THE EFFECT OF A HAMSTRING CONTRACT-RELAX-AGONIST-CONTRACT INTERVENTION ON SPRINT AND AGILITY PERFORMANCE IN MODERATELY ACTIVE MALES

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DECLARATION

I, Timothy Vadachalam, hereby declare that the work on which this dissertation is based is my original work (except where acknowledgements indicate otherwise) and that neither the whole work nor any part of it has been, is being, or is to be submitted for another degree in this or any other university.

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LIST OF ABBREVIATIONS

J	Joules
$N.m^{-1}$	Newtons per metre
$°.sec^{-1}$	Degrees per second
s	Second(s)
m	Metre(s)
min	Minute(s)
N	Newton
$N.deg^{-1}$	Newtons per degree
kg	Kilogram(s)
$m.s^{-1}$	Metres per second
SD	Standard deviation
ICC	Intraclass coefficient correlation
VO_{2max}	Maximal oxygen uptake
BMI	Body mass index
EMG	Electromyography
MRI	Magnetic resonance imaging
MVC	Maximal voluntary contraction
ROM	Range of motion
SLR	Straight leg raise
MTU	Musculotendinous unit
TPU	Teno-periosteal unit
AKE	Active knee extension
PNF	Proprioceptive neuromuscular facilitation
CR	Contract-relax
CRAC	Contract-relax-agonist-contract

GLOSSARY OF TERMS

Stretching	Any movement applied by an external and/or internal force in order to increase muscle flexibility and/or joint range of motion {120}.
Flexibility	The ability of a joint or series of joints to move through a full, unrestricted, pain free range of motion {33}.
Proprioceptive neuromuscular facilitation (PNF)	A stretching technique that involves the use of an isometric contraction of the target muscle (antagonist) followed by facilitated stretching which is either active, passive or both active and passive {69, 97, 100}.
Contract-relax-agonist-contract (CRAC)	A form of PNF which involves an isometric contraction of the antagonist from a stretched position followed by a concentric contraction of the muscle group which produces motion of the joint in the opposite direction to that of the antagonist (referred to as the agonist) {46, 93, 131}.
Creep	The tissue deformation that continues until a new length is reached in response to a constant force {110}
Stress relaxation	The decrease in force over time that would be required to hold a tissue at a particular length {110}.
Thixotropy	The property of a tissue to become more liquid after motion and return to a stiffer, gel-like state at rest {60, 106, 118}.
Agility	The ability to change directions rapidly while maintaining balance and without loss of speed {89, 99}.
Sprint testing	A high performance athletic test of varying distance which may evaluate maximal acceleration from rest and/or maximal running speed {62, 67, 96, 98, 107}.

ABSTRACT

Background: The demands of modern day sport require athletes to reach their optimal sporting performance. Flexibility is an important component of exercise performance. The high incidence of hamstring strain injuries in various sporting codes has been linked to reduced hamstring flexibility. Stretching has been used as the primary method to improve or maintain flexibility as a prophylactic prevention of muscle strains in many sporting codes. While a variety of stretching techniques exist, contract-relax-agonist-contract (CRAC) stretching, a type of proprioceptive neuromuscular facilitation stretching, appears to induce greater flexibility improvements than other forms of stretching. However, the effectiveness of this stretch as a method of enhancing agility and sprint performance, as functional measures of athletic performance, has yet to be determined.

Objective: To determine the effect of hamstring contract-relax-agonist-contract stretch on flexibility, agility and sprint performance as functional measures of muscle performance in moderately active adult males.

Methods: Forty healthy male volunteers between the ages of 21 and 35 years, who performed between three and five hours of physical activity per week were recruited for this study, which had a true experimental design. Participants provided written informed consent, and completed medical- and exercise-related questionnaires. Body mass, stature and body mass index were measured. Participants were randomly assigned to either an experimental group, which received the CRAC intervention, or the control group, which did not receive CRAC intervention. Participants attended a total of three testing sessions. During the first session, hamstring flexibility and sprint and agility times were measured. In the second session, pre- and post-CRAC hamstring flexibility was measured and the best of two-timed trials was recorded for the sprint and agility tests. During the final testing session, pre-CRAC hamstring flexibility was recorded and following a standardised warm-up, post-CRAC hamstring flexibility was measured at specifically timed intervals (0, 2, 4, 6, 8, 15, and 20 min) on a randomly selected leg (referred to as the “thixotropy” leg). The hamstring flexibility of the opposite leg (the “control” leg) was measured at 0 and 20 min only. A standardised warm-up was performed prior to the hamstring CRAC stretch in all testing sessions.

During testing sessions, participants in the control group were asked to rest in supine lying for 6 min, which was equivalent to the time taken to perform the CRAC stretch for participants in the experimental group following the warm-up.

Results: There was a significant difference between groups in body mass ($p = 0.02$), with participants in the experimental group ($n = 20$) having a significantly higher body mass, compared to participants in the control group ($n = 20$). There were no significant differences between groups for any other descriptive variables. There was a significant increased percentage change in hamstring flexibility of the experimental group, compared to the control group ($p <.001$). No significant differences were found in the percentage of change of agility, best 10 m or best 25 m sprint times between groups. There was a significant difference between groups with repeated flexibility measurements conducted over regularly timed intervals ($F_{(7,\ 266)} = 38.95$; $p <.001$). Hamstring flexibility remained significantly increased for the duration of 8 min in the experimental group post-CRAC stretch, compared to the control group ($p <.001$). There were no significant differences between the knee extension angles of the “thixotropic” and ”control” leg in the experimental and control groups at the 20 minute interval when compared to baseline knee extension angles within each group.

Conclusion: Hamstring flexibility was significantly increased for up to 8 min following the CRAC stretch. However, the CRAC stretch was ineffective in enhancing agility and sprint performance. The need for further research into the use of CRAC stretching as a method of functional performance enhancement was highlighted. There should be a standardised protocol of CRAC application, and future studies should determine the effects of chronic stretch adaptations following regular, long-term hamstring CRAC application on measures of exercise performance. This study showed that CRAC is an effective, time-efficient method of stretching that does not have a detrimental effect on exercise performance.

1. INTRODUCTION AND SCOPE OF THE THESIS

1.1 Introduction

Sporting individuals endeavour to maximise their abilities and train to influence physical factors which determine sporting performance, including agility, speed, explosive capacity, endurance and flexibility {3, 11, 25, 26, 75}. Of these factors, flexibility is an often understated or disregarded component of optimal athletic performance {20, 120}. One of the most common sports-related injuries is a hamstring strain {105}. Hamstring strain injuries have been positively linked to decreased hamstring flexibility in numerous studies {20, 49, 126}. From an anatomical and biomechanical perspective, the hamstring muscle complex is at an increased risk of injury due to its biarticular structure and its function as a hip extensor and knee flexor {57}. This is particularly evident in sports that require sudden acceleration and deceleration, such as field hockey and soccer {10, 26}.

Decreased hamstring flexibility has been identified as a risk factor that increases the propensity for hamstring strain injuries {20, 49, 50, 126}. The reported incidence of hamstring strains is high, and accounts for a significant amount of missed competition for elite athletes in a variety of sporting codes {9, 26, 50}. Further, the biarthrodial position of the hamstring contributes to a greater risk of strain during sporting activities which involve sudden acceleration/deceleration and jumping (such as football) {57, 78}. There is a high rate of hamstring strain re-occurrence, which impacts on the athlete’s return to play and indicates the difficult nature of the injury as experienced by sports physiotherapists during hamstring strain rehabilitation {68, 129}. Stretching has been advocated as a method of improving or maintaining flexibility and has been used prophylactically in many sporting codes to prevent muscle strains. This is despite the lack of clear evidence for the proposed benefits of improved flexibility and injury reduction {90, 103, 104}. There are different stretching techniques, such as static, ballistic and proprioceptive neuromuscular facilitation (PNF) stretching {74, 94}.

However, a particular PNF technique, the contract-relax-agonist-contract (CRAC) stretch, appears to induce greater increases in flexibility compared to other forms of stretching {74, 94}. Despite evidence for the efficacy of CRAC stretching, there are few studies that have investigated the changes in hamstring flexibility following CRAC stretching {93, 131}. Previous studies have used isolated and functional measures of muscle performance, in an attempt to understand the relationship between stretching and exercise performance. While electromyographic (EMG), peak torque and maximal voluntary contraction (MVC) data serve as valid laboratory-based isolated measures, field tasks such as agility and sprint tests are more appropriate for use as functional measures of muscle performance in the sporting realm {3, 56, 98, 99, 102}.

1.2 Statement of the problem

Further, while previous studies have shown that the decrease in peak torque following PNF stretching was 3% to 5% less than that produced by static stretching, the CRAC technique was not specifically investigated and the hamstring muscle was not studied in isolation {63, 71, 112, 120}. Previous studies have demonstrated inconsistencies in PNF stretch application; and a lack of consensus of an optimal and standardised method of application. Additionally, the relationship between increased hamstring flexibility following CRAC stretching and functional measures of performance has not been investigated. While the duration of maintained flexibility has been defined following acute static and contract-relax (CR) hamstring stretching protocols, this effect has not been established following acute hamstring CRAC stretching {22, 106}. Therefore, the principle aim of this thesis was to determine the effects of hamstring CRAC stretch on flexibility, agility and sprint performance as functional measures of muscle performance. The secondary aim was to establish the duration of maintained hamstring flexibility after acute application of the hamstring CRAC stretch.

1.3 Aim and objectives

1.3.1 Aim

The aim of this study was to investigate the effect of hamstring contract-relax agonist contract intervention on sprint and agility performance in moderately active males.

1.3.2 Specific objectives

Specific objectives of this study were:

- To determine whether there was a significant difference between hamstring flexibility, agility, and sprint performance in an experimental group that performed a CRAC stretch, and a control group that received no intervention.
- To determine the duration of effect of a CRAC stretch on hamstring flexibility in the experimental group, compared to the control group that received no intervention.
- To determine thixotropic effects of a CRAC stretch on hamstring flexibility in a "thixotropic" leg assessed at regular time intervals after the intervention; compared to a "control" leg assessed before and after the intervention and at the final time interval.

1.3.3 Significance of the study

Physiotherapists working with teams and individual athletes are often involved in warm-up preparations before training and competition. Stretching is a common intervention used in warm-ups. However, there is limited evidence for the effectiveness of stretching, and in particular, CRAC stretching on hamstring flexibility and exercise performance.

In addition, the duration of effect of stretching interventions has not been systematically investigated. This study will provide new information regarding the effects of CRAC stretching on hamstring flexibility and indicators of exercise performance. This is of practical relevance for physiotherapists working with athletes and teams. The findings of this study may assist in the development of guidelines for stretching before training and competition.

1.4 Conclusion

In preparation for the randomised, experimental study of the thesis, a review of the literature on the hamstring muscles, stretching techniques, mechanisms of action of stretching and effects of stretching (with an emphasis on CRAC) will be presented (Chapter 2). This will be followed by a description of the study designed to provide evidence for the potential benefit of hamstring CRAC stretching during agility and sprint tests as functional measures of muscle performance. The methods will be presented in Chapter 3, and the results will be presented in Chapter 4. This will be followed by a discussion of the study findings (Chapter 5). The summary and conclusion section will complete this thesis (Chapter 6).

2 LITERATURE REVIEW

2.1 Introduction

It has been hypothesised that reduced hamstring flexibility is a predisposing factor for the subsequent development of a hamstring strain {25, 126}. However, there is equivocal evidence for the proposed benefits of improved flexibility associated with stretching, such as decreased musculotendinous injuries, reduced muscle soreness and improved performance {63, 64}.

Stretching is associated with acute and chronic adaptations. Recent studies have examined isolated measures of stretch-induced effects on muscle performance. These isolated measures include peak torque, mean power output and passive and active range of motion, examined from acute {22, 29, 33, 65, 97, 106, 122} or chronic adaptation perspectives {7, 31, 48}. A focus on these abovementioned isolated measures of stretch-induced effects improves scientific reasoning for the clinical use of stretching. However, due to the lack of evidence on the use of functional tasks as measures of stretch-induced effects on muscle performance, it is difficult to provide evidence-based practical application in the context of sport. Examples of functional measures of athletic performance include sprinting and agility tests {87, 91, 107}.

Stretching may be categorised into three methods, namely static, ballistic and proprioceptive neuromuscular facilitation (PNF). Static stretching involves the use of a slow passive force to place the required muscle in a position of stretch, held for a duration ranging from 6 s to 60 s {5, 94}. Ballistic stretching involves muscle being actively stretched rapidly to its physiological limit and then rebounded immediately and repeated at a fast rate {5, 120}. Proprioceptive neuromuscular facilitation stretching may be further sub-divided into three primary techniques, namely contract-relax (CR), hold-relax swing (HRS) and contract-relax-agonist-contract (CRAC).

Proprioceptive neuromuscular facilitation stretches generally emphasise minimal use of external force, active muscular contractions, verbal cues and tactile stimulation (usually provided by a trained therapist) to facilitate movement in specific patterns by activating target muscle groups {69, 97}. Target muscle group activation occurs through isometric and/or concentric muscular contraction and is dependent on both the PNF technique and the specific joint selected for which facilitated range of motion (ROM) is required. There is evidence to suggest that the CRAC stretch is a particularly effective method of improving muscle flexibility {27, 30, 94}. However, there is a lack of information regarding the effects of this specific stretch technique on functional performance measures, such as sprinting and agility performance. In addition, despite recent evidence of the duration of effect of stretching {22, 106}, further studies are needed to specifically determine the duration of effect of the CRAC stretch.

The factors discussed above suggest a need for further research due to potential implications for clinical practice and sports performance. To illustrate this gap in research and further emphasise the need for this study, the anatomy and function of the hamstring muscle group and epidemiology of hamstring injuries will be discussed, followed by factors contributing to hamstring injuries. Thereafter, the concepts of flexibility and stretching, the mechanisms of stretching and stretching techniques with a focus on PNF will be reviewed. A brief discussion regarding measures of functional athletic performance and hamstring flexibility follows. Data was sourced from sports medicine and science literature using searches on PubMed, Medline, EBSCO, PEDro and Web of Science. Keywords used in the search included *“hamstring stretching”, “proprioceptive neuromuscular facilitation”, “stretching effects”, “agility”, “sprint testing” “stretching and exercise performance”, “stretching in athletes”, “hamstring flexibility”* and *“injury prevention”.*

2.2 Anatomy and function of the hamstring muscle complex

The hamstring muscle group consists of three muscles which are semitendinosus, semimembranosus and the two heads (long and short) of biceps femoris. The semitendinosus originates from the lower medial facet of the lateral section of the ischial tuberosity and inserts, together with the tendon of the long head of biceps femoris, onto the medial surface of the medial condyle of the tibia {82}. The semimembranosus muscle lies deep to semitendinosus and originates from the upper lateral facet of the ischial tuberosity to insert in a horizontal groove on the posteromedial surface of the medial tibial condyle, while its superolateral fibres spread from the insertion to form the oblique popliteal ligament {82}. The long head of biceps femoris originates from the lower medial facet of the ischial tuberosity and runs laterally across the posterior aspect of the thigh, superficial to the sciatic nerve and the short head of biceps femoris {82}. The short head of biceps femoris originates between the lower lateral lip of the linea aspera and the upper lateral supracondylar line of the femur. The long and short heads of biceps femoris merge to form a common tendon which inserts primarily onto the head of the fibula, while some tendon fibres join the fibular collateral ligament, the posterior aspect of the lateral intermuscular septum and the lateral tibial condyle {82}. The semitendinosus, semimembranosus and long head of biceps femoris are supplied by the tibial division, while the short head of biceps femoris is supplied by the common peroneal division of the sciatic nerve (root value L5, S1 and S2) {82}.

The primary functions of the hamstring muscles as a group is knee flexion and hip extension. When functioning from their insertions, the semitendinosus and semimembranosus assist hip extension from a position of trunk flexion. When functioning from their origins, these muscles produce knee flexion, medial rotation of a semi-flexed knee and lateral rotation of the femur and pelvis on the tibia (when the foot is fixed in weight-bearing) {82}. Biceps femoris works with semitendinosus and semimembranosus to flex the knee, but produces lateral rotation of a semi-flexed knee and medial rotation of the femur and pelvis on the tibia (when the foot is fixed in weight-bearing) {82}. All three muscles work eccentrically to control motion during trunk flexion and during deceleration of the forward motion of the tibia during knee extension in the swing phase of normal gait {82}.

According to Rosenthal & McMillian (2003) the muscle group is at its most injury-prone position during the "*late swing phase of the gait cycle*" {105}. The hamstring group is required to make a rapid transition from an eccentric to concentric contraction at the instantaneous moment of heel strike {105}. This transition must occur from an elongated position which further contributes to the mechanical disadvantage {78}.

Sports which require rapid active knee extension, multiple stretch shortening cycles and maximal muscle lengthening, such as sprinting, jumping, rugby and soccer, display the highest prevalence of hamstring strains due to the repetition of this injury-predisposing movement {9, 18, 128}. Due to the anatomical origin and insertion, the hamstring muscle group has a bi-articular influence and functions as a hip extensor, knee flexor and knee rotator {82}. These multiple functions predispose the hamstring muscle group to injury in sports which require maximal contractions, sudden acceleration or deceleration and change of direction {57, 82}.

2.3 Epidemiology of hamstring injuries

The prevalence of hamstring injuries in various sports are summarised in Table 2.1.

Table 2-1: ***The quantity of hamstring injuries expressed as a percentage of all injuries within team sports (Adapted from Brooks et al {9})***

Authors	Sporting Code	Percentage Contribution Hamstring Injuries (%)
Arnason et al (2004)	Australian Rules football	16
Meeuwisse et al (2003)	Basketball	6
Orchard et al (2002)	Cricket	11
Gabbe et al (2006)	Soccer	12 – 16
Seward et al (1993)	Rugby Union	6 – 15

Eighty percent (80%) of all muscular strains in soccer players involved the lower extremities of which 47% affected the hamstrings {26}. According to video analysis studies in Australian Rules football, the majority of the muscle strains occurred during sprinting, especially when running with the body leaning forward {9}. During this sprinting phase, the hamstrings work eccentrically to support the weight of the trunk towards an upright posture and maintain the trunk in slight flexion to increase forward momentum {82}. The hamstrings simultaneously perform rapid and maximal concentric work to minimise ground contact time and provide lower limb thrust {82}. Current epidemiological research also suggests that hamstring strains are correlated with eccentric overload {12}. Siegel {105} described the heightened eccentric activity in the hamstring muscle during sprinting as a result of a shortened deceleration phase performed in an elongated position {105}. Hamstring muscle strain was the most common injury cited as the reason for missed games and accounted for 20% of all missed games in Australian Rules football {114}. Injuries are defined according to the anatomical site involved, namely the muscle belly, tendon, musculotendinous or teno-osseus junctions {68}. The majority of hamstring tears occur at the musculotendinous junction of the biceps femoris {105, 114, 129}. However, the reoccurrence rate of hamstring muscle strains ranges from 34% to 77%, which indicates the nature of the pathology and the inherent difficulty associated with hamstring strain rehabilitation {129}.

