goals. A real need exists to identify optimal training parameters, which currently remain elusive. As reported in this study, participants experienced discomfort and paraesthesia in response to vibration, although no sensory alterations persisted beyond the study duration. However, Cronin et al. (2004) reported more serious side effects from whole-body vibration in a substantial number of his participants. Such reports of adverse effects that occur within the range of recommended training parameters should be investigated.

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APPENDICES

Appendix 1. UREC ethics permission

Unitec
NEW ZEALAND
Te Whare Wānanga o Wairaka

phone +64 9 849 4180 fax +64 9 815 2901 web www.unitec.ac.nz
address Private Bag 92025, Auckland Mail Centre, Auckland 1142, New Zealand
Mt Albert campus Carrington Rd, Mt Albert, Auckland, New Zealand
Waitakere campus Ratanui St, Henderson, Auckland, New Zealand

[redacted]

December 14, 2007

Dear [redacted]

Your file number for this application: 2007.786
Title: The effects of segmental vibration on hamstring range of motion

Your application for ethics approval has been reviewed by the Unitec Research Ethics Committee (UREC) and has been **approved** for the following period:

Start date: 12 December 2007
Finish date: 31 December 2008

Please note that:
1. the above dates must be referred to on the information AND consent forms given to all participants
2. you must inform UREC, in advance, of any ethically-relevant deviation in the project. This may require additional approval.

This letter has been copied to the Principal Supervisor for Unitec student research projects.

You may now commence your research according to the protocols approved by UREC. We wish you every success with your project.

Yours sincerely

Portia Richmond

pp Deborah Rolland
Deputy Chair, UREC

RMOL ref#: 1067

cc: Assoc Prof Andrew Stewart
Carla Sutton

Appendix 2. UREC ethics amendment.

Unitec
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address Private Bag 92025, Auckland Mail Centre, Auckland 1142, New Zealand
Mt Albert campus Carrington Rd, Mt Albert, Auckland, New Zealand
Waitakere campus Ratanui St, Henderson, Auckland, New Zealand

[redacted]

3 June 2008

Dear [redacted]

Your file number for this application: 2007.786
Title: The effects of segmental vibration on hamstring range of motion

Your application to amend your research project to make changes top the rate and length of vibration has been reviewed by the Unitec Research Ethics Committee (UREC) and has been **approved**.

Please note that you must inform UREC, in advance, of any further ethically-relevant deviation in the project. This may require additional approval.

Yours sincerely

pp Deborah Rolland
Deputy Chair, UREC

Appendix 3. Recruitment poster.

RESEARCH STUDY

Are you a healthy, recreationally active male, aged18-35 who can't touch your toes because of tightness in your hamstrings?

I am looking for volunteers to participate in a study investigating the effects of vibration on range of motion at the knee joint. The study will take approximately 45 minutes to complete, in building 115 at the Mount Albert Unitec campus.

Interested?! Please contact [redacted]

[redacted] [redacted] [redacted] [redacted] [redacted] [redacted] [redacted] [redacted]

Appendix 4. Participant information form.

Participant information form

THE EFFECTS OF SEGMENTAL VIBRATION ON HAMSTRING RANGE OF MOTION

My name is xxxxx and I am a second year Master of Osteopathy student at Unitec. As part of the master degree program students must undertake a research project. I will be investigating the effects of segmental vibration on the flexibility of the hamstrings muscles, and seek your help in this research. I have the approval of the School of Health Science at the Unitec Carrington campus to perform this study at their location.

The aim of the project:

I am investigating the effects of low-frequency vibration on the flexibility of the hamstring muscles in healthy adult males. By taking part in this research you will be helping me to gain more information as to the effects of vibration, as well as whether this may be a potential future treatment modality for poor flexibility of muscle tissue.

Your participation will involve:

Initial meeting with the researcher

- Meeting for 10 minutes to measure hamstring range of motion and discuss relevant past medical history and current health status. This will determine your suitability for participation.

Participation in the project

- You will be asked to give approximately 45 minutes of your time.
- You will undertake a short warm up period of cycling for five minutes at a moderate speed.
- The range of motion of both hamstring muscles will be measured.
- One leg will be exposed to a five-minute period of vibration.
- The range of motion will then be retested up to and including 15 minutes afterwards.
-

Results will be recorded by a computer program and statistically analysed. Any personal information that may identify you such as your name and other details will be kept completely confidential. The information gained will be stored in password protected files, and your information will only be accessible to you, the researcher and supervisors.

Risks:

There are risks associated with very high or low frequency, high amplitude vibration that is applied to tissues repetitively over long periods. An example of this is transmission to the head or lumbar spine causing injury. This study will use segmental vibration applied in a position that should minimise any forces to the head or lumbar area. The frequency, amplitude and exposure time of vibration has been used in similar studies with no reported adverse effects. You will be asked to wear ear-muffs to protect your hearing during the procedure.

Some heat or itchiness of the skin on the thigh may be experienced for a short period following vibration, which may be unpleasant to the participant. Additionally stretching the hamstring during the range of motion measures may also be uncomfortable. To minimise the risk of injury you will undertake a warm-up, and end of range will be determined by your perception of the end point. The risk of harm in this study is considered low, however in the unlikely event of injury the appropriate medical resources will be sought should they be required (at the participant's expense).

Joining the study:

If you agree to participate, you will be asked to sign a consent form. Should you later decide that you no longer want to participate you have the right to withdraw, however you must do this within two weeks following the experiment. I hope that you are interested and agree to take part. If you have any queries about the project please contact xxxxx, phone xxxxx or email xxxxx. If you have any concerns you may contact my supervisor xxxxx, phone xxxxx or email xxxxx.

UREC REGISTRATION NUMBER: 2007.786

This study has been approved by the Unitec Research Ethics Committee from December 2007 to December 2008. If you have any complaints or reservations about the ethical conduct of this research, you may contact the Committee through the UREC Secretary (ph: 09 815 4321 ext 7248). Any issues you raise will be treated with confidence and investigated fully, and you will be informed of the outcome.

Appendix 5. Participant consent form.

Participant consent form

THE EFFECTS OF SEGMENTAL VIBRATION ON HAMSTRING RANGE OF MOTION

I have had the research project explained to me by ________________(name) and I have read and understood the information sheet. I have had the opportunity to have any questions answered.

I understand that participation is voluntary and that I do not have to participate in this project if I do not want to. I understand that I have the right to withdraw from participation up to two weeks following the experiment, without any consequence.

I understand that my personal identifying details and any information collected from this project will be kept completely confidential and will only be available to the researcher and their supervisor. Any reported data will remain anonymous. I also understand that all information I give will be stored securely for a period of 5 years.

I understand that I can see the finished research document.

I agree to take part in this project.

Participant Signature: ___________________________

Participant Name: ___________________________

Date: ____________________________

The participant should retain a copy of this consent form. If you have any queries about the project please contact xxxxx, phone xxxxx or email xxxxx. If you have any concerns you may contact my supervisor xxxxx, phone xxxxx or email xxxxx.

UREC REGISTRATION NUMBER: 2007.786
This study has been approved by the Unitec Research Ethics Committee from December 2007 to December 2008. If you have any complaints or reservations about the ethical conduct of this research, you may contact the Committee through the UREC Secretary (ph: 09 815 4321 ext 7248). Any issues you raise will be treated with confidence and investigated fully, and you will be informed of the outcome.

Appendix 6. Participant instruction handout.

We will conduct two different tests on both of your legs

Test One

I will raise your straight leg **without your help**.

Click when you feel the **first point of stretch or firm resistance**.

This test will be performed three times on one leg

The other leg will then be tested in the same way

Test two

I will put you into position.

When we are ready you will **slowly straighten your lower leg to the maximal point** and hold for one second. Keep your knee against the board.

I will tell you when to relax your knee.

This test will be performed three times.

The other leg will then be tested in the same way.

Appendix 7. Mean range of motion reliability data for the passive straight leg raise and active knee extension test.

	Passive straight leg raise test			Active knee extension test		
Participant	Trial 1 (°)	Trial 2 (°)	Trial 3 (°)	Trial 1 (°)	Trial 2 (°)	Trial 3 (°)
1	72.6	72.7	69.1	64.6	60.7	61.8
2	59.6	56.0	57.1	37.6	33.7	39.4
3	63.9	63.0	66.3	48.9	46.5	46.6
4	53.6	63.6	59.3	43	45.6	42.5
5	71.8	66.4	77.8	47.6	46.8	42.7
6	70.4	77.0	71.3	40.3	38.1	43.4
7	68.4	76.4	70.2	52.7	53.3	50.7
8	82.4	83.2	82.5	70.8	67.5	68.1
9	56.7	55.0	63.1	39.4	39.2	43.2
10	66.6	68.1	70.5	43.7	37.3	41.7
11	66.9	63.4	63.2	60.7	61.3	61.4
12	62.2	62.5	59.3	38.2	31.6	36
13	62.4	62.6	58.9	52.8	51.2	48.3
14	54.7	55.5	58.3	36.7	39.5	38.2
15	69.3	68.8	67.4	52.5	51	46.8
16	67.9	66.8	67.7	39.5	39.6	40.1
17	72.5	70.4	68.8	56.1	48.1	49
18	83.2	83.0	85.5	63.2	60.5	61.9
19	59.6	60.7	64.0	47.9	43	39
20	67.8	69.7	72.6	45.1	46.4	41.2
Mean ± SD	66.6 ± 8.0	67.2 ± 8.2	67.7 ± 7.8	49.1 ± 10	47.1 ± 9.9	47.1 ± 9.2

Note: Mean range of motion was calculated from three consecutive measurements at that time point.