2.4 The relationship between hamstring injury and flexibility

Numerous studies have identified flexibility as the primary variable which influenced the risk of hamstring injury {19, 25, 26, 33, 49, 61, 126}. Alter (1996) defined flexibility as "*the ability of a joint or series of joints to move through a full, unrestricted, pain free range of motion*" {33}. Flexibility may be affected by gender, age, increased adipose tissue, skin, stiff muscle, ligaments and tendons {8}. Flexibility may also be classified as either static or dynamic. Static flexibility refers to the ability to reach end-points in the ROM passively, while dynamic flexibility is the ability to actively move a joint via muscle contraction quickly through its ROM with minimal resistance {8, 11, 101}.

Other factors which may have contributed to an increased risk of hamstring strain include older age, previous hamstring strain and previous lower limb muscular strains {9, 18, 50}. Brooks {9} suggested that black/aboriginal ethnic origin is a non-modifiable risk factor that increases the risk of hamstring strains, despite a lack of scientific evidence. However, it has recently been shown that predisposing factors for hamstring strain are not isolated to any specific population {105}.

Stretching has been recommended as a preventative measure to improve or maintain hamstring flexibility, thereby reducing the potential for strain injuries {61}. Apart from the use of stretch intervention, previous studies have established correlations between reduced flexibility and the rate, occurrence and risk of hamstring strains {19, 49, 50, 126}. Brief critical analyses of these studies are outlined below to describe the relationship between hamstring injury and flexibility.

Witvrou et al {126} investigated the correlation between reduced hamstring flexibility measured during pre-season and risk of musculoskeletal injury during the season in professional soccer players. Of the 146 players who sustained in-season injuries, 67 were muscular injuries affecting the lower limb of which 31 involved the hamstring specifically {126}. Compared to pre-season (baseline) flexibility measurements, there was a significant correlation between decreased hamstring flexibility and the occurrence of hamstring injury {126}. However, the study did not specify the exact mechanism of the hamstring injury and the authors assigned reduced hamstring flexibility as the causative factor by default {126}. Due to the confounding effect produced by this methodology, caution should be exercised when analysing these results. However, Witvrou et al {126} recommended further studies to determine risk factors for hamstring strains.

Hartig and Henderson {49} investigated the effect of hamstring flexibility on the rate and occurrence of lower extremity overuse injuries in military infantry basic trainees. Over the 13 week infantry basic training course, pre- and post-test hamstring flexibility, measured by the passive knee extension test (PKE), was recorded for both control (n = 148) and intervention (n = 150) groups {49}.

Both groups undertook basic training simultaneously and performed the same regimen except for three additional static hamstring stretch sessions per day for the intervention group (five repetitions per leg held for 30 s, three times per day) {49}. Lower extremity overuse injuries were recorded at weekly intervals over the duration of the basic training. Mean hamstring flexibility increased significantly (indicated by a decrease in PKE) in the intervention group (41.7° to 34.7°) compared to the control group (45.9° to 42.9°). The incidence of injury in the intervention group (n = 25) was also significantly lower compared to the control group (n = 43) {49}. Expressed as a percentage of all participants within each respective group, the intervention group experienced 17% injury incidence compared to 29% injury incidence within the control group {49}. However, the results would have held greater credibility if the "*Army routine assignment*" responsible for random assignment of participants into either group {49} was described in greater detail in the methodology. The intervention group was inherently more flexible than the control group as seen in pre-test flexibility measurements {49}. However this factor was not controlled for in statistical analyses or substantiated in the discussion. The study design lacked control of possible contamination amongst groups as the population was selected based on convenience. Further, the monitoring of the stretch intervention, technique and regime compliance was poorly controlled, which may have allowed for result bias.

Cross and Worrell {19} demonstrated a 48.8% reduction in lower limb musculotendinous strains in college football players as a result of a daily static stretching regime instituted in 1995. The incidence rates of musculotendinous strains between the season using the stretch intervention (1995) were compared with the season prior (1994) which did not utilise the stretching intervention {19}. In the 1995 season, 21 out of 195 players reported muscular strains compared to 43 out of 195 players in the 1994 season {19}. While a relationship between static stretching and reduction of musculotendinous injury may be inferred, caution should be exercised when analysing the results. Confounding variables such as field conditions, variations in fitness levels/training methods and the addition or loss of players due to recruitment or transfers/graduation were not controlled for {19}. Considering the use of static stretching as the intervention, pre- and post-season flexibility, as an important outcome measure, was not assessed {19}.

The reduction in lower limb musculotendinous strains was assigned to the introduction of the stretch intervention by default, despite the absence of flexibility measures as evidence for correlation {19}. Furthermore, the athletic training staff within each college supervised the stretching {19}, which is a poor method of monitoring consistent stretch application or compliance with the stretching regime.

Henderson et al {50} assessed 36 elite professional soccer players at pre-season for hamstring isokinetic strength, peak torque, anaerobic fitness, explosive leg power and hamstring flexibility (via active and passive straight leg raise (SLR) video analysis). Players were monitored over the 45 week season and of the 104 injuries reported, 14 were disruptions to the hamstring musculature (confirmed by magnetic resonance imaging (MRI) scans). Statistical analyses were performed to compare individual physical and performance capacities of a player with predisposition to sustain a hamstring injury. It was determined that for every one degree (1°) decrease in active SLR and for each one year increase in age, propensity for injury increased by a factor of 1.29 and 1.78 respectively {50}. Further, Henderson et al {50} showed for each one centimetre increase in non-counter movement jump (NCM) performance (a measure of explosive leg power), propensity for hamstring injury increased by a factor of 1.47. The results linked increased hamstring strain propensity with increased explosive leg power producing a dilemma as greater NCM value is an often used pre-requisite to determine successful performance in elite soccer {50}.

The collective evidence suggests that decreased hamstring flexibility is a primary factor for increasing the risk of hamstring injury, despite the methodological flaws of some studies. The uses of stretching for the purpose of decreasing risk of injury are due to its effects on muscle tissue and flexibility {104, 111}. Over the past 30 years, our knowledge of the effects of stretching via direct and indirect mechanisms of action has improved and provided further rationale for the uses of stretching {104}. The direct mechanism of action refers to the reduction of muscle stiffness by affecting the passive viscoelastic components of muscle. The indirect mechanism of action refers to neurological stretch effects, such as reflex muscle inhibition, and the resultant effect it has on viscoelastic properties of muscle. The concepts and definitions of stretching and compliance will now be discussed, and will be followed by a description of the mechanisms of stretching.

2.5 Stretching and Compliance

2.5.1 Stretching

Stretching is defined as "*movement applied by an external and/or internal force in order to increase muscle flexibility and/or joint range of motion*" {120}. Taylor et al {110} showed that during stretching, the overlap between myosin and actin filaments within the sarcomere decreased which resulted in muscle fibre elongation until maximum resting length. After reaching the maximum resting length, a maintained stretching force acts upon the non-contractile elements such as tendon, perimysium, epimysium and endomysium {57, 110}. To understand the concept and application of stretching, the physiological characteristic of compliance must first be discussed.

2.5.2 Compliance

Compliance is defined as "*the reciprocal of stiffness, and mathematically it is equal to the length change that occurs in a tissue divided by the force applied to achieve the change in length*" {104}. According to this definition, the equation to calculate compliance can be expressed as follows:-

$$\textit{Compliance (c)} = \textit{(Final length – Initial length).Applied Force}^{-1} \ \{104\}$$

For example, a tissue that is easy to stretch is compliant because it lengthens significantly with very little force. While the compliance of active muscle is dependent on the number of active actin-myosin bonds, compliance of resting muscle is determined by the muscle cytoskeleton. Within the resting muscle cytoskeleton, titin serves as the primary contributor to compliance {24, 92}. The relationship between the compliance of muscle or tendon and factors such as exercise efficiency, stretch-induced impairments and injury risk has been previously studied {6, 7, 17, 42, 122, 127}. Brief descriptions of studies that demonstrate the role of compliance after stretching follow.

Behm et al {6} determined that static stretching negatively affected force, balance, reaction time and movement time. It was hypothesized that such stretch-induced impairments were due to changes in muscle compliance which affected the muscle's ability to both identify and react to change of length and rate of change of length {6}. This theory suggested a link between muscle compliance and neurological mechanisms affected by stretching (which will be discussed later). From an electromechanical perspective, a more compliant muscle as a result of static stretching produced a delay in force transmission {6, 7, 92}. Witvrou et al {127} suggested the use of stretching to reduce musculotendinous stiffness and subsequent risk of injury in sports that utilise many stretch-shortening cycles (SSC) (such as soccer or basketball) by increasing tendon compliance and energy absorption capacity.

The effect of a more compliant musculotendinous unit (MTU) on the efficiency of exercise has been previously investigated {17, 42}. Godges et al {42} found no significant change in running economy following a static stretching regime, while Craib et al {17} demonstrated a reduced level of economy in more flexible runners. However, only external hip rotation and ankle dorsiflexion ROM were significantly correlated with the reduced running economy {17}. Furthermore, there was no control of confounding variables such as runners' training programmes and kinematic, anthropometric and physiological data {17, 120}. Based on these results {17, 42}, the effect of muscle compliance on running economy as a measure of exercise efficiency is not conclusive. The concepts of stretching and compliance have been defined and described as a precursor to the following discussion of biomechanical and neurological mechanisms through which stretching affects muscular tissue.

2.6 Mechanisms of stretching

The mechanisms of stretching will be subdivided into discussions regarding the biomechanical and neurological mechanisms affected during stretching followed by the effects of immediate (acute) and long-term (chronic) stretching. The mechanisms of stretching are explained by its influence on biomechanical properties of the MTU (ROM, creep, stress relaxation, hysteresis and thixotropy) and by neurological mechanisms (Hoffman reflex, autogenic and reciprocal inhibition) {19, 120}.

2.6.1 Biomechanical mechanisms of stretching

A brief overview of the structure of skeletal muscle will be provided as a background to the biomechanical mechanisms of stretching. On a macroscopic level, skeletal muscle may be divided into two elastic components, series and parallel. Skeletal muscle forms the contractile element while the non-contractile tendons form the series elastic component {57}. Both structures share the continuous collagen fibres of the perimysium and epimysium. These collagen fibres form the common structural link between bones and muscle via the teno-periosteal junction (TPU) {57}. The parallel elastic component consists of all levels of muscular connective tissue, including the sarcolemma, perimysium, endomysium and epimysium {57, 78}.

Both elastic components ensure smooth transmission of muscle tension during a contraction, and the return of the muscle to pre-contraction resting state after a contraction {78}. The elastic components also absorb energy according to the rate of force application and disperse energy in a time dependent manner {78}. The musculotendinous unit (MTU) consists of three linked components, including contractile muscle, parallel and series elastic components. The MTU serves as the intermediary between force production, via muscle contraction, and force transmission to the skeleton via the teno-periosteal unit (TPU).

Muscular tissue responds by adapting to the demands imposed upon it, either due to pathological or physiological stimuli {57, 78}. Examples of such adaptations include age-related sarcopenia, especially of type II fibres {8}; muscular atrophy following limb immobilisation in a cast {132}; and muscular hypertrophy following regular resistance training {8}. In response to the demand of stretching, the MTU allows an initial elastic elongation up to the limit of ROM, followed by further viscous elongation up to a new ROM limit if the stretch is held and kept at constant load {78}. In response to stretching of the hamstrings, Gajdosik {39, 41} suggested that the increased muscle length may be due to an increased number of sarcomeres in series. Within the MTU during stretching, sarcomeres that show greater compliance are more easily damaged when stretched beyond their optimal length for actin-myosin overlap {103}. The sarcomere damage may produce a physiological trigger to activate sarcomere hyperplasia {103}.

Differences in muscle morphology influence the response of muscle to stretch intervention and should be accounted for when comparing the effects of stretching in previous studies. From a cellular perspective, microscopic factors may also influence the macroscopic biomechanical elements of muscle tissue. Other than actin and myosin, both intra- and extra-sarcomeric muscle cytoskeletons contain additional proteins that assist structural organisation of the sarcomere.

Vimentin, desmin and synemin develop myofibril stability, while integrin helps connect myofibrils to surrounding connective tissue {8, 57, 78}. Nebulin maintains the vital lattice array of actin and titin connects the myosin filament to the Z-disk, functioning as a longitudinal stabiliser to keep the myosin filament centred within the sarcomere {57}. Titin also provides some elasticity during sarcomere stretching {41}. The structural support and elasticity provided by these proteins ensures a relatively constant sarcomere length and assists force production by adjusting cross-bridge kinetics.

2.6.1.1 Viscoelasticity

The viscoelastic property of the MTU may be divided into viscous and elastic components. The viscous property may be defined as the ability of the MTU to allow elongation under the influence of a slow, constant force and the ability to resist forces which attempt elongation by rapid application {110}. The elastic property may be defined as the ability of muscle tissue to allow a change in length after force application, with an almost immediate return to the original resting muscle length following withdrawal of the force {110}. This elastic recoil will occur provided that the initial force does not exceed the physiological elastic limits of muscular tissue, that is, it does not produce plastic changes as based on the load-deformation curve (Figure 2.1) {57, 78, 110}. Muscle as a viscoelastic tissue combines time dependent force application (viscous properties) and force dependent lengthening (elastic properties) to adjust elongation under the influence of stretching load {78}. Viscoelastic properties within the MTU consist of the phenomena of creep, stress relaxation, hysteresis and thixotropic properties.

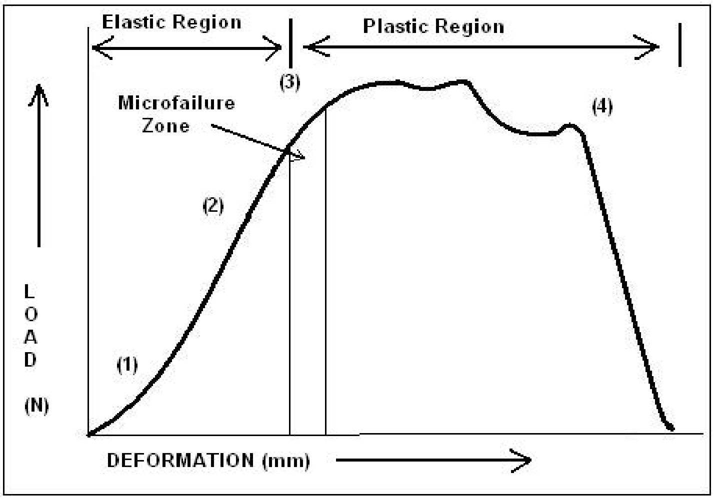


Figure 2-1*: The load-deformation curve indicating the physiological limits of muscle as a viscoelastic tissue (Adapted from Brooks et al {5}, Nordin and Frankel {36}).*

2.6.1.2 Creep

Creep may be defined as "*the tissue deformation that continues until a new length is reached in response to a constant force*" {110}. This may be observed as an immediate, but temporary effect following stretching which influences elastic deformation of the musculotendinous unit {106}.

DePino et al {22} investigated the duration of maintained hamstring flexibility, as measured by passive knee extension, following a static stretching protocol (four static hamstring stretches, each held for 30 s with 15 s rest between repetitions on the right lower limb). The results showed an inability to maintain significant knee extension beyond 3 min, which was credited to the temporary effect of creep {22}. However, there was no use of randomisation of the limb receiving intervention (right limb selected as default) or control for the thixotropic property of muscle (experimental group participants were allowed to flex the knee between stretches) {22}, which is in contrast to a previous study {106}.

Taylor et al {109} used rabbit muscle, which has morphological and histological similarities to human muscle, to demonstrate the effect of creep. A passive stretching protocol was applied to the extensor digitorum muscle in-vitro. Each trial consisted of a gradually applied force ranging from an initial 1.96 N to a peak of 78.4 N, which was held for 30 s and then returned slowly to 1.96 N {109}. Ten trials were performed on each muscle. The results showed a 3.45% increase in the extensor digitorum muscle length to counteract the predetermined stretching force {109}. The increase in muscle length was a measure of the tissue deformation that occurred until a new length was reached in response to a constant peak force {110}.

The clinical significance of creep is that a constant stretching force applied slowly to a muscle will result in an immediate but temporary increase in muscle length, provided that the magnitude of the stretching force does not exceed the elastic limit of the muscle.

2.6.1.3 Stress Relaxation

Stress relaxation may be defined as "*the decrease in force over time that would be required to hold a tissue at a particular length*" {110}. According to Magnusson et al {63}, stress relaxation is an acute response of the parallel elastic component to reduce the load across the injury-prone MTU. In a study which investigated passive energy absorption (measured in Joules (J)), Magnusson et al {64} first determined the maximal oxygen uptake in one minute during maximal running for each participant as a measure of aerobic fitness (VO_{2max}). Magnusson et al {64} found that despite a significant increase in intramuscular temperature following 10 min and 30 min of running at 70% and 75% of VO_{2max} respectively, the passive energy absorption of human skeletal muscle (left hamstring) was unaffected. However, static stretching (three repetitions of 90 s each, resting 30 s between stretches) resulted in a 29% stress relaxation {64}. Stress relaxation produced an immediate and significant decline in passive energy absorption (10.8 ± 1.8 J after the third stretch compared to 14.5 ± 1.7 J pre-exercise; and 13.5 ± 1.9 J after 10 min of running {64}.

The decline in passive energy absorption was not sustained after 30 min of running at 75% of VO_{2max}, which showed that hamstring stress relaxation was temporary and dependent on the duration of static stretching rather than increased intramuscular temperature {64}. However, the sample population consisted of only eight participants selected according to inclusion criteria that were not specified {64}. The use of participants who "*exercised recreationally on a regular basis*" {64} does not explicitly describe inclusion criteria, which is an important factor for relatively small sample groups. Further, randomisation was not used to determine the leg exposed to stretch intervention {64}, which does not control the potential confounding effect of limb dominance on the results.

Taylor et al {109} investigated stress relaxation following stretching of rabbit muscle. The in-vitro stretching protocol consisted of ten repetitions per muscle held at 10% of resting length followed by immediate release, which allowed the muscle to return to its initial position.

The results showed a 16.6% reduction in the peak tension (force) required to stretch rabbit extensor digitorum muscle to 10% of its resting length following repeated stretching trials {109}. The practical significance of stress relaxation may be observed when physiotherapists apply stretches to increase flexibility in a specific muscle; and find that a decreased amount of force is required to reach the limit of ROM upon consecutive stretches, as compared to the initial stretch.

2.6.1.4 Hysteresis

Hysteresis may be defined as the energy dissipated in an extension-recoil cycle of a tendon, expressed as a percentage of the energy for the extension from zero to peak strain {5, 36}. In terms of the load-deformation curve (Figure 2.1, page 17, the area between loading and unloading curves is representative of hysteresis of the musculotendinous unit {78}. This is the energy lost in the form of heat due to internal modulation of loading forces {120}. Generally, tendons lose 3% to 5% of the energy of a load-unloading cycle, but have the ability to temporarily store this energy while any lost energy is converted to frictional heat {59, 78,}. Ligaments have broadly similar mechanical properties as tendons; however they display a greater degree of hysteresis due to the presence of more elastin [5, 36, 59}. When viscoelastic tissue experiences consecutive load and unloading forces, the load-deformation curve shifts to the right with each cycle {57}.

Kubo et al {58, 59} produced significant reductions in tendon stiffness (10% and 8%) and hysteresis (34% and 29%) of the plantarflexors, respectively. The intervention in both studies was passive stretching of the plantar flexors from neutral into 35° of dorsiflexion at a rate of $5°.s^{-1}$; the only difference was the use of 10 min {58} compared to 5 min {59} for the duration of stretch application. Based on these results {58, 59}, it appears that the duration of the applied stretching force has minimal influence on these outcome variables. Only a 2% difference for plantarflexor tendon stiffness and a 5% difference for hysteresis were found despite a twofold increase in applied force duration. However, use of small sample groups (n = 7 {58} and n = 8 {59}) made statistical power of the studies questionable.

Further, the applicability of the results of these studies {58, 59} to the hamstring muscle group is problematic due to differences in muscle architecture and morphology between the plantar flexors and the hamstrings {57}. Hysteresis may have clinical significance in that viscoelastic tissue (muscle) should be loaded appropriately (cyclic/static), under the correct physical conditions (such as temperature) and at an appropriate loading rate. These conditions will dissipate the energy of hysteresis resulting in more reliable and efficient muscle contractions.

2.6.1.5 Thixotropy

Thixotropy may be defined as "*the property of a tissue to become more liquid after motion and return to a stiffer, gel-like state at rest*" {60, 106, 118}. It is postulated that thixotropy in muscle arises from an increase in the number of stable bonds between actin and myosin in a muscle at rest, which results in increased muscle stiffness {106}.

Whatman et al {122} investigated knee ROM and passive hamstring stiffness after passive hamstring stretching with or without active movement post-stretch, compared to a control condition (no stretch). All nine participants were exposed to the experimental conditions (active movement and no movement post-stretch) and control condition over three separate days {122}. The physiotherapist-applied stretch intervention consisted of four repetitions of 20 s seated static stretching of the hamstring to "*maximal tolerable tension*" {122}. Significant reductions in passive stiffness immediately post-stretch and at 20 min post-stretch intervals were found between experimental (active movement post-stretch) and control conditions {122}.

According to Whatman et al {122}, the results demonstrated the effect of motion immediately post-stretch in the experimental condition as compared to the control condition, in which participants sat still during repeated knee ROM tests performed over 20 min. However, randomised selection of the limb to undergo intervention was not specified {122}. Further, the study design may have been improved with the use of a separate control group as results may have been biased based on intention-to-treat and learning effects amongst participants. Poor control of these confounding factors may have influenced the validity of the results {122}.

Spernoga et al {106} showed a correlation between the duration of effect of a hamstring PNF stretch and the length of time spent in relative immobilisation. Thirty participants were randomly assigned to an intervention (n = 15) or control (n = 15) group following pre-participation screening. The inclusion criteria for participation included hamstring tightness defined as a "*limitation of 20° or more from full knee extension*" as measured by the active knee extension (AKE) test. A repetition of the modified hold-relax hamstring stretch adopted the following sequence: a passive SLR held for 7 s at "*mild stretch sensation*"; 7 s isometric hamstring contraction; 5 s rest; and; 7 s passive SLR held at "*mild stretch sensation*" {106}. The stretch protocol consisted of five repetitions and was applied to the experimental group only.

Repeated flexibility measurements were taken post-intervention at specific time intervals (0, 2, 4, 6, 8, 16 and 32 min) for both groups. Participants from both groups were instructed to rest in supine lying for the duration of the repeated flexibility measurements. However, the control group lay supine for 5 min longer than the experimental group, to account for the time taken to complete the stretching protocol for the experimental group. The results showed significantly improved hamstring flexibility which was maintained for 6 min post-stretch in the experimental group {106}. Further, the thixotropic property of muscle was demonstrated, as both groups tended to return towards baseline flexibility after 6 min. There was a significantly greater decrease in the control group AKE (i.e. beyond baseline flexibility of 40.53° ± 10.97°) demonstrated by an increased AKE after 2 min of inactivity (43.33° ± 11.42°) {106}.

Despite increased flexibility following stretching, due to the property of thixotropy in viscoelastic tissue, the duration of effect of the stretch is influenced by muscle activity. As an example of the practical significance, physiotherapists may use therapeutic exercise after stretching to manipulate the effect of thixotropy for active or sporting individuals that require sustained flexibility for longer durations.

2.6.2 Neurological mechanisms of stretching

The neurological mechanisms through which stretching has its effect may be classified into three components which include Hoffman reflex (H-reflex) inhibition, autogenic inhibition and reciprocal inhibition. Muscle maximal voluntary contraction (MVC) and electromyographic (EMG) data following electrical or mechanical stimulation of a mixed peripheral nerve have been used to study neurological mechanisms {1, 13, 23, 73, 109, 117, 137, 138}. Different forms of stretching techniques induce effects by manipulation of either an isolated neurological mechanism, or a combination of neurological mechanisms. Neurological mechanisms of stretching have many pathways of action. These pathways include the interaction between peripheral nerves and muscles via motor end-plates, intramuscular neural systems and the synaptic connections between the spinal cord (as a component of the central nervous system) and peripheral nerves {100}.

2.6.2.1 H-reflex inhibition

The H-reflex is an artificially induced reflex which may be defined as "*the electrical analogue of the stretch reflex*" {137}. The H-reflex is elicited by applying an electrical stimulus pulse to a mixed peripheral nerve, having sensory and motor components, which innervates a group of muscles {13}.

The largest sensory Ia axons from the muscle spindles are activated and send a surge of action potentials to the spinal cord which in turn activate the alpha motoneurons that supply the muscles innervated by the stimulated peripheral nerve {13, 44, 73, 117, 137}. The resultant reflex-twitch response recorded in the muscle is referred to as the H-reflex {117}. The amplitude of H-reflex is normally measured by EMG signal and usually compared to the baseline and MVC EMG data of the same muscle {117}. If H-reflex amplitudes are reduced after stretching, it may be inferred that the technique produced an inhibition of the reflex excitability of the motoneurone pool {13, 73, 109}

Avela et al {1} found that reduced reflex sensitivity (as measured by H-reflex and stretch reflex) persisted for two days in seven elite triathlon athletes after marathon running (as a long duration, low intensity stretch-shortening cycle (SSC) exercise). Isometric MVC, H-reflex and stretch reflex for the gastrocnemius and soleus muscles were recorded pre-marathon run (as the baseline values) and immediately post-marathon run {1}. Repeated reflex measurements were conducted at 2 h, 2 days, 4 days and 6 days after the marathon run {1}. The results showed that maximal H-reflex amplitude declined by 74.5% ± 16.3 % immediately post-marathon run; remained significantly reduced after 2 h and recovered to pre-marathon values after 2 days {1}. While Avela et al {1} did not investigate H-reflex depression after stretching; the results provided scientific explanation for measures of decreased muscle performance after endurance-based exercise which may have practical significance for sport-based medical professionals.

Vujnovich and Dawson {117} investigated the effect of sequentially applied static then ballistic stretch compared with static stretch alone on the H-reflex of the gastrocnemius and soleus muscles in 23 participants. H-reflexes were recorded under control conditions (no stretch) and during both stretch conditions using EMG. The left foot was passively dorsiflexed to the limit of ROM (determined by the participant) and either maintained in this position for 160 s (static stretch) or followed by rapid and repeated dorsiflexion at a velocity and rate of 1 radian.sec^{-1} every 10 s for 160 s (static-ballistic stretch) {117}. The results showed a significant decrease in H-reflex amplitude, expressed as a percentage of the control H-reflex amplitude, following static stretch (60%) and static-ballistic stretch (15%) {117}. While sequential static-ballistic stretching produced a 45% greater reduction of H-reflex amplitude compared to static stretching alone, the difference in group size between static (n = 14) and static-ballistic (n = 5) {117} requires careful interpretation of the results. The overall dosage of stretch, as measured by duration of application, was not equal between groups (160 s and 320 s for static and static-ballistic groups, respectively) {117}. Further, only the left foot was used and randomised selection of the leg for H-reflex measures, as previously suggested {73, 137}, was not conducted {117}. These confounding factors were poorly controlled and may have influenced the reliability of the results of this study {117}.

Guissard et al {44} investigated mechanisms of decreased motoneurone excitation during passive stretching of the triceps surae into 10° and 20° of ankle dorsiflexion in 11 participants. Baseline H-reflex values were recorded by EMG with the ankle in neutral plantigrade position and compared with H-reflexes at 10° and 20° dorsiflexion {44}. To differentiate between pre- and post-synaptic mechanisms, transcranial magnetic stimulation was used to induce a motor-evoked potential by transcranial motor cortex stimulation {44}. Pre-synaptic mechanisms included reduced synaptic transmission capacity with repetitive tasks and reduced recruitment of Ia afferents {44}. Post-synaptic mechanisms included autogenic inhibition, Renshaw loop recurrent inhibition and articular/cutaneous receptor inhibition of afferent input {13, 44, 137}. The results showed that pre-synaptic and post-synaptic mechanisms were responsible as the dominant mechanisms during smaller (10° dorsiflexion) and larger (20° dorsiflexion) stretching amplitudes, respectively {44}.

Moore and Kukulka {73} investigated the depression of H-reflexes after voluntary isometric plantarflexion contractions (using the CR principle) in 16 female participants. The results showed that average post-contraction H-reflex reached 16.7% of control H-reflex amplitude, which was a significant 83.3% depression {73}. Further, H-reflex depression began almost immediately from 0.05 s and remained significantly depressed up to 1 s post-contraction, with recovery to 70% of control H-reflex amplitude by 5 s {73}.

Based on the results of these studies {1, 44, 73, 117} practical implications of the inhibitory effect of stretching on the H-reflex may be inferred. As an example, following an isometric contraction during a CR stretch, the muscle should be stretched immediately or at least within the first 5 s after relaxation to maximise the benefit of the depressed H-reflex amplitude. While passive stretch should be applied as soon as possible after the isometric contraction, it should be done at a slow rate to avoid eliciting the stretch reflex {69, 100}.

2.6.2.2 Autogenic inhibition

This was initially defined as "*the inhibition of the homonymous muscle alpha motor neurons via Golgi tendon organ stimulation*" {116}. Autogenic inhibition results in reduced muscle activity, which allows for less muscular resistance during stretching. During earlier execution of PNF techniques, maximal isometric contractions were used to manipulate this phenomenon on the basis of maximal Golgi tendon organ (GTO) stimulation {69}. However, studies that have examined the effect of submaximal contraction intensities have shown that the GTO is also sensitive to lower magnitudes of force {29, 100}. The current belief is that autogenic inhibition is the result of afferent Group II nerve fibres originating from muscle spindles and possibly from thinly myelinated articular mechanoreceptor fibres, which are partially responsible for pain sensation from the joints {29, 100}.

Zytnicki et al {138} investigated the reduction of Ib autogenic inhibition in motoneurons during contractions of ankle extensor muscles (plantaris (PL), medial gastrocnemius (GM) and lateral gastrocnemius (GL)) in anaesthetised cats. Within these muscles, tetanic contractions at a rate of 10 twitches.s^{-1} were produced by electrical stimulation of the respective nerve or the muscle directly. The results showed that contraction-induced inhibitory potentials, produced by GTO input, declined rapidly towards the end of the tetanic contractions in GM alpha-motoneurons {138}. The same results were observed during tetanic stimulation of the GL and PL alpha motoneurons, which had no excitatory connections to Ia afferents of the GM {138}. Zytnicki et al {138} concluded that since GM GTO discharge persisted during prolonged contractions, the autogenic inhibition observed was due to a spinal mechanism involving Ib afferent and/or inhibitory interneurons.

Edin and Vallbo {23} identified 102 single afferents from the finger extensor muscles in human participants using a microneurographic technique to isolate radial nerve afferent fibres. EMG activity was recorded from individual portions of the finger extensors with surface electrodes and correlated with the microneurograph afferent signals {23}. Following four neurophysiological tests, the afferents were classified as primary muscle spindle afferents (62 of 102), secondary muscle spindle afferents (22 of 102) and GTO afferents (18 of 102) {23}.

The results showed that only 75% of all spindle afferents, compared to 100% of GTO afferents, had increased discharge during an isometric contraction {23}. However, while the primary muscle spindle afferents produced a distinct burst of discharge during rapid muscle relaxation after isometric contraction, GTO afferent activity was negligible during relaxation {23}. The predominant discharge of GTO activity during isometric contraction adds credibility to the role the GTO plays during autogenic inhibition of a homonymous muscle.

Although previous studies supported GTO-induced inhibition of the homonymous motoneurone pool, physiological pathways exist that allow the GTO to elicit either an inhibitory or excitatory effect upon the homonymous or heteronymous motoneurone pool {15, 100}. This concept supports the hypothesis suggested by previous studies for more complex neurologically mediated mechanisms (central/peripheral) together with autogenic inhibition to reduce target muscle activity following an isometric contraction {13, 15, 23, 100, 138}. Irrespective of the specific neural pathway, the clinical significance of the concept of autogenic inhibition is its inhibitory effect on post-contraction excitability of the homonymous muscle alpha motoneurons. With regard to practical significance, PNF stretching techniques such as CR and CRAC usually employ isometric contractions of the agonist muscle, as opposed to ballistic and static stretching techniques. The use of the autogenic inhibition concept during such PNF techniques allow for the agonist muscle to be neurologically manipulated during the post-isometric contraction phase to allow greater relaxation and less resistance to further gains in ROM {69, 100}.

2.6.2.3 Reciprocal Inhibition

This concept may be defined as “*a reflex loop between two opposing muscles*” {69, 97}. Theoretically, when an agonist muscle contracts as a result of efferent motor input, simultaneous efferent excitatory input is provided to the Ia-inhibitory interneurons, which synapse with the alpha motor neurons of the antagonist muscle {97, 100}. The degree to which inhibitory drive is supplied to the antagonist is directly proportional to the fusi-motor demand placed on the agonist muscle {97, 100}, as an example the inhibition of the hamstring muscle group during an MVC test of the quadriceps.

Condon and Hutton {15} investigated soleus and tibialis anterior muscle EMG activity during four stretching procedures (static, CR, AC and CRAC) of equal duration in 12 participants. Pre-stretch measures of plantarflexor MVC and H-reflexes (pre-, during- and post-stretch) were recorded and all participants performed the four stretching protocols in a randomised order. The results showed that while soleus muscle EMG levels were higher during the AC and CRAC, the H-reflex amplitudes were significantly smaller compared to the respective values measured during static and CR techniques {15}.

The primary difference between CRAC and AC compared to static and CR stretching was the active agonist contraction (tibialis anterior) during CRAC and AC soleus stretch {15}. It was concluded that the observed decrease in H-reflex amplitude was due to reflex inhibition of the soleus muscle. The results further suggested that the increased EMG levels during AC and CRAC stretch were produced by alternate neural input, which could have affected alpha motoneurons and distorted the reciprocal inhibitory effect {15}.

Previous studies by Moore and Hutton {74} and Osternig et al {81} provided similar evidence regarding levels of antagonist muscle EMG activity during stretch protocols. Moore and Hutton {74} used hamstring and quadricep muscle EMG data to investigate the individual effect of static, CR and CRAC stretch applied to the hamstrings of 21 female gymnasts. After comparing hip joint angles and intra-individual EMG’s across stretch conditions, the results showed that CRAC (agonist hip flexor contraction) produced greater increases in hip flexion and significantly greater hamstring EMG activity, compared to static and CR techniques {74}.

Osternig et al {81} investigated the effect of PNF techniques, including stretch-relax (SR), CR and agonist-contract-relax (ACR) on hamstring muscle activity (via EMG) and knee extension ROM in 20 participants. The results showed that ACR produced 3% and 6% greater increases in knee extension ROM, and 71% and 155% increased hamstring EMG activity compared to CR and SR techniques, respectively {81}.

Osternig et al {81} concluded that despite the increased knee extension ROM, the significantly increased hamstring EMG activity during the ACR stretch increased the risk of strain injury due to the increased tension produced. However, alternative neurological pathways that may have safely mediated the response to ACR stretch were not considered {81}. Further, both studies {74, 81} did not include an examination of the H-reflex amplitude {15}, which was an important adjunct to substantiate the observations which otherwise were made from muscle EMG data alone.

The concept of reciprocal inhibition suggests that antagonist muscle activity, as measured by EMG, should theoretically decrease during an agonist contraction {120}. Previous studies {15,74,81} showed that while forms of PNF stretching which utilised agonist contractions (AC, CRAC and ACR) were more effective in producing gains in ROM compared to static and other forms of PNF, there was an associated paradoxical increase in agonist EMG activity. Complex neurological pathways including recurrent inhibition and pre-synaptic inhibition of Ia afferents of the antagonist, which are sensitive to joint position and muscle length, may assist reciprocal inhibition {13, 15, 100}. The practical significance of reciprocal inhibition may be seen during active contractions of the agonist group of muscles during a PNF stretch technique. Theoretically, the antagonist muscle group may be inhibited by a combination of reflex inhibition and other potential neural mechanisms to allow smooth motion of the limb in the direction of the agonist thereby producing an active stretch within the antagonist.

The biomechanical and neurological mechanisms of stretching function simultaneously and harmoniously during stretching interventions {100}. Due to the inherent properties of muscle tissue and the neural pathways which modulate muscle activity, short term (acute) and regularly repeated (long-term) application of stretching have been able to produce their respective effects. The effects of acute and long-term stretching are discussed in the following section.

2.7 Effects of acute stretching

According to previous studies {6, 22, 28, 65, 77, 97, 106, 122} the effects of acute stretching refer to the immediately observed physiological changes following a stretching protocol that has been applied for a relatively small period of time. In the context of this review, the time period referred to the duration taken to perform one to five sets of repetitions which were applied to one or multiple muscle groups. The stretch protocol was classified as acute if it was applied once or over one week only. The effects of acute stretching included a temporary viscoelastic effect, age-dependent flexibility changes and an increased pain threshold during stretch.

2.7.1 Temporary viscoelastic effect

Taylor et al {109} demonstrated that when the loading force applied was appropriate, stretching produced an effect on both creep and stress relaxation. The result of stretching on viscoelastic properties was an increase in joint ROM (either active or passive depending on measurement protocols). The duration of this temporary effect varied from 3 min {22} to 6 min {106}. In addition, DePino et al {22} used four repetitions of 30 s static hamstring stretches separated by 15 s rests between each repetition, while Spernoga et al {106} used five repetitions of 26 s CR hamstring stretches (rest between stretches not specified). Due to the differences in stretching technique, number of repetitions and overall duration of stretching (3 min {22} compared to 5 min {106}), the results are difficult to compare despite the application of stretch intervention to the hamstrings in both studies {22, 106}. Further, the exact duration of the temporary viscoelastic effect is inconclusive due to differences in control of muscle thixotropy (discussed later) between studies {22, 106}. Magnusson et al {64} investigated hamstring intramuscular temperature and passive energy absorption both before and after 10 min and 30 min of treadmill running either with or without static stretching (two test conditions conducted on separate days) in eight male participants. Passive energy absorption and resistance to stretch were measured using a passive knee extension (PKE) test performed on an isokinetic dynamometer {64}.

The stretch protocol consisted of one repetition of static hamstring stretching held for 90 s at the point of discomfort which was performed before running, after 10 min and 30 min of running, and three additional repetitions after 10 min of running in the stretch condition {64}. The results showed that the increased intramuscular temperature produced by running had no effect on the viscoelastic properties of the hamstring compared to the significant 29% stress relaxation and reduced passive energy absorption produced by the repeated static stretch protocol {64}. Based on the results of a previous study {63} that used identical measures and intervention, Magnusson et al {64} concluded that there was no hamstring contractile activity which may have contributed to stretch resistance or stress relaxation during static stretching. Similarly, the absence of significant muscle EMG levels during the increase in creep as reported by Taylor et al {109}, suggested that the temporary effects on creep and stress relaxation produced by acute stretching were due to viscoelastic properties and not a decrease in muscle activation {13, 63, 64, 109}.

2.7.2 Age-dependent effects on increasing flexibility

Feland et al {28} investigated the effect of CR compared to static stretch of the hamstrings on flexibility (as measured by goniometry during a PKE test) in 97 senior athletes (age range 55 yrs to 79 yrs). The CR group (n = 40) performed one repetition consisting two cycles of 6 s maximal isometric hamstring contraction followed by 10 s rest periods during which passive SLR stretch was maintained at a "*point of mild discomfort*" (32 s in total). The static stretch group (n = 38) underwent one repetition of passive SLR to held at the point of discomfort for 32 s, while the control group (n = 19) received no intervention {28}.

The results showed that hamstring CR produced greater increases compared to static stretching in knee extension ROM for men and participants younger than 65 years old, while CR and static hamstring stretching produced similar increases in women and participants older than 65 years old {28}. Considering that the duration of stretching was equal (32 s) and only one repetition of each technique was used, Feland et al {28} demonstrated that the participants' age influenced the effect of an acute stretch on flexibility.

Feland et al {28} suggested that the increase in flexibility following the CR hamstring stretch in male senior athletes was due to greater preservation of type II muscle fibres in male athletes compared to female athletes. Senior male athletes may have retained a greater amount of neuromuscular association and had a greater observed effect by the process of autogenic inhibition {28}.

2.7.3 Increase in the pain threshold during stretch

Halbertsma et al {45} investigated the acute effect of repeated passive stretching on passive muscle moment and flexibility of the hamstring muscle group in 17 participants. The main outcome measures included lift force, hip ROM, pelvic-femoral angle, hamstring surface EMG data and the first onset of pain sensation. These outcomes were measured using specialised instrumentation which included a force transducer, electrogoniometers and a stretch tolerance indicator which applied a passive SLR to the left hamstring of each participant {45}. The passive stretching protocol consisted of five successive repetitions of passive SLR at an angular velocity of $3°.s^{-1}$ to the limit of ROM as determined by the participant {45}. The results showed a slight increase in stretch tolerance (the maximal limit of SLR ROM which was tolerable for each individual) after the stretch protocol compared to the initial tolerance level {45}. Similarly, Magnusson et al {63} showed an increased length and force across the muscle after repeated stretching to the onset of pain. Theoretically, if the increased length was limited only to the viscoelastic properties, then only muscle length would have increased and not force across the muscle {104}. Magnusson et al {63} concluded that the results indicated the effect of an analgesic mechanism {63, 104}.

Moore and Hudson {74} showed that while a hamstring CRAC stretch produced the largest increase in hip flexion ROM compared to static and CR stretch techniques, CRAC produced the greatest amount of electrical activity within the hamstring muscle. It was suggested that the increase in hamstring EMG activity level during the CRAC stretch should theoretically have increased hamstring muscle stiffness. Participants were asked to rate their perception of pain and perceived stretch effectiveness during each of the three stretching techniques.

There were significant relationships between participant perception and decreasing EMG activity, but not with ROM {74}. The results showed that the participants gained the greatest increase in ROM, despite the increased EMG activity, following CRAC stretching but were not aware of the significantly increased ROM {74}. These findings demonstrated the effects of altered stretch perception and pain sensation following stretching. While these studies {45, 63, 74} provided evidence of analgesic mechanisms following acute stretching protocols, the exact neural pathways by which this effect is elicited has not been determined. Shrier {104} suggested that the analgesic effect may be controlled at the spinal cord or at the cerebral level.

2.8 Effects of long-term stretching

According to previous studies the effects of long-term stretching refer to the physiological changes observed following a stretching protocol which has been applied for a relatively long period of time {8, 30, 47, 55, 62, 125, 131}. In the context of this review, the time period referred to the duration over which the stretching was performed including a minimum stretch frequency of twice weekly, conducted over two or more weeks {30, 47, 55, 62, 131}. The physiological effects of long-term stretching include stretch-induced hypertrophy and hormonal adaptations.

2.8.1 Stretch-induced hypertrophy

Stretch-induced hypertrophy refers to an increase in muscle force production following a regularly applied long-term stretching protocol. Evidence for stretch-induced hypertrophy has been shown in previous studies which have found improved peak torques {47, 131}, MVC {125}, EMG activity {30}, jump height {55} and acceleration {62}.

Handel et al {47} conducted a study using a unilateral CR stretch protocol for the hamstrings and quadriceps muscle groups, performed three times per week over eight weeks in 16 male athletes from various sporting codes. The main outcome measures included peak torque during eccentric and concentric activity.

The muscle groups of the contralateral limb did not receive intervention and served as the control {47}. The CR protocol for each muscle group consisted of eight repetitions of 10 s isometric contraction at 70% of MVC followed by 2 s of rest and 10 s to 15 s of passive stretch {47}. Compared to baseline values taken prior to the eight week protocol, the results showed significantly increased peak torque in the CR stretch leg during eccentric hamstring (18.2 %) and quadriceps contraction (23 %) {47}. Further, significant increases were found for isometric hamstring peak torque (11.3%) and concentric hamstring peak torque which reached an increase of 9.4% at 60°, 180° and 240 °.sec^{-1} compared to the control leg.

While there were individual differences in the sample group as participants were not from the same sporting code, the data were normalised and confounding factors such as differences in individual training programmes were accounted for during statistical analyses {47}. The study compared differences between the stretch-exposed leg and control limb. Therefore, factors that affect the state of both legs such as improved fitness during the training season and adjustment to the peak torque measurement procedure were negated {47}. Further, validity of the outcome measures was ensured by the elimination of stretching 24 h prior to re-testing {47}, which reduced the possible effect of result bias caused by an acute stretching response.

Worrell et al {131} compared CRAC and static hamstring stretching conducted on 19 participants over three weeks to determine the effects of increased flexibility on isokinetic hamstring peak torque. Flexibility was measured using the AKE test, while both eccentric and concentric hamstring peak torques were recorded at 60°.sec^{-1} and 120°.sec^{-1} using an isokinetic dynamometer {131}. Each participant performed the static stretch on a randomly selected leg and the CRAC stretch on the opposite leg. The participants performed one set of the respective protocol five days per week over three weeks {131}. Both the static and CRAC protocols consisted of one set of four repetitions, performed in standing. Each static stretch was held for 15 s to 20 s at the point of stretch sensation with 15 s rest between repetitions, while each CRAC stretch consisted of 5 s maximal isometric hamstring contraction, 5 s rest followed by 5 s maximal isometric quadricep contraction and a final 5 s rest {131}.

While increased hamstring flexibility between legs was not significant, the CRAC stretch produced a 1.5° greater increase in AKE compared to static stretch {131}. The results showed an 8.5% and 13.5% increase in eccentric hamstring peak torque at 60°.sec^{-1} and 120°.sec^{-1} respectively, and an 11.2% increase in concentric hamstring peak torque at 120°.sec^{-1}{131}. Although the stretch protocols were self-applied, participant compliance and stretch-technique performance were monitored daily with an attendance record of 99.3% over the three week study {131}. Interestingly, both of the above studies {47, 131} used PNF techniques (CR and CRAC respectively) and produced significantly increased eccentric hamstring peak torque, which suggests a potential relationship between the PNF techniques and eccentric strength.

Hunter and Marshall {55} investigated the effects of power and flexibility training on countermovement and drop jump techniques in 50 male athletes. The participants were randomly assigned to one of four groups, which consisted of power training, flexibility training, a combination of flexibility and power training and a control group respectively. The main outcome measures for drop jump analysis included stretch tolerance, jump height, vertical ground reaction force and eccentric lower limb stiffness {55}. Eccentric leg stiffness was calculated as the ground reaction force in relation to the change of body mass position during eccentric muscle action while the participant was still in contact with the ground {55}. The flexibility training consisted of 10 weeks of lower limb static stretching (hamstrings, quadriceps, gluteals, plantarflexors, hip adductors and abductors) performed four times per week, with the inclusion of one PNF session per week after the third week. Static stretches were applied to each muscle group (bilaterally) and consisted of two sets of three repetitions. Each repetition was held at mild discomfort for 20 s and the duration was increased by 10 s every two weeks (60 s at week 10) {55}. Stretch tolerance was measured prior to and after the 10 week training period. The results showed that stretch tolerance of the hamstrings and quadriceps increased significantly after 10 weeks of flexibility training; and maximum height during drop jumps improved with lower eccentric leg stiffness {55}. Hunter and Marshall {55} concluded that improved stretch tolerance was an influential factor which contributed to decreased eccentric leg stiffness {55}.

Wilson et al {125} investigated the effect of eight weeks of flexibility training of the deltoid and pectoral muscles on rebound (RBP) and purely concentric bench press (PCBP), as measures of upper body MVC, in 16 professional weightlifters. Pre- and post-training measures of ROM, series elastic component (SEC) stiffness and MVC were recorded {125}. Participants were randomly assigned to either the experimental group that received stretching (n = 9) or the control group (n = 7) {125}. The stretch protocol was conducted twice per week; each session provided 10 min to 15 min of stretching and consisted of six to nine repetitions of modified PNF stretching performed bilaterally on each muscle group {125}. The results showed significantly increased ROM (3%) and RBP load (5.4%) while the SEC stiffness decreased significantly by 7.2% within the experimental group {125}. Further, experimental participants' increased RBP load was due to significantly greater work during the initial concentric lift phase of the RBP {125}. It was concluded that decreased SEC stiffness increased the use of stored elastic strain energy used in the RBP as an example of stretch-shortening cycle exercise.

Previous studies have shown an increase in eccentric strength {47, 131} and decreased SEC stiffness {125} following long-term stretching. Based on these results, it may be inferred that a more compliant MTU is able to elicit greater force production due to a more efficient use of stored elastic strain energy resulting from long-term adaptations within connective and viscoelastic tissues. Brooks et al {8} stated that regular stretching added sarcomeres to the muscle fibres, which facilitated an increased ROM. The increased ROM consequently resulted in decreased muscle stiffness because of decreased force per unit muscle length {19}. However, Shrier {104} suggested that stretch-induced hypertrophy occurred via an unknown mechanism of viscoelastic modulation on the myofibrillar level. This hypothesis was based on the proportional relationship between increased muscle cross-sectional area and "*muscle stiffness*" and the suggestion that only stretch tolerance, not viscoelasticity, was affected by long-term stretching {104}. In summary, there is evidence that regular, long-term stretching has the ability to facilitate muscular hypertrophy, as demonstrated by increased eccentric strength {47, 131}, and greater force production {125}. However, it appears that PNF techniques elicit a greater eccentric strength improvement compared to static stretching {47, 131}.

2.8.2 Hormonal adaptations

Yang et al {132, 133} investigated the role of insulin-like growth factor 1 (IGF-1) in local muscle growth and within changes of muscle fibre phenotype after six days of stretching or disuse. Passive stretch of the tibialis anterior, extensor digitorum longus and soleus muscle was achieved by plaster cast immobilisation in the appropriate stretch position for each muscle on the left hind limb in separate rabbits {132, 133}. The results showed a significant and rapid increase in muscle mass in the stretched limb, while IGF-1 was strongly expressed together with neonatal and slow type 1 myosin in an increased number of fibres within the muscles exposed to stretch {132, 133}. Yang et al {133} concluded that IGF-1 expression following stretching was correlated with hypertrophy and muscle phenotype adaptation in response to the stretch and overload stimuli. The IGF-1 isoforms that were expressed in stretched rabbit muscle have a similar hormonal structure to human mechano-growth factor (MGF) isoforms {92, 132}. Similarly, Hill and Goldspink {52} found that MGF, an isoform of IGF-1, activated satellite cells which initiated tissue repair after exposing the stretched tibialis anterior muscles of rats (immobilised by plaster casts in plantarflexion) to mechanical damage. Based on the results, MGF functioned as the activation stimulus for satellite cells, stimulated protein synthesis and hypertrophy and mediated local tissue repair and remodelling {43, 52}. While stretching protocols conducted on animal models {52, 132, 133} are not appropriate options of application for human participants, both human and rabbit muscle tissue share morphological and histological similarity which may suggest similar hormonal effects in humans.

In summary, the effects of acute stretching include a temporary viscoelastic effect, an age-specific effect on flexibility and an increase in the pain threshold, while the effects of long-term stretching include stretch induced hypertrophy and hormonal changes. The clinical implication of the acute and long-term effects of stretching allows us to make evidence-based decisions regarding the application of stretching in sports medicine and rehabilitation.

2.9 Stretching Techniques

Stretching may be divided into three basic types: proprioceptive neuromuscular facilitation (PNF), static and ballistic stretching {116, 120}. Static stretching involves the use of a slow passive force to place the required muscle in a position of stretch. Static stretches are held at the limit of ROM, determined by either the participant's perception of onset of stretch sensation {22}, mild discomfort {28} or maximal tolerable tension {122}, for a duration ranging from 6 s to 60 s {5, 94}. Ballistic stretching involves the muscle being actively stretched to the limit of ROM and then rebounded immediately at a rapid rate for many repetitions (usually 15 to 20) {5, 94}. Ballistic stretching allows greater tension and hysteresis development within the MTU because time dependent viscoelastic adaptations are eliminated {5, 120}. Due to concerns of trauma to connective tissue, ballistic stretching is not commonly used to improve flexibility in practice {111}, despite a lack of scientific evidence to support this view {120}. In a recent review, Witvrou et al {128} advocated the use of ballistic stretching to increase tendon compliance as it induced the stretch-reflex in muscle, thereby suggesting an increased energy transfer to tendons than the subsequently contracted (stiffer) muscle.

Proprioceptive neuromuscular facilitation stretching involves the use of an isometric contraction of the target muscle (antagonist) followed by facilitated stretching which is either active, passive or both active and passive (depending on the technique) {69, 97, 100}. The muscle group which produces motion of the limb in the opposite direction to that of the agonist is referred to as the agonist {46, 69, 93, 97}. The concept of PNF stretching is based on neurophysiological principles including reciprocal and autogenic inhibition {97, 116}. The principles of PNF include the use of manual contact; diagonal and spiral movement of the limb; and normal timing which facilitate sensory input, functional muscle contraction (including synergist overflow), sequential contraction and coordinated movement, respectively {116}. Further, traction and approximation are used to stimulate joint receptors to facilitate either movement or stability, respectively {116}. The combined biomechanical and neurological effects assist to relax the tensed muscle resulting in an enhanced relaxation of the MTU after the isometric contraction.

Further, motor pool excitability, as measured by the H-reflex, is depressed after PNF stretching, which uses the transient period of reduced motor capacity to maximise the benefits of an unimpeded stretch {27}. Previous studies have suggested that PNF stretching conditions the reaction and modulates the input both to and from stretch receptors, which alters the participant's perception of stretch and stretch tolerance {45, 63, 74, 100}. The use of PNF techniques requires skill and is usually applied by an appropriately trained physiotherapist {97}.

PNF stretching may be divided into three commonly applied techniques: contract-relax (CR), contract-relax-agonist-contract (CRAC) and hold-relax-swing (HRS) {46}. In the next sections of this review, PNF stretching, specifically CRAC, will be discussed in greater detail and will include a description of the proposed mechanisms of action of CRAC. The proposed benefits of PNF stretching will also be reviewed.

2.9.1 Contract-relax (CR)

In a CR stretch, the antagonist muscle is initially passively stretched, followed by 7 s to 15 s of isometric contraction, and is then relaxed for 2 s to 3 s in the stretched position; followed by passive stretch for 10 s to 15 s with the aim of going further into ROM {46}. Previous studies have used isometric contraction of the antagonist within the time range as suggested by Hall and Brody {46}, which include 5 s {30, 65}; 6 s {28, 29}; 7 s {106} and 10 s {47}. Only one previous study used a 30 s isometric antagonist contraction {33} and produced similar ROM results to studies that used shorter contraction periods. Earlier studies investigating PNF generally involved a maximal isometric contraction of a lengthened muscle, followed by further lengthening using either active or passive force {100}. However, the use of submaximal intensities of antagonist isometric contraction during the CR technique was investigated. The use of 20% and 60% of hamstring MVC during isometric contraction were equally effective as 100% MVC, with a non-significant increase of 0.13° in ROM following 100% hamstring MVC compared to 20% hamstring MVC {29}. The practical significance of the study suggests a reduced risk of contraction induced injury by the use of submaximal contraction intensities during CR {29}.

2.9.2 Hold-relax swing (HRS)

The HRS is similar to the CR procedure except that the passive stretch as the final component of CR is replaced by a dynamic stretch in HRS. The antagonist is initially passively stretched and is followed by a 6 s to 15 s maximal isometric contraction {46}. After 2 s to 3 s of rest, the participant is asked to perform an active stretch of the antagonist by swinging the limb in the direction of pull of the agonist muscle group at a fast rate for 15 s (dynamic stretching) {46}, with an aim of progressing into greater ROM with each swing. Due to the inclusion of dynamic stretching performed at a rapid rate, HRS is not widely used as it is preferentially applied to athletes with greater stretch-reflex control {46}.

2.9.3 Contract-relax-agonist-contract (CRAC)

In a CRAC stretch, the antagonists are first passively stretched, followed by a 6 s to 15 s isometric contraction, followed by an immediate 6 s to 15 s concentric contraction of the agonists. A 20 s rest is needed between repetitions {46}. Previous studies which used the hamstrings as the antagonist muscle began the CRAC sequence with a slow passive SLR to the point of "*mild discomfort*" {131} or "*stretch sensation*" {93} as determined by the participant. The durations of isometric hamstring (antagonist) contraction during CRAC in these studies ranged from 5 s {131} to 7 s {93}. While the rest duration was not explicitly specified, it was inferred that Ryan et al {93} used an immediate transition to concentric quadriceps (agonist) contraction after the isometric hamstring (antagonist) contraction. In contrast, Worrell et al {131} specified that the limb was maintained in the position of stretch for a 5 s rest period after the isometric hamstring (antagonist) contraction. The duration of quadriceps (agonist) contraction ranged from 4 s {93} to 5 s {131}, which was not within the duration range suggested previously {46, 116}. In addition, Ryan et al {93} used a concentric quadriceps contraction, while Worrell et al {131} asked participants to perform a maximal isometric quadriceps contraction, further demonstrating the differences in documented techniques of CRAC stretching. No previous studies have provided conclusive evidence of an optimal rest period between repetitions of the CRAC stretch technique. However, previous studies have suggested rest periods between stretch repetitions of 10 s to 20 s {65, 93, 131}.

Differences in CRAC application {93, 131} and the paucity of studies which have investigated CRAC stretching contribute to the current lack of a standardised evidence-based CRAC protocol. However, as a result of the agonist and antagonist contractions involved in CRAC, as compared to CR and HRS, this stretch has a potentially greater advantage and practical significance for sports physiotherapists (see Section 2.10, page 45).

Previous studies and reviews which compared static, ballistic and PNF stretching techniques have suggested that PNF was the most effective form of stretching {27, 33, 94, 100, 123}. However, there are many variations of PNF stretching protocols (Table 2.2 and 2.3). For example, previous studies and reviews have reported varying agonist isometric contraction times ranging from 3 s to 15 s {28, 29, 30, 97, 100, 106}. There is no consensus among studies regarding the specific duration of fundamental components of PNF stretches, which include the durations of initial passive stretch, maximal isometric contraction, antagonist contraction, rest between isometric and antagonist contractions, rest between isometric contraction and passive stretch and rest between repetitions. Further, the total "*dose*" of stretching also determines cumulative stretch impact. The "*dosage of stretch*" may be measured by total stretch duration; number of stretches per session; amount of sessions per day or week and the course of time over which the protocol was conducted. As a result of the lack of consensus regarding the optimal PNF duration and frequency of application, critical evaluation of PNF and its outcomes becomes difficult.

Table 2-2: ***A summary of the PNF stretching protocols used in previous studies.***

Study Reference	**Feland et al {28}**	**Feland and Marin {29}**	**Ferber et al {30}**	**Funk et al {33}**	**Handel et al {47}**	**Marek et al {65}**	**Ryan et al {93}**	**Worrell et al {131}**	**Schuback et al {97}**	**Spernoga et al {106}**
PNF intervention	CR	CR	CR and ACR	CR	CR	CR	CRAC	CRAC	SRHR	CR
Initial Passive stretch (s)	NA	NA	NA	NA	NA	NA	NS	NS	NA	7
Isometric contraction (s)	6x2	6x3	CR=5	30	10	5	7	5	15	7
Agonist contraction (s)	NA	NA	ACR=5	NA	NA	NA	4	5	NS	NA
Final passive stretch (s)	10	10	CR=5 ACR=5	NS	10 to 15	30	NA	NA	NA	7
Rest between isometric contraction and passive stretch (s)	10	10x2	CR=5	NS	1 to 2	0	NS	5	NA	5
Rest between isometric and agonist contractions (s)	NA	NA	CR=NS ACR=5	NA	NA	NA	NS	5	15	NA
Rest between stretches (s)	NA	NA	CR=0 ACR=0	NS	NS	20	10	15	0	NS
Number of repetitions	1	3	CR=2 ACR=2	NS	2 per muscle group	4	4	4	4	5
Number of sets	1	1	CR=4 ACR=4	1 set of 5 min	1	1	1	1	1	1
Rest between sets (s)	NA	NA	CR=300 ACR=300	NA	NA	NA	NA	NA	NA	NA

Study Reference	**Feland et al {28}**	**Feland and Marin {29}**	**Ferber et al {30}**	**Funk et al {33}**	**Handel et al {47}**	**Marek et al {65}**	**Ryan et al {93}**	**Worrell et al {131}**	**Schuback et al {97}**	**Spernoga et al {106}**
Main outcome measures	PKE ROM	PKE ROM	AKE ROM, hamstring EMG	AKE ROM	PKE & AKE ROM, PT	APKB, PSLR	APSI, MLSI	AKE, PT	PSLR	AKE
Results	↑ 5° post CR	↑5° at 20 % MVC; ↑5.13° at 100% MVC	29 % ↑ ROM and 65 % ↑ EMG post ACR compared to CR	↑ ROM by 9.6% post CR	↑ 6.3° in ROM, ↑ 21.6% in PT	↑ 1.6° AKPB, ↑ 0.5° PSLR,	↑ MLSI post CRAC	↑ 9.5° AKE, ↑ PT by 8.5% to 13.5%	↑12.6° post CRAC	↑ ROM for 6 min post CR

Table abbreviations: NA – Not applicable; NS – Not specified; CR – Contract-relax; ACR – Agonist-contract-relax; CRAC – Contract-relax-agonist-contract; SRHR – Slow-reversal-hold-relax

Table 2-3: ***Outline of studies that have compared the effects of PNF and static stretching.***

Authors	Participants	Stretch intervention	Main outcome measures	Results
Funk et al {33}	20 male and 20 female Division 1 college athletes, baseball (20), field hockey (13), rowing (7)	CR- 30 s hamstring isometric contraction, rest period NS performed for 5 min Static- 15 s passive hamstring stretch at point of mild discomfort, 30 s rests between reps, performed for 5 min	ROM (AKE test)	↑ ROM by 9.6% (after exercise) and 7.8% (without exercise) following CR
Sady et al {94}	43 (control (n = 10); static (n = 10); ballistic (n = 11); PNF (n= 12))	Static (3 reps of 6 s); ballistic (20 repeated movements); PNF (3 reps of 6 s). Intervention conducted 3 d per week for 6 w, in the respective group	ROM	↑ ROM of 9.4° (hamstring flexibility) in PNF group
O'Hora et al {79}	45 university students (15 per group – control, static and PNF)	Static hamstring held for 30 s CR- 6 s isometric hamstring contraction, relax period NS	ROM (PKE)	CR ↑ ROM by 4.27° compared to static stretch
Moore and Hutton {74}	21 female gymnasts	CR, CRAC and static hamstring stretching performed in random order by each participant	EMG (hamstring) and ROM (hip flexion)	↑ Hamstring EMG but also ↑ ROM following CRAC compared to static and CR
Marek et al {65}	19 (male (n = 9), female (n = 10))	Static- 30 s quadriceps stretch, 20 s rest, 4 reps CR- 5 s isometric quadriceps contraction followed by 30 s passive stretch, 20 s rest, 4 reps. 4 reps of each stretch conducted in 2 different positions	PT at 60°.sec^{-1} & 300°.sec^{-1}, MP, EMG, MMG,AROM, PROM	↓ PT, MP and MMG by 2.8% following static and CR. NS differences between static and CR
Ferber et al {30}	24 older adult males	Static- 80 s passive hamstring stretch CR- 5 s isometric hamstring contraction, 5 s rest with further passive stretch, 8 reps (80 s) ACR - 5 s concentric quadriceps contraction, 5 s rest with passive hold of the knee at ROM limit, 8 reps (80 s) Each stretch performed in random order by each participant	Hamstring EMG and ROM (knee extension, technique NS)	ACR ↑ ROM by 29% and 34% and ↑ hamstring EMG by 65% and 119% compared to CR and static stretch, respectively
Feland et al {28}	97 senior athletes (male (n = 66), female (n = 31)). CR group (n = 40), static group (n = 38), control (n = 19)	CR- 6 s isometric hamstring contraction followed by 10s rest with passive stretching performed twice Static- passive SLR held at mild discomfort for 32 s	ROM knee extension (PKE)	↑ ROM following CR for men and participants < 65 yr compared to static stretching

Authors	**Participants**	**Stretch intervention**	**Main outcome measures**	**Results**
Condon and Hutton {15}	12 (male (n = 6), female (n = 6))	Static- 11 s light DF torque followed by 50 s large DF torque(passive stretch) AC- 11 s light DF torque, 50 s large DF torque with submaximal dorsiflexor contraction CR- 5 s light DF torque, 5 s isometric plantarflexor MVC, 1 s rest followed by 50 s large DF torque CRAC- 5 s light DF torque, 5 s isometric plantarflexor MVC1 s rest, 50 s large DF torque with submaximal dorsiflexor contraction. Stretches randomly performed	EMG (soleus and tibialis anterior), H-reflex (soleus), ankle DF ROM (electrogoniometer)	↑ soleus EMG and ↓ H-reflex amplitude during AC and CRAC compared to CR and static stretching

Table abbreviations: NS – Not specified; CR – Contract-relax; AC – Agonist-contract; ACR – Agonist-contract-relax; CRAC – Contract-relax-agonist-contract; DF – Dorsiflexion; EMG – Electromyographic data; MMG – Mechanomyographic data; PT – Peak torque; MP – Mean power output; A/PROM – Active or passive range of motion; SLR – Straight leg raise; AKE – Active knee extension; PKE – Passive knee extension

2.10 Proposed mechanism of action of CRAC stretching

The use of isometric contraction during CRAC serves a dual purpose: the fatigue of fast twitch fibres and sensory receptor stimulation. Firstly, fatigue of the fast twitch fibres reduces their capacity for maximum force production when exposed to subsequent stretch resistance {8}. Isometric contraction induces post-isometric relaxation in the muscle which results in reduced muscle tone. Post-isometric relaxation has been defined as the 15 s refractory period after isometric contraction during which the new point of resistance of a joint or muscle may be achieved with greater ease {69}.

Secondly, sensory receptor stimulation occurs due to the effect of isometric contraction on the Golgi tendon organs (GTO) and muscle spindle fibres. The isometric contraction of a stretched muscle serves to pre-tension the GTO {29, 100}. The increase in tension causes inhibition of the contracting antagonist, while there is simultaneous stimulation of the agonist muscle by the process of autogenic inhibition {23, 69, 100, 120}.

The muscle spindle, a receptor sensitive to the magnitude of muscle length and rate of change of muscle length, is also stimulated during the isometric contraction {23, 138}. The extrafusal and intrafusal fibres contract such that the central portion of the receptor stays at its optimal length. During isometric contraction, a mismatch occurs as there is an increase in extrafusal muscle tension but no change in muscle length, thus inducing the negative stretch reflex {8, 120}.

As a practical example, CRAC stretching applied to the hamstrings (antagonist) may begin with a slow passive hamstring stretch, to prevent the stretch reflex, to the point of stretch sensation onset {100, 106, 117}. During this initial passive stretch, the viscoelastic properties of the hamstring muscle are manipulated to allow an increase in muscle length {22, 64, 106, 109}. An isometric hamstring contraction follows from the position of stretch, which prevents the effect of creep that would produce elastic recoil of the muscle to its original resting length {78}.

During an isometric contraction, the fast-twitch fibres of the hamstring muscle should fatigue while hamstring compliance should increase via autogenic inhibition and post-isometric relaxation should be induced {8, 23, 29, 69, 100, 120, 138}. Quadriceps muscle (agonist) activity should reduce as a result of reciprocal inhibition during the isometric hamstring contraction {15, 74, 81, 97}. Further, following isometric contraction, H-reflex inhibition would result in a temporarily decreased excitability of the motoneurone pool that supplies the hamstrings {44, 73, 117}.

During the transient period of decreased hamstring sensitivity and excitability caused by autogenic inhibition, post-isometric relaxation and H-reflex inhibition, the concentric quadriceps contraction would be initiated. Although hamstring EMG activity may increase {13,15}, smooth knee joint motion should occur during the quadriceps contraction because of hamstrings which are relaxed according to the principle of reciprocal inhibition {15}. The increased stretch tolerance and pain threshold after stretching {45, 63, 74}, combined with the above neurological mechanisms should facilitate increased knee ROM and hamstring muscle length {104, 120} following hamstring CRAC stretching.

Due to the heterogeneity in study designs that have investigated PNF, differences in PNF application (Table 2.1), and the limited number of studies {93, 131} that have investigated CRAC stretching specifically, it remains difficult to generalise evidence for the benefits of CRAC stretching to larger populations. The gap in literature provides a rationale for further investigation of CRAC stretching and the effect it may have on variables such as injury risk and sports performance. Further research should be conducted with the view towards reaching consensus of an optimal, standardised method of CRAC stretching.

2.11 The benefits of stretching

Stretching has been shown to have numerous effects, including a reduction of injury risk, enhanced athletic performance, and increased flexibility. Of these effects, an increase in flexibility is the most commonly cited benefit with little debate regarding this specific effect of stretching {28, 29, 77, 86, 94}. Further, acute and long-term stretching protocols produce varying results as discussed earlier (Sections 2.7 and 2.8). Currently, there is little consensus regarding the role of stretching on reducing the risk of muscle strain injuries {104}. However, numerous studies suggest that there is a decreased risk of muscle strain injury associated with regular stretching {50, 68, 69, 111}. The discussion that follows regarding the benefits of stretching includes benefits related to both static and PNF protocols.

Cross and Worrell {19} used a stretching protocol conducted regularly over the course of a football season which was performed bilaterally and consisted of three repetitions of static stretch, each held for 15 s at the point of "*stretch sensation*", for the hamstrings, quadriceps, hip adductors, gastrocnemius and soleus muscle groups. However, as discussed earlier (Section 2.4), although Cross and Worrell {19} showed a 48.8% reduction in musculotendinous strains in college football players, the flaws of the study design and poor control of confounding variables did not demonstrate a clear correlation between stretching and reduced risk of strain injury.

Hartig and Henderson {49} investigated the effect of hamstring flexibility on the rate and occurrence of lower extremity overuse injuries in 298 military infantry basic trainees. Lower extremity overuse injuries including stress fractures, patellofemoral knee pain, muscle strains, tendonitis, plantar fasciitis, shin splints and anterior compartment syndromes were recorded over 13 weeks {49}. Pre- and post-training measurements of hamstring flexibility were performed using the PKE test. The control (n = 148) and intervention (n = 150) groups performed the same 13 week basic training simultaneously {49}. The control group performed a general static stretching routine, including a hamstring stretch, once per day prior to training while the intervention group performed hamstring stretches three times per day (prior to meals). The hamstring stretch protocol used by the intervention group consisted of five repetitions per leg of static stretch held for 30 s at the point of hamstring stretch sensation {49}. There was a significant decrease in PKE ROM in the intervention group (41.7° to 34.7°), which indicated increased hamstring flexibility, compared to the control group (45.9° to 42.9°) {49}. Further, there was a significant decrease in incidence of injury in the intervention group (25 injuries) compared to the control group (43 injuries), which reflected a 17% and 29% incidence of injury within each group respectively {49}.

Behm et al {6} investigated the effect of static stretching on movement and reaction time. The results of the study suggested that greater MTU compliance was associated with increased energy absorption, which delayed force production within the muscle. Theoretically, the energy absorbed reduced the mechanical overload on muscle fibres, thereby reducing the risk and severity of muscular injury {6, 120}. Witvrou et al {127} hypothesised that stretching may be more effective in preventing injury in sports that have a higher intensity or frequency of stretch-shortening cycles, such as football or basketball, compared to sports that require a lower demand of these cycles on the MTU, such as swimming. Shrier {104} stated that while evidence for pre-exercise stretching as a method to reduce risk of injury was conflicting, stretching outside periods of exercise and post-exercise may prevent injury. A limited number of studies have investigated the benefit of reduced risk of injury after stretching {19, 49}. In addition, both studies investigated static stretching only {19, 49} and did not examine the rate or incidence of hamstring injuries. The lack of scientific evidence warrants further research regarding the potential benefit of CRAC stretching as a method to reduce the risk and rate of hamstring injuries.

2.11.1 Increasing flexibility and decreasing muscle stiffness

Increased flexibility and decreased muscle stiffness are the most common outcomes of research in stretching {28, 33, 77, 86, 94}. Nordez et al {77} investigated the effect of a static stretching protocol on passive stiffness of the hamstrings. Muscle stiffness was calculated using different mathematical models that were based on torque, joint angular position and joint angular velocity data {77}. Maximum knee extension ROM was defined as the position in which the participant perceived "*maximum tolerable hamstring muscle stretch*" and was performed by PKE on an isokinetic dynamometer {77}.

The stretch protocol consisted of five cycles of PKE to 80% of maximal knee extension ROM at a speed of $5°.s^{-1}$, held for 30 s static stretch at this point then unloaded at the same rate, without rest between stretches {77}. Hamstring stiffness ($N.m^{-1}$) was assessed at 5°, 25° and 45° of knee extension ROM. The results showed a significant decrease in passive stiffness of the hamstring MTU after static stretching at each angle of assessment, with larger amounts of decreased stiffness towards the end of ROM (0.046 $N.m^{-1}$ at 5° compared to 0.118 $N.m^{-1}$ at 45°) {77}. Knee ROM also increased significantly by 6.8% after static stretching compared to the initial ROM. While Nordez et al {77} showed that static stretching increased knee ROM and decreased hamstring stiffness, the findings emphasised the need for careful selection of appropriate mathematical calculations to measure muscle stiffness, as different equation models produced dissimilar result values.

Feland et al {28} compared the acute effects of a CR technique with static stretch, both applied to the hamstrings for 32 s, in 97 senior athletes. The CR group (n = 40) performed two repetitions of 6 s maximal isometric hamstring contraction followed by 10 s rest period during which passive SLR stretch was maintained at a "*point of mild discomfort*" (32 s in total). The static stretch group (n = 38) underwent one repetition of passive SLR to held at the point of discomfort for 32 s, while the control group (n = 19) received no intervention {28}. The hamstring CR stretch significantly increased hamstring flexibility, measured using the AKE test, by 7.5° in male athletes less than 65 y compared to static stretching (4°) {28}.

Although both stretch techniques were applied for 32 s, the CR stretch consisted of two repetitions (16 s each) compared to the single 32 s static stretch repetition {28}, which may have produced biased results as stretch frequency is an influential factor for ROM measures {120}.

Funk et al {33} investigated the effect of hamstring CR and static stretching, both with and without prior exercise, on hamstring flexibility in 40 Division 1 college athletes. To control for participant variability such as different sporting codes, gender, anatomical differences and learning effect (due to repeated flexibility measurement), a counterbalanced within-subject design was used {33}. The CR protocol consisted of a passive SLR followed by 30 s maximal isometric hamstring contraction which was "*repeated until the 5 minute time period was concluded*" {33}. The static stretch protocol consisted of 15 s static stretch held at the point of hamstring stretch sensation followed by 30 s rest which was repeated for 5 min {33}.

Hamstring flexibility was measured using the AKE test recorded at baseline, pre-exercise and post-exercise while the results expressed hamstring flexibility as the percentage change in final AKE ROM compared to baseline values {33}. The results showed that CR stretch significantly increased hamstring flexibility by 9.6% after an hour of exercise and by 7.8% without exercise intervention {33}. While the results showed that CR stretching increased hamstring flexibility, protocol details were not explicitly specified, such as the number of repetitions and duration of rest between repetitions or after isometric hamstring contraction {33}. Further, the duration of the isometric contraction during CR stretch (30 s) was twice that of static stretch (15 s) and there was no mention of randomisation of leg selection to undergo stretch intervention {33}. While both CR and static hamstring stretch protocols were applied for 5 min, the difference in stretch frequency, including duration of specific stretch components and number of repetitions, may have contributed toward result bias {33, 120}. While there was no significant difference of increased hamstring flexibility between CR and static stretching techniques, Funk et al {33} recommended that athletes predisposed to hamstring injury should perform CR stretching before and after exercise to prevent injury.

Sady et al {94} investigated the effects of ballistic, static and PNF stretch protocols on trunk, shoulder and hamstring flexibility in 65 male college students. The participants were randomly assigned into one of four groups, which included static (n = 10), ballistic (n = 11), PNF (n = 12) and control (n = 10) groups {94}. Flexibility was measured using a flexometer and was recorded during two separate days prior to (baseline measures) and after the six week training program {94}. The ballistic protocol (20 rapidly repeated movements), static protocol (three repetitions of 6 s per muscle group) and the PNF protocol (three repetitions of 6 s per muscle group) were applied three days per week for six weeks {94}. The results showed that only the PNF group had flexibility increases (10.6°) greater than the control group (3.4°) and hamstring flexibility (9.4° increase) improved more than that of the trunk (5.2° increase) {94}. The findings showed that PNF was the most effective stretching technique to increase hamstring flexibility. Participants demonstrated significant variability on a daily basis in their flexibility scores, which further emphasised the importance of establishing baseline ROM data for studies that involve flexibility training {94}.

Reid and McNair {86} investigated the effects of a six-week static hamstring stretch protocol on passive resistance force, knee extension ROM and muscle stiffness in 43 male students (mean age = 15.8 ± 1 yr) from two schools. To prevent participant interaction, the school which received intervention was randomly selected and formed the stretch group (n = 23), while the other school which received no intervention formed the control group (n = 20) {86}. Measures of hamstring flexibility, maximal passive resistive force, maximal passive knee extension and stiffness in the final 10% of knee extension ROM were recorded prior to and after the six week intervention {86}. An isokinetic dynamometer was used to measure hamstring flexibility (PKE test at $10°.sec^{-1}$ to the point of stretch sensation), muscle stiffness (the ratio of change in force to change in angle), maximum PKE (the point of "*maximum tolerable stretch on the hamstring*") and maximal passive resistive force {86}. The protocol consisted of three repetitions per leg of 30 s static hamstring stretch performed in stance standing once a day, and this was repeated five times per week for six weeks {86}.

Within-group results showed significantly increased knee extension ROM (°) (16.1 ± 7.1 to 6.0 ± 6.8), stiffness ($N.deg^{-1}$) (3.31 ± 1.49 to 4.18 ± 0.96) and passive resistive force (N) (72.7 ± 34.3 to 114.4 ± 30.6) in the hamstrings of participants in the stretch group {86}. Interestingly, hamstring stiffness over the last 10% of a newly gained knee extension ROM increased significantly in the experimental group, which suggested structural adaptations in the muscle. Such adaptations included an increased number of sarcomeres in series, following long-term static stretching {39, 41, 86}. The randomised controlled study ensured result reliability and validity by conducting pilot testing and controlled bias by the use of randomisation and participant blinding {86}. However, the results may not be generalised due to the structural and morphological differences between adults and the maturing tissue in teenage participants {8, 28, 57, 86}. Further, due to the differences in mechanisms of action between stretch techniques, the results may be applicable only to studies which have investigated long-term static hamstring stretch protocols {86}.

The findings of the studies discussed above demonstrate that while an improved ROM and decreased muscle stiffness are common outcomes following various stretching regimes, there is no standardised method of stretch application {28, 33, 77, 86, 94}. Further, while it appears that PNF produced greater gains in ROM compared to static stretching, the hamstring CRAC technique has not been specifically investigated.

2.11.2 Duration of effect

DePino et al {22} investigated the effect of an acute static hamstring stretch on hamstring flexibility using 30 male cadets who were randomly assigned to either the experimental (n = 15) or control (n = 15) group. Six repetitions of the AKE test with 60 s rest period between repetitions were performed and the final AKE was recorded as the baseline measure of hamstring flexibility {22}. To measure the duration of effect, one post-intervention AKE test was recorded at specifically-timed intervals (1, 3, 6, 9, 15 and 30 min) for both groups {22}. The stretch protocol was performed in standing and consisted of four repetitions of 30 s static hamstring stretch held at the point of "*stretch sensation*" with 15 s rest between repetitions {22}.

The results showed that the static hamstring stretch increased AKE ROM by 6.8°, which was maintained at a significantly increased level for 3 min {22}. Control group participants remained in supine for 3 min (the same duration taken to perform the stretch protocol in the experimental group) before AKE tests were performed which controlled for the thixotropic properties of muscle {22, 60, 118}. However, the static stretch protocol was self-applied and corrective verbal feedback was used {22}, which may not have been as effective as therapist-applied manual correction for maintaining optimal participant position during the stretch {22}. Further, the right lower limb was chosen by default and random leg selection for the application of stretch intervention was not used {22}.

Interestingly, a study by Spernoga et al {106}, modelled similarly to DePino et al {22}, found that a modified CR hamstring stretch significantly increased and maintained hamstring flexibility for 6 min. The modified CR protocol consisted of five repetitions of a 7 s passive SLR held at "*mild stretch sensation*", 7 s isometric hamstring contraction followed by 5 s rest and 7 s passive SLR held at "*mild stretch sensation*" {106}. Both studies {22, 106} were similarly designed, used the same number of cadet participants (30); inclusion criteria for participation (limitation of 20° or more from full knee extension); measured hamstring flexibility by AKE testing; and; controlled for the influence of thixotropy on hamstring flexibility in the control group. Considering these similarities, the results of these studies {22, 106} suggest that modified CR produced a greater duration of maintained hamstring flexibility (6 min {106}) compared to static stretching (3 min {22}).

In summary, while there may be no consensus regarding the role which stretching may play in reducing the risk of muscular strain injuries, there is evidence which shows that regular stretching decreases the propensity of a strain {50, 68, 69, 104, 111}. However, the stretch technique that may best serve this purpose has not been defined. Similarly, while the proposed benefits of stretching include an increase in flexibility and the duration of sustained effect (of increased ROM), to date, there has been no standardised protocol for the application of stretching techniques. However, while both static and PNF techniques induce these benefits, there is evidence to suggest that PNF techniques produce a greater effect with regard to ROM and duration of sustained effect {22, 28, 33, 94, 106}.

In the realm of sports, it is pivotal to investigate the potential positive or negative influence which a particular therapy may impart to performance {11, 57}. Considering the many proposed benefits of stretching discussed thus far, in pursuit of optimum performance, sports physiotherapists are appropriately positioned to understand and investigate the role of stretching in exercise performance.

2.12 The effect of stretching on exercise performance

The effects of stretching on exercise performance may be assessed by examining isolated measures of muscle performance which include MVC, peak torque and power output (work) {7, 29, 47, 65, 122, 125, 131} and functional measures of muscle performance which include drop jump height, vertical jump height, sprinting and agility tests {55, 62, 87, 91, 107}. The majority of previous studies have found that there is usually a stretch-induced deficit in muscle performance after an acute stretching protocol {7, 65, 71, 112}, with conflicting evidence to suggest improvements in performance following long-term stretching protocols {47, 55, 62, 125, 131}. Further, there is also conflicting evidence for the degree of stretch-induced deficit between different stretch techniques {63, 71, 112, 120}. The results of isolated measures of muscle performance following stretching have been used to suggest possible impact on functional measures of performance {65, 71}. These suggestions are based on the concept that a stretch-induced deficit in a particular muscle group may negatively impact functional task performance. This concept may be flawed as it tends towards older models of exercise physiology and does not account for evidence that functional measures of muscle performance are mediated by multiple physiological and cerebral feedback systems {76}.

The effects of stretching on muscle cytoskeleton and the subsequent effect on force production and transmission should be considered when evaluating potential stretch-induced deficits in muscle performance. Behm et al {6} investigated the effect of an acute static stretching protocol on force, balance, reaction time and movement time in 16 male participants who each underwent the stretching and control condition, conducted on separate days.

Balance was measured using a computerized wobble board which recorded the duration and frequency of board perimeter floor contact during 30 s {6}. Using an illumination apparatus linked to an electronic timer and two switches, reaction time was measured as the time between illumination and release of the start switch; while movement time was measured as the time between the start of leg movement and the depression of a stop switch placed 50 cm anterior to the leg {6}. Reaction time, movement time and balance were expressed as the percentage change between pre- and post-stretch or pre- and post-control values for the respective condition {6}. The static stretching protocol (hamstrings, quadriceps and plantarflexors of each leg) consisted of three repetitions held for 45 s per muscle group at the point of "*discomfort*", with 15 s rest between repetitions {6}.

There was a significant increase in reaction time and movement time (4.0% and 1.9%, respectively) after static stretching, while balance scores improved significantly by 17.3% in the control group only {6}. Behm et al {6} suggested that impaired reaction time and movement time after static stretching were due to a slower rate of tension development within the muscles because of increased MTU compliance. It was theorised that increased MTU compliance, which was the difference between stretch and control conditions, impaired muscle spindle and GTO function resulting in slower reaction time and movement time {6}. However, only quadriceps MVC was analysed without providing rationale for the exclusion of hamstring MVC {6}. Importantly, there were no significant differences in quadriceps MVC between stretch and control conditions {6}. The stretch-induced performance deficit concept is based on the theory that a more compliant MTU has non-optimal sarcomere cross-bridge kinetics after stretching, which delays the production of tension within the sarcomere and the subsequent force transmission from the musculotendinous unit to the teno-periosteal unit {6, 7, 120}. Behm et al {6} provided conflicting evidence for stretch-induced deficit in muscle performance considering the impaired reaction time, movement time and balance scores (functional measures) after static stretching were not associated with an expected decrease in muscle MVC (isolated measure).

Later, Behm et al {7} showed that a four week flexibility programme significantly increased ROM, but an acute static stretch decreased hamstring and quadricep MVC. While the muscle groups subjected to the stretching protocol remained the same as the earlier study {6}, the duration of static stretch application differed {7}. The protocol consisted of three repetitions per muscle group held for 30 s at the point of discomfort, followed by 30 s rest between stretches. The results of the study showed that while ROM improved after long-term stretching, measures of muscle performance (MVC, drop jump contact time and countermovement jump height) decreased when exposed to an acute static stretch. Further, there was no correlation between ROM and the stretch-induced deficits in muscle performance. It was proposed that similar impairments in performance were observed, irrespective of ROM or muscle stretch tolerance, because the relative stress placed on each muscle was similar as stretching was held at the subjective "*point of discomfort*" as determined by the participant {7}. However, it should be noted that participants may have different levels of tolerance with respect to discomfort and so different levels of stress may have been applied. While Behm et al {7} used the same stretch protocol as performed previously {6}, the change in stretch duration was not substantiated {7} which added to the difficulty of comparing stretch interventions.

Ferreira et al {31} investigated the effects of a six week static stretching programme on hamstring flexibility and muscle performance in 30 participants. Hamstring flexibility was measured using the PKE test while peak torque, angle of peak torque and work of the hamstrings and quadriceps were measured using an isokinetic dynamometer {31}. Peak torque for each muscle group was recorded at angular velocities of $60°.s^{-1}$ and $300°.s^{-1}$ and work was calculated according to the same angles {31}. Flexibility and isokinetic muscular performance measures were recorded prior to and after the six week flexibility protocol and the hamstring static stretch protocol was performed bilaterally five times per week for six weeks {31}. There was a significant increase in knee extension ROM (averaging 12.6°); while hamstring and quadriceps peak torque and work were also significantly increased at both angular velocities after the static stretching programme {31}. Although Ferreira et al {31} showed improvement of isolated muscle performance measures following long-term static stretch, similar results were demonstrated using PNF protocols {47}.

Handel et al {47} investigated a unilateral CR stretch protocol for the hamstring and quadriceps muscles, performed three times per week over eight weeks in 16 male athletes from various sporting codes. The CR protocol consisted of eight repetitions per muscle group that began with a 10 s isometric contraction at 70% of MVC, followed by 1 s to 2 s rest and finally 10 s to 15 s of passive stretching.

The main outcome measures included peak torque during eccentric and concentric activity recorded at $60°.s^{-1}$, $180°.s^{-1}$ and $240°.s^{-1}$. Peak torque was expressed as the percentage increase between pre- and post-flexibility training. There was a significant increase of 18.2% and 23.0% peak torque in the CR-exposed leg during eccentric hamstring and quadriceps contraction, respectively, after flexibility training {47}. Interestingly, the peak torque of the hamstrings was significantly increased at all angles, especially under eccentric loading {47}. Although participants were not from the same sporting code and potential individual differences, the data were normalised and the confounding factor of differences in individual training programmes was accounted for during statistical analyses {47}. Further, validity of the outcome measure and subsequent results was ensured because stretching 24 hours prior to re-testing was not permitted, which reduced the possibility of stretch-induced deficits in muscle performance as a result of acute stretching {7, 47}.

Wilson et al {125} investigated an eight week flexibility training programme performed by 16 professional weightlifters, involving the deltoid and pectoral muscles, and its subsequent effect on rebound and purely concentric bench press as functional measures of muscle performance,. While rebound bench press may be considered a form of MVC (isolated measure of muscle performance) of the pectoral and deltoid muscles, rebound bench press may also be considered a functional measure of muscle performance in professional weightlifting {125}. Pre- and post-training measures of ROM, series elastic component stiffness and MVC were recorded. Participants were randomly assigned to either the experimental group that received stretching (n = 9) or the control group (n = 7). The stretch protocol was conducted twice per week; each session provided 10 min to 15 min of stretching and consisted of six to nine repetitions of modified PNF stretching performed bilaterally on each muscle group.

The results showed significantly increased ROM (3%), rebound bench press load (5.4%) and series elastic component stiffness decreased significantly by 7.2% within the experimental group {125}. Further analysis showed that experimental participants' increased rebound bench press load was due to significantly greater work during the initial concentric lift phase of the rebound bench press {125}. Wilson et al {125} concluded that the decreased series elastic component stiffness increased the use of stored elastic strain energy used during rebound bench press, which was an example of a stretch-shortening cycle exercise.

Worrell et al {131} investigated the effects of a static and PNF stretching protocol using 19 participants classified as having "*short hamstrings*" in a controlled clinical trial. The static stretching consisted of a 15 s static hold followed by 15 s rest while the CR protocol consisted of 5 s isometric hamstring contraction followed by 5 s rest {131}. The protocols were conducted simultaneously on the participants as one leg was randomly selected for static and the other leg for CR stretching by default. The regime was performed four times per day (per stretch), five days per week over three weeks. The results showed no significant difference between techniques as both static and CR stretch significantly improved eccentric hamstring strength at $60°.s^{-1}$ and $120°.s^{-1}$ and concentric hamstring strength at $120°.s^{-1}${131}. However, the difference in duration of static stretching (15 s) and the isometric contraction component of CR stretching (5 s) required careful interpretation of the results of the study, as static stretch duration may have produced result bias by influencing overall stretch dosage {92, 120}.

Weerapong et al {120} summarised and compared the peak torque production results amongst PNF and static stretch protocols in studies by Toft et al {112}, McNair et al {71} and Magnusson et al {63}. The results demonstrated that acute application of either PNF or static stretching reduced peak torque, however PNF did so by 3% to 5% less than the reduction produced after static stretching {63, 71, 112, 120}. Previous reviews {100, 123} have recommended that a static (isometric) contraction of the target muscle followed by the shortening (concentric) contraction of the opposing muscle (CRAC) is a more effective stretch. CRAC stretching maximises the effects of the autogenic and reciprocal inhibition response, the latter via active contraction {69}.

While there is evidence that CRAC produced longer-lasting increases in flexibility {27, 94} and that increased flexibility reduces the risk of injury {19, 49, 126}, there is no evidence for the potential effects of hamstring CRAC stretching on improving performance or decreasing injury risk. This gap in research regarding the possible role of CRAC stretching in the reduction of injury risk and performance enhancement requires further investigation.

2.13 Measuring hamstring flexibility

Many instruments may be used to quantify flexibility, including the flexometer {72, 94}, inclinometer {2, 95} and the goniometer {22, 33, 106}. With regards to measures of hamstring flexibility, the reliability and validity of both the measurement instrument and the testing procedure needs to be established. Reliability in goniometry refers to the repeatability of ROM measurements, if the application of an instrument and test procedure will yield the same measurements consistently under the same conditions {38}. Validity in goniometry refers to the degree of accuracy of the measurement instrument and test procedure {38}. Goniometric measurements have limitations because ROM results are expressed and limited to the degree units (°) of a circle which would be valid if a fixed axis of motion was assumed {38}. However, this is not true for human articular structures which exhibit sliding, rotation and glide movements about axes of motion which are not fixed {38, 57, 78}.

The validity of ROM measurements have been confirmed using objective measures including photographic, video and radiographic motion analyses {38} while reliability of ROM measurements and tests are described using statistical calculations including intraclass coefficient correlation (ICC) and Pearson-product moment correlation coefficient (r) {14, 16, 38, 95, 134}. Intra- or inter-tester reliability, which refer to measurements conducted by the same or different examiners, respectively, are further statistical tests conducted to show reliability while the standard error of measurement (SEM) is often provided as an estimate of measurement precision {38, 119}.

2.13.1 The inclinometer

Compared to the goniometer, the advantage of the inclinometer is that it responds to gravity and there is no need to establish an axis of rotation during ROM measurements {37}. Saur et al {95} investigated the reliability and validity of the inclinometer for measures of trunk flexibility. The results showed that lumbar ROM measurements taken radiographically and by inclinometer exhibited near linear correlation for total lumbar ROM (r = 0.97) and lumbar flexion (r = 0.98) which justified the conclusion that it was a valid and reliable instrument {95}.

Hopper et al {53} used a pelvic and a knee inclinometer to measure posterior pelvic rotation and the total ROM during a passive straight leg raise, such that the hip flexion angle (the difference between the straight leg raise ROM and posterior pelvic rotation) reflected hamstring flexibility. The results of the pilot study {53} conducted on 15 participants showed high intra-tester reliability for hip flexion angle measurement (ICC = 0.95 and SEM = 1.8°).

Cornbleet et al {16} used an inclinometer to calculate the hip joint angle during the sit and reach test as a measure of hamstring flexibility in 410 primary school participants. The results of the pilot study {16} conducted on 20 participants showed high inter-tester reliability (ICC = 0.98) for hip joint angle measurement. Using two experienced therapists, Clapis et al {14} compared the reliability of the inclinometer and goniometer for hip extension flexibility in 42 participants using the modified Thomas test. The results showed high inter-tester reliability for each instrument (r = 0.91 - 0.93; ICC = 0.89 - 0.92), high inter-tester reliability between instruments (r = 0.86 - 0.92; ICC = 0.86 - 0.92) and high intra-tester reliability for each examiner between instruments (r = 0.89 - 0.92; ICC = 0.91 - 0.93). While Clapis et al {14} compared the reliability of the inclinometer and goniometer using hip extension, to date no studies have compared instrument reliability using the AKE test as a measure of hamstring flexibility.

Youdas et al {134} provided opposing evidence for the use of an inclinometer as a valid measurement tool of hamstring flexibility during the sit and reach test. A pilot study showed high intra-tester reliability of the inclinometer (ICC = 0.98; SEM = 1.9°) for hip joint angle measurement during the sit and reach test. Hamstring flexibility was compared using hip flexion angle during the sit and reach test (measured by an inclinometer) and passive SLR (measured by a goniometer). The moderate correlation (r = 0.59) between passive SLR and hip flexion angle values during the sit and reach test accounted for only 35% of the variability between the two measures of hamstring flexibility {134}.

Youdas et al {134} concluded that the measurement of hip joint angle using an inclinometer during the sit and reach test was not a valid method of assessing hamstring muscle length in individuals who could achieve long-sitting independently. However, the findings should be interpreted with caution as the passive SLR procedure, participant positioning and goniometer positioning during SLR was not explicitly described and a pilot study to establish goniometer intra-tester reliability was not conducted.

Historically, stretch-based studies have relied on static flexibility measures (ROM) which are easier to examine but may not accurately reflect joint motion in humans or the behaviour of the MTU {38, 57, 63, 120}. Although stretching has been shown to improve ROM, one should question the origin of the increased ROM because both the MTU and joint capsule contribute to ROM limitations, which impact on static and dynamic flexibility {104}. Gajdosik and Bohannon {38} caution against invalid interpretation of ROM measurements. Many additional factors may influence ROM measurements including pain, adhesions, strength deficits and muscle hypertrophy {38}. However, the validity of ROM is related specifically to the degrees recorded, while factors that may influence ROM should be measured by other means with appropriate units of measurement {38}.

2.13.2 Active knee extension (AKE)

Hamstring flexibility is most commonly measured by objective muscle length tests, including the sit and reach test {16, 88, 134}, straight leg raise test {40, 41, 50, 134}, the passive knee extension test {28, 40, 79} and the AKE test {22, 37, 40, 106}. There is no conclusive evidence to suggest the superiority of one test over another {40, 88}. However, the advantages of the AKE test are the ability to isolate hamstring muscle length, and the minimised amount of pelvic motion and neural stretch compared to the straight leg raise {40}. Further, compared to the SLR test, movements at the hip joint, sacro-iliac joint and lumbar spine are controlled by stabilisation during the AKE test {37, 84}. The AKE test position requires the participant to lie supine and the leg to be tested is positioned at 90° of hip flexion and 90° of knee flexion while the pelvis and opposite leg are stabilised using adjustable straps. A detailed description of the AKE test position may be found in Section 3.4.3 (page 76). Sullivan et al {108} studied the effect of pelvic position on hamstring flexibility. A two-way ANOVA test that compared stretching technique (static and PNF) and pelvic position (anterior and posterior tilt) found that anterior pelvic tilt significantly increased hamstring flexibility. Further, there were no significant differences between stretching techniques or for hamstring flexibility during the posterior pelvic tilt position, which suggests that pelvic position was more influential for hamstring flexibility than stretching technique. Sullivan et al {108} concluded that it was necessary to control pelvic motion during flexibility measurements.

Rakos et al {84} investigated the inter-tester reliability of the AKE test. The results of the pilot study established high intra-tester reliability (ICC = 0.99, 0.99 and 0.95) of three examiners, for the AKE test as a measure of hamstring flexibility. While the results of the study showed good inter-tester reliability (ICC = 0.79), the ankle position and hip rotation was poorly controlled which may have influenced the results {84}. Further, Rakos et al {84} asked participants to stop at the point of myoclonus during AKE, defined as *“an alternating contract relax pattern between quadriceps and hamstrings*”. Following the myoclonus point, the examiner performed passive knee flexion to the point where myoclonus subsided and then recorded the AKE measurement {84}.

Gajdosik and Lusin {37} investigated the intra-tester reliability of the AKE test performed bilaterally on 15 male participants. The results showed high intra-tester reliability for test-retest measurements (ICC = 0.99 for both lower limbs), which suggest that the AKE test was an objective and reliable test when conducted by one examiner under controlled and standardised conditions {37}. The difference in the AKE measurement procedure used by Gajdosik and Lusin {37} compared to Rakos et al {84}, was the use of slow active knee flexion by the participant (self-applied) to the point at which myoclonus subsided. This difference may have accounted for decreased AKE inter-tester reliability (ICC = 0.79) found previously {84}, compared to the higher AKE intra-tester reliability found by Gajdosik and Lusin {37} (ICC= 0.99).

Gabbe et al {34} investigated the inter-tester and test-retest reliability of the AKE test as a measure of hamstring flexibility together with other common lower extremity screening tests. Two examiners performed each of the screening tests one week apart on 15 participants and the results showed high inter-tester reliability (ICC= 0.93) and high test-retest reliability (ICC = 0.94 to 0.96) for the AKE {34}. However, Gabbe et al {34} did not control pelvic motion or stabilise the contralateral limb during the AKE test which may have influenced the ROM measurements as suggested previously {37, 108}.

Webright et al {119} conducted a pilot study on 12 participants who performed test-retest ROM measurements to establish intra- and inter-tester reliability of the AKE test using two examiners. There was high intra-tester (ICC = 0.98 for both examiners) and inter-tester reliability (ICC = 0.98, SEM = 1.67°) of the AKE test as a measure of hamstring flexibility {119}. Webright et al {119} used a goniometer to ensure 90° hip flexion and asked participants to maintain thigh contact with a cross-bar apparatus during the AKE test and used video analysis to record ROM measurements. However, the participants were asked to hold the AKE at the limit of ROM for one second and this value was recorded as the AKE ROM measurement {119}, compared to the previous use of the point of myoclonus as an indicative measure of the limit of AKE ROM {37, 84}.

The results of previous studies {34, 37, 84, 108, 119} suggested that differences in participant positioning and control of confounding factors including pelvic, hip, sacro-iliac, lumbar spine and neural tissue movement may influence reliability of the AKE test as a measure of hamstring flexibility. Further, Gajdosik and Bohannon {38} concluded that clinicians should adopt standardised procedures of testing and should not interpret ROM results as measurements of factors that may affect ROM. In summary, the AKE test is a reliable and valid measure of hamstring flexibility which uses active muscle contraction to examine active ROM compared to the application of external force during the PKE test {37, 40} which examines passive ROM {65}. The AKE test may therefore provide a more realistic measure of hamstring flexibility, as active ROM that is induced by active muscle contraction may simulate performance scenarios during sport more accurately.

2.14 Functional measures of athletic performance

Functional measures of muscle performance in studies that have investigated stretch interventions include tests of agility, speed and vertical and countermovement jump height. For the purposes of this review, a discussion of agility and sprint tests as functional measures of muscle performance follows. Agility tests are designed to measure the ability of an individual to maintain balance and speed during multiple changes of direction {83, 89, 135}. Sprint tests are designed to measure the straight-line acceleration and speed of an individual upon completion of a given distance within a minimal amount of time {62, 67, 96, 98, 107}. Agility and speed tests are dependent upon time which is normally recorded by stopwatches or electronic timing {3, 51, 67, 87}. The measurement of agility and speed requires minimal human error, reduced bias potential and precision. Further, control of these factors would ensure reduced absolute error, increased result reliability and validity. While electronic gates are more accurate (0.001 s), the use of a hand-held stopwatch may provide convenient and comparable accuracy (0.01 s) when used by an experienced tester {3, 51, 56}. Previous studies which have measured agility via a 20 yard {67} and 30 yard shuttle {87} found that hand-held stopwatches produced reliable results.

Hetzler et al {51} compared the reliability and accuracy of hand-held stopwatches to electronic timing during the measurement of sprint performance. A group of 26 timers (10 males and 16 females) used hand-held stopwatches to record single-split and multiple-split times of two 200 m sprint trials performed by 18 participants {51}. The results showed high intra-tester reliability (ICC = 0.98) for the hand-held stopwatch multiple-split times and a high intra-tester reliability average (ICC = 0.98) across electronic timing and hand-held stopwatches {51}. While hand-held stopwatch times were faster in two-thirds of the splits timed compared to electronic timing, Hetzler et al {51} concluded that hand-held stopwatch times should not be corrected during analysis as an attempt to represent greater accuracy may increase the timing error in one-third of cases.

Previous studies have conducted functional tests as measures of agility including the agility shuttle run {87}, the 505 test {102}, the T-test {83, 99} and the Illinois agility test {35, 56, 89, 115}. The agility shuttle run consists of 30 foot return sprints (from the starting point to the 30 foot point and back to the start) performed twice {87}, while the 505 test consisted of a 5 m sprint from the starting point to a turning point ahead followed by a 180° pivot and a return sprint to the starting point {102}. The T-test requires the participant to sprint forward 10 yards from the starting point followed by three lateral shuffle movements in a straight line (five yards to the left, 10 yards to the right and five yards to the left) and a return to the starting point with a 10 yard back-pedal {83, 99}. While these tests produced high intra-tester and test-retest reliability, the Illinois agility test seems more applicable to sports that require multiple changes of direction, such as soccer or rugby {35, 56, 89}; compared to the 505 test, which is more applicable to running between creases for cricket batsmen {102}.

2.14.1 Illinois agility test (IAT)

The IAT is a modified version of the T-test {89}. Semenick {99} described the T-test as a "*measure of 4-directional agility and body control that evaluates the ability to change directions rapidly while maintaining balance and without loss of speed*". Pauole et al {83} showed high intra-tester reliability (ICC = 0.98) using the T-test as a measure of agility using 152 college-aged male and female participants. Roozen {89} stated that agility is determined by the ability of an individual to combine "*muscle strength, starting strength, explosive strength, balance, acceleration and deceleration*" and described the IAT as an accurate measure of agility.

The IAT is a modified version of the T-test described by Semenick {99}, which consists of a course 10 m x 5 m (length x width) marked by four cones along the rectangular perimeter with an additional four cones placed 3.3 m apart along the midline of the testing area {89}. The participant started in prone lying with the chin in line with the start line and hands at shoulder level. On command, the participant is required to get up as fast as possible and complete the course in the randomly chosen direction (left to right or vice versa) without knocking down any cones {89}. The IAT norms for males are presented below in Table 2.4.

Table 2-4: ***The Illinois agility test norms for males including classification according to time (Adapted from Roozen {89}).***

Classification	**Time (s)**
Excellent	Less than 15.2
Good	15.2 – 16.1
Average	16.1 – 18.2
Fair	18.2 – 18.3
Poor	More than 18.3

Katis and Kellis {56} investigated the effects of small-sided games on physical conditioning and performance in 34 young soccer players (age range of 13 ± 0.9 yr). The agility component of performance testing was measured using one trial of the Illinois agility test which was timed by hand-held stopwatch {56}. There was high intra-tester reliability (ICC = 0.94) of the Illinois agility test as a high performance measure of agility. Vescovi et al {115} described the physical performance characteristics of 414 high-level female soccer players (practicing three to four times per week) ranging in age from 12 to 21 years. Similar to a previous study {56}, functional field tests, including the Illinois agility test as a measure of agility, were conducted to compare performance variables. The tests were conducted after a standardised 10 min to 15 min warm-up and the best electronic time of two to three trials was recorded for analysis {115}. While the pilot study was not described, Vescovi et al {115} reported high intra-tester reliability (ICC = 0.98) for the Illinois agility test as a measure of agility.

Both studies {56, 115} investigated agility as a component of performance in soccer players, while Gabbett {35} investigated the physiological characteristics of sub-elite junior (n = 88) and senior (n = 71) rugby league players using similar functional performance testing. Agility was measured using the Illinois agility test and the fastest time of two trials was recorded using hand-held stopwatches and analysed {35}. The results showed high intra-tester test-retest reliability (ICC = 0.86) with a low technical error of measurement of 2.02 % for the Illinois agility test as a measure of agility. However, while performance testing was conducted in a random order for each participant, a standardised warm-up protocol was not used and there was no control for the confounding factor of stretching prior to test performance, thereby requiring cautious interpretation of IAT reliability results in this study {35}. Based on the results of previous studies {35, 56, 115}, the IAT appears to be a reliable measure of agility performance.

2.14.2 Sprint tests

Sprint tests may be conducted to assess the maximal running speed or acceleration of an individual {62, 67, 96, 98, 107}. Sprinting is a functional measure of athletic performance that requires maximal force production within muscular tissue. From an architectural perspective, fibre pennation angle, fibre length and predominating fibre type are intrinsic factors which determine maximal force generation {57}. Previous studies have used sprint courses of varying distance including 50 yards {98}, 40 m {107}, 30 m {3, 96, 135}, 20 m {62, 67} and 10 m {62}. The results of 10 m sprints in which the participant begins from a stationary starting position may be used to calculate maximal acceleration {62}. Sprint tests that used a flying start of either 15 yards {98} or 10 m {62} prior to the measurement of the required sprint distance (50 yards or 20 m, respectively) were used to calculate maximal velocity.

Little and Williams {62} investigated the effects of different stretching protocols (static, dynamic and no stretching) during a standardised warm-up on sprint and agility performance in 18 professional male soccer players. The results showed that a stationary 10 m sprint and a flying 20 m sprint had high test-retest reliability (ratio limits of agreement 0.999/1.042 and 0.997/1.040, respectively). The flying 20 m sprint, in which participants sprinted 20 m from a maximal speed start, was performed immediately after the stationary 10 m sprint and was considered a measurement of maximal velocity under the assumption that acceleration was maximal and constant after 10 m {62}.

Markovic et al {67} investigated the effects of sprint and plyometric training on muscle function and athletic performance in 93 male physical education students. Athletic performance was measured using horizontal jump performance (explosive ability), stationary 20 m sprint (maximal speed) and 20 yard shuttle run (agility) tests {67}. While the coefficient of variation (CV) and intra-tester ICC of the sprint test was not specifically stated, Markovic et al {67} reported high absolute (CV range = 1.9% to 4.1%) and relative reliability (ICC range = 0.91 to 0.96) for all athletic performance tests.

Sayers et al {96} investigated the effect of static stretching on phases of sprint performance in 20 elite female soccer players. Each participant was required to perform three 30 m sprints from a stationary start which were timed with ET gates positioned at 10 m and 30 m. Each 30 m sprint was divided into the acceleration phase (measured at 10 m), overall sprint time (measured at 30 m) and the time spent in maximal velocity phase (the difference between overall time and 10 m time) {96}. Sayers et al {96} reported high inter-tester correlation for overall 30 m sprint time (ICC = 0.999), acceleration (ICC = 0.993) and maximal velocity time (ICC = 0.991).

Baker and Davies {3} investigated the relationship between high intensity cycle ergometry and athletic performance field tests, including 30 m sprint and 40 m agility shuttle run, in 12 elite sprinters. All times were recorded using hand-held stopwatches by the same experimenter and the fastest of three trials was used for analysis {3}. Baker and Davies {3} reported high test-retest reliability (r = 0.94) for the 30 m sprint test while the reliability of the 40 m agility shuttle was not stated. Based on these results, Baker and Davies {3} concluded that high intensity sporting ability may be better assessed by sport-specific field tests (including sprinting), compared to high performance laboratory tests (cycle ergometry). Further supporting the concept of task specificity, Young et al {135} concluded that agility and sprint training are separate regimes which do not produce beneficial transfer to each other.

Based on the results of previous studies {3, 62, 96, 135}, the 10 m and 30 m sprint tests are suggested as reliable measures of maximal running speed. The 30 m sprint test course consists of three cone gates positioned in a straight line at 10 m, 30 m and 60 m from the starting point. On command, the participant should accelerate from a stationary start as fast as possible and complete a straight line 30 m sprint {62}. The participant should continue to sprint until the second gate {62} after which a gradual deceleration phase should occur until reaching the third gate (60 m). The 30 m sprint norms for males are presented below in Table 2.5.

Table 2-5: ***The 30 m sprint test norms for males (Adapted from Field {32}).***

Classification	**Time (s)**
Average	3.9 – 4.1
Good	3.6 – 3.9
Elite	3.3 – 3.6

2.15 Summary of the literature

Hamstring strain is one of the most common forms of injury in many sporting codes {9, 10, 18, 26, 114, 128} and is responsible for a long delay in the return to sport at an elite level {9, 114, 129}. Hamstring tears are most common in the MTU of the biceps femoris {105, 114, 129} and there is a high reoccurrence rate of hamstring muscle strains ranging from 34% to 77%, which indicates the difficulty associated with hamstring strain rehabilitation {129}. A lack of flexibility has been identified as the primary influential factor that may increase the risk of hamstring strain {19, 20, 25, 26, 33, 49, 61, 126}.

As a method of strain prevention, hamstring flexibility may be improved by various forms of stretching, which include static, ballistic and PNF techniques (CR, ACR and CRAC). To quantify the effect of stretch intervention, functional tasks such as the IAT and 30 m sprint test, the AKE test and the inclinometer have been shown to be reliable measures of agility, maximal speed and hamstring flexibility, respectively. Stretching techniques affect the viscoelastic muscle tissue due to the biomechanical and neurological mechanisms of action {100, 120}. However, based on the proposed mechanism of action of CRAC and current evidence, more complex neurological mechanisms are activated and manipulated during CRAC stretch as compared to static stretching {13, 15, 23, 74, 81, 100, 120, 138}. While both static {4, 5, 6, 22, 122} and CRAC {93, 131} stretching have produced increased hamstring flexibility, it has been shown that CRAC stretching produced greater gains in flexibility {74, 94}.

Stretching produces numerous effects other than increased flexibility, including an increase in pain threshold {45, 63, 74, 104}, stretch-induced hypertrophy {30, 47, 55, 62, 125, 131} and hormonal adaptations {43, 52, 92, 132, 133}. The benefits of stretching include a decrease in risk of hamstring injury {19, 49}, decreased muscle stiffness {6, 28, 33, 77, 86, 94} and duration of sustained flexibility {22, 106}.

Importantly, hamstring CR stretching {106} produced a greater increase in flexibility in a smaller amount of application time and a greater duration of sustained flexibility compared to static hamstring stretching {22}. However, there are no studies to date which have investigated the duration of sustained flexibility effect following hamstring CRAC stretching. The effect of stretching on exercise performance is unclear. The majority of studies suggested a stretch-induced deficit in muscle performance following an acute stretching protocol {7, 65, 71, 112}, while some suggest an improvement in following long-term stretching {47, 55, 62, 125, 131}. Muscle performance during exercise may be viewed from two perspectives which include isolated means such as peak torque, MVC, EMG activity and work {7, 29, 30, 47, 65, 122, 125, 131} or functional measures such as vertical jump height, agility tests and sprint tests {55, 62, 87, 91, 107}. Regarding isolated measures, previous studies have inferred correlation between significantly improved peak eccentric hamstring torques and long-term hamstring CR {47} or CRAC stretch {131} as compared to static stretch. Previous studies have further shown that while acute application of both PNF and static stretching reduce peak torque, the torque reduction following PNF was 3% to 5% less than that produced by static stretching {63, 71, 112, 120}.

To date, no studies have investigated the effect of hamstring CRAC on sprinting and agility performance as functional measures of muscle performance. The only study which has investigated postural control as a functional measure following hamstring CRAC was conducted by Ryan et al {93}. Further contributing to the scarcity of studies regarding the effect of hamstring CRAC stretching on functional measures of performance, there is no consensus of an optimal or standardised method of CRAC application.

Considering the common nature of hamstring injuries in sport and the lack of conclusive evidence regarding the effect of CRAC stretching on exercise performance, this experimental study of this thesis was designed to investigate the role of hamstring CRAC stretch on sprint and agility performance as functional measures of exercise performance. The information gained from this study will also add scientific evidence for the potential benefits of CRAC stretching on functional measures of exercise performance. The findings of this study may potentially be used to inform future clinical decision-making and practice; and may have practical implications for athletes and sports performance.

3 METHODOLOGY

3.1 Introduction

Hamstring strain injury is one of the most common sporting injuries {11} and stretching exercises are usually prescribed on the basis of injury prevention by increasing ones flexibility {36, 80, 101}. Flexibility is conventionally achieved by stretching modalities and is an important aspect of athletic performance. Increased flexibility has been previously shown to play an important role in injury prevention {49, 126}. Despite doubts over the preventative effect of stretching exercises {104, 111}, hamstring flexibility plays an important role in maintaining muscular and postural balance {130}.

Many stretching methods and regimes, previously described in the literature, have been used to increase hamstring flexibility {45, 62, 100, 111}. PNF techniques and static stretching are two of the more commonly employed forms of stretching exercises described in the literature {5, 94, 116, 120}. Previous studies comparing these stretching exercises have yielded conflicting results regarding their relative effectiveness {13, 28, 30, 33, 136}. However, reviews by Wilkinson {123} and Sharman et al {100} agree that a static contraction of the target muscle followed by a shortening contraction of the opposing muscle, contract-relax-agonist-contract (CRAC), is the most effective stretch. While evidence exists to support the role of hamstring CRAC stretching to improve medial-lateral postural stability {93}, to date there is scarce evidence of the role that hamstring CRAC stretching may have in improving athletic performance**.** The dynamic nature of CRAC stretching maximises the effects of the autogenic and reciprocal inhibition response via active muscular contraction {69}, as compared to static stretching techniques which are passive. While CRAC is suggested as being the most effective stretch, scientific evidence for its effects on athletic performance is lacking. Earlier studies have investigated isolated features of muscle performance such as peak torque {65}, EMG activity in target muscles {6, 30} and passive stiffness {77, 122} following stretching protocols as compared to functional measures of athletic performance, such as sprinting.

Based on previous suggestions by Weerapong et al {120}, the primary purpose of this study was to investigate the effect of hamstring CRAC stretching compared to no stretch intervention on sprint and agility performance. This was conducted by examining the effects that the hamstring CRAC stretch had on hamstring flexibility and its subsequent effect on measures of athletic performance, which consisted of the Illinois agility test and a split-timed 25 m sprint test. Further, the duration of effect and the thixotropic effect of the hamstring CRAC stretch was investigated to provide evidence-based practical application for the use of the stretch protocol in sport.

3.2 Study design

The study used a true randomised control experimental design.

3.3 Participants

Forty healthy male volunteers were recruited for the study through advertisements placed at gymnasiums in the Southern Suburbs of Cape Town, South Africa, and through word of mouth. Participants were randomly assigned to an experimental group that received a CRAC stretch or a control group that received no intervention.

3.3.1 Sample size determination

Data from a previous study that measured hamstring flexibility using the active knee extension test was used to ensure that the sample size would provide sufficient statistical power {106}. Hamstring flexibility was selected to determine the required sample size, as it is one of the main outcome measures of this study. Required sample size for hamstring flexibility was calculated using a smallest meaningful difference of 15º, and a standard deviation of 10º. With statistical significance accepted as $p < 0.05$, groups of 15, 20 and 24 participants would provide 80%, 90% and 95% statistical power for hamstring flexibility respectively. Therefore 40 participants were recruited for this study, to ensure sufficient statistical power if some participants were unable to complete the study.

3.3.2 Inclusion criteria

Participants included healthy, active males between the ages of 21 and 35 years, who performed between three and five hours of physical activity per week. Female runners were not included in this study as the main outcome measure was exercise performance, and the menstrual cycle may influence exercise performance {75}.

3.3.3 Exclusion criteria

Participants were required to complete a questionnaire which requested relevant medical, surgical and training-related history as a method to screen for possible exclusion criteria and determine participant eligibility for the study. Participants that had a previous history of hamstring injury or pathology of the hip, knee, thigh or lower back over the last three months {5}; regular use of muscle relaxing, analgesic, steroidal or non-steroidal anti-inflammatory drugs; orthopaedic or neuromuscular disease of the lower limbs were excluded from the study {53}.

3.3.4 Randomisation

Participants were randomly assigned to either the experimental group or control group at the baseline testing session, following the completion of the informed consent form and questionnaires. Randomisation was conducted by asking participants, to draw a piece of paper from an envelope. The envelope contained an equal number of “experimental” and “control” group slips. Therefore, 20 participants were randomly allocated to the experimental group, and 20 participants formed the control group. A pilot study was not conducted prior to the testing protocol used in this study.

3.4 Instrumentation

3.4.1 Informed consent and questionnaire

Participants were informed of the purpose of the study, the testing to be undertaken, potential risks involved in participating, the benefits of participation and their right to withdraw from the study at any time. All participants completed an informed consent form before commencing the study (Appendix II). Furthermore, participants were required to complete a questionnaire to determine any relevant medical and surgical history, injury history and current physical activity levels (Appendix III).

3.4.2 Body composition measurements

Body mass (kg) was recorded using a calibrated scale and stature (m) was recorded using a wall-mounted stadiometer. Body mass index (BMI) was calculated using the following formula {85, 113}:

$$BMI = \text{Body mass (kg)} / (\text{Stature (m)})^2$$

3.4.3 Hamstring flexibility: Active Knee Extension (AKE) test

Hamstring flexibility was assessed using the AKE test {21, 124}. Participants were positioned in supine lying without a pillow. Participants were also instructed to allow the ankle to plantarflex during testing to limit the effect of potential increased neural tension that may occur with ankle dorsiflexion {53}. An adjustable strap was placed over the anterior superior iliac spines to limit pelvic movement during testing. An additional strap was placed over the thigh of the leg not being tested to maintain hip extension {54, 97}. The leg being tested was placed on a wooden platform which was used to maintain 90º of hip and knee flexion. These positions were established using a universal goniometer. An inclinometer was aligned with the head of the fibula and lateral malleolus and zeroed.

The participants were instructed to extend the knee actively at a slow rate to avoid hamstring muscle spindle excitation until the first onset of a stretch sensation, as opposed to discomfort, was perceived {54}. At this point, the angle on the inclinometer was recorded. The participant then returned the leg to the starting position and rested for one minute. The average of three inclinometer recordings was recorded. The AKE test was then repeated on the opposite leg.

Figure 3-1*: The starting position for the AKE test showing the left leg in 90°of hip and knee flexion with adjustable straps stabilising the anterior super iliac spines and the right thigh.*

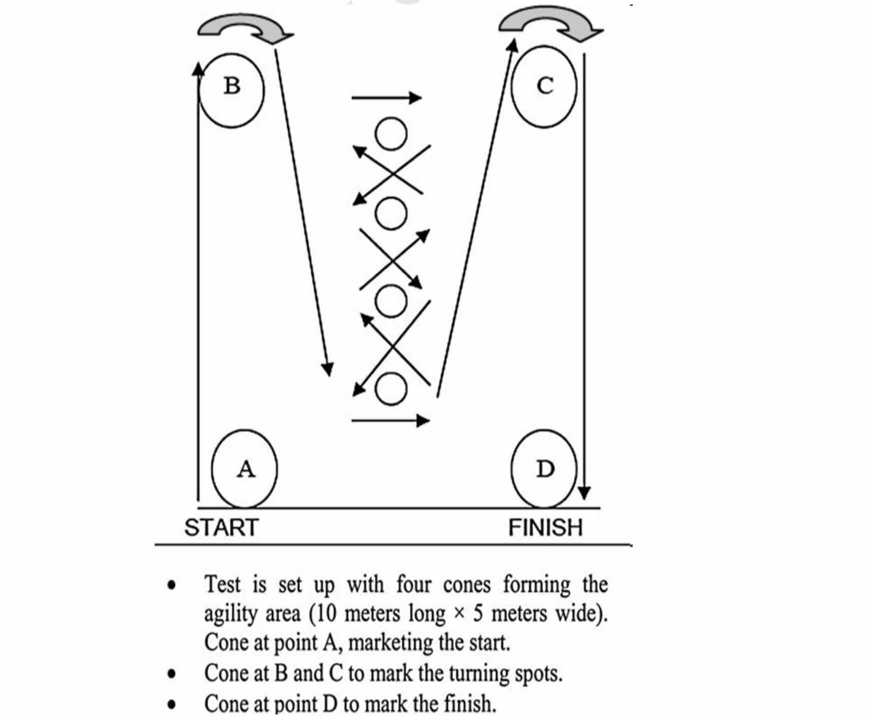
3.4.4 Warm-up protocol

Participants in the experimental and control groups were required to perform a non-specific, short duration warm-up prior to the agility and sprint performance tests. The purpose of the warm-up was to minimise the risk of injury associated with performance tests and stretching protocols {33, 111, 120}. The warm-up consisted of 5 min of cycling between 100 watts to 120 watts on a stationary cycle ergometer with a magnetic resistance flywheel {6, 7}.

3.4.5 Illinois Agility test

The Illinois agility test was used to determine agility performance {89}. The test involved explosive speed, rapid changes of direction, deceleration and the ability to maintain momentum and balance as a measure of four-directional agility. Eight cones demarcated the obstacle course. The course was 10 m x 5 m (length x width) marked by four cones along the rectangular perimeter. Four additional cones were placed linearly along the midline of the area, approximately 3.3 m apart (Figure 3.2).

Participants started the test in prone lying, with their chin in line with the start line, and their hands at shoulder level. On the command "*go*", the stopwatch (accurate to 0.01 second) was initiated and the participant got up and completed the course as fast as possible (Figure 3.2). Timing stopped at the instant the participant's trunk passed the final cone. This was followed by a three-minute recovery period. The test was repeated in the same direction. Participants were given standard verbal encouragement during the test, and were requested to complete the course "*as fast as possible*". The best time was recorded. Previous studies have determined that the Illinois agility test is a valid and reliable method of testing agility {89}.



- Test is set up with four cones forming the agility area (10 meters long × 5 meters wide). Cone at point A, marketing the start.
- Cone at B and C to mark the turning spots.
- Cone at point D to mark the finish.

Figure 3-2: ***The course of running for the Illinois agility test (Adapted from Roozen {89}).***

3.4.6 Sprint test

Sprint performance was determined by measuring the sprint time over 10 m and 25 m. The course consisted of three cone gates positioned linearly at 10 m (gate 1), 25 m (gate 2) and 50 m (gate 3) away from the starting line (Appendix IV) measuring maximum acceleration and speed over 10 m and 25 m. Participants started the test in prone lying. On the command "*go*", the stopwatch (accurate to 0.01 s) was initiated and the participant got up and completed a maximal straight line sprint to the 25 m cone. Split times were recorded at the instant the participant's trunk passed the 10 m and 25 m cones. The participants then came to rest at 50 m cone, thereby allowing gradual deceleration to occur over 25 m as an eccentric hamstring strain prevention strategy. This was followed by a two-minute recovery period after which the test was repeated. Participants were given standard verbal encouragement during the test, and were requested to complete the course "*as fast as possible*". The reliability of the 10 m sprint has previously been established {62}.

3.4.7 Contract relax agonist contract stretch

The participant lay supine on a plinth and adjustable straps were placed over the anterior superior iliac spines to limit pelvic movement during intervention. An additional strap was placed over the thigh of the opposite leg to maintain hip extension {54, 97}. The investigator guided the leg into a straight leg raise until the participant reported the first onset of stretch sensation in the hamstring {97}. This position was maintained for 15 s, with the investigator using the shoulder to support the participant's ankle {46, 97}. The participant then performed a maximal isometric contraction of the hamstring for 6 s {28, 46} pushing the leg into hip extension. The investigator resisted the contraction at the level of the participant's ankle to assist ergonomic endurance {69}. To prevent an increase in blood pressure via the Valsalva manoeuvre {69} and to reduce compensatory muscle recruitment during the isometric contraction, the participant was instructed to breathe normally and avoid hip elevation. Immediately after the hamstring isometric contraction the participant was asked to perform concentric hip flexion against the investigator's manual resistance.

The investigator encouraged the participant to reach their personal limit of hip flexion ROM, which the participant maintained for 6 s. Hip flexion ROM was based on the participant's perception of his individual limit and stretch sensation. The