Appendix 8. Experimental and control group mean range of motion data for the passive straight leg raise test.

	Experimental Leg			Control Leg		
Participant	Baseline (°)	P1 (°)	P2 (°)	Baseline (°)	P1 (°)	P2 (°)
1	75.1	74.7	71.0	68.5	72.4	71.0
2	64.2	64.7	69.4	61.0	58.8	62.1
3	56.3	59.3	55.6	57.0	56.7	59.0
4	62.3	65.8	63.7	60.3	52.4	57.0
5	76.1	81.8	75.6	70.3	80.0	74.1
6	62.6	64.7	66.1	68.9	65.3	67.4
7	69.8	65.7	63.3	67.4	61.1	64.9
8	60.0	55.9	61.4	72.1	56.6	59.6
9	55.7	61.2	62.4	52.4	57.8	55.0
10	55.5	57.8	55.1	62.9	61.5	55.3
11	50.3	50.4	52.3	46.2	52.1	45.3
12	49.9	49.4	50.0	50.4	52.6	53.8
13	58.5	54.9	58.0	56.2	55.2	56.6
14	62.0	62.9	64.2	61.3	65.1	72.8
15	72.0	69.2	69.1	80.0	82.8	78.7
16	61.0	73.4	63.4	68.9	75.7	75.2
17	56.7	58.6	58.6	49.3	47.6	52.6
18	64.5	70.0	68.8	72.3	74.5	75.8
19	57.3	61.7	61.3	58.9	63.5	66.6
20	55.0	59.8	66.2	56.3	60.8	62.9
21	57.5	56.9	61.0	60.0	60.4	60.4
22	73.8	81.4	74.4	68.5	66.9	71.2
23	52.3	54.4	56.8	57.8	55.2	57.3
24	67.2	64.5	63.6	62.0	61.8	58.5
25	69.9	67.5	64.7	68.8	60.9	59.1
26	72.4	72.0	72.6	66.9	71.6	72.9
27	57.4	61.4	63.2	66.2	62.4	68.7
28	68.5	68.7	65.4	71.6	68.7	66.1
29	64.7	60.3	61.0	61.3	53.7	56.7
30	66.7	67.6	69.4	69.3	67.9	71.5
31	69.5	75.5	73.0	84.2	84.6	83.4
Mean	62.7	64.3	63.9	63.8	63.4	64.2
± SD	± 7.4	± 8.1	± 6.3	± 8.6	± 9.3	± 8.9

Note: Mean range of motion was calculated from three consecutive measurements at that time point.

Appendix 9. Experimental and control group mean range of motion data for the active knee extension test.

	Experimental Leg			Control Leg		
Participant	Baseline (°)	P1 (°)	P2 (°)	Baseline (°)	P1 (°)	P2 (°)
1	60.5	54	63.1	68.1	66.6	67.5
2	42.1	47	51.2	34.8	33	31.6
3	39.1	34.3	39.8	35.7	30.9	30.6
4	40.5	49.5	42.5	41.4	38.9	36
5	44.7	47.7	47.5	49.9	51.6	48.6
6	27.5	27.8	28.2	39.3	35	38.9
7	48.3	35.1	38.4	47.8	42	43.6
8	47.4	47.2	43.8	54.1	45.9	47.1
9	38.8	37.7	43.3	42.6	32.8	26.7
10	54.1	53.1	55.5	62.1	61.2	61.4
11	40.3	43.6	44.1	44.1	43.1	39.6
12	45.2	42.5	41.9	49.7	38.6	38.9
13	53.2	57.2	50.7	54.3	53.5	49.7
14	46	48	48.6	49.5	45	44.1
15	60.3	54.5	58.3	62.7	57	64.7
16	54.5	55.7	53.2	60.5	55.7	56.4
17	46.1	45.7	40.1	46.6	42.3	40.2
18	62	63.7	65.5	68.2	69.1	68.3
19	37.1	36.3	36.3	39.9	39.1	38.2
20	42.1	40.5	45.5	42.4	34.7	35.8
21	32.8	35.2	33.7	39.1	33.7	37.9
22	41.6	53	43.5	46.9	46.8	50.7
23	44.4	38.7	40.2	45.6	46.5	42.4
24	45.3	44.1	38.3	50	44.8	38.6
25	48.4	42.3	36.7	50.4	40.9	40
26	45.1	44.5	41	41.7	42	41.3
27	37.9	35.6	41.4	43.3	42.4	43.8
28	39.3	39.5	43.4	40.3	43.6	47.2
29	34.8	40.8	43.6	37	37.4	36.4
30	51.6	50.6	54.5	61.3	61.1	58.4
31	62.8	56.1	62.1	64	63.7	60.5
Mean	45.6	45.2	45.7	48.8	45.8	45.3
± SD	± 8.6	± 8.3	± 8.8	± 9.7	± 10.5	± 11

Note: Mean range of motion was calculated from three consecutive measurements at that time point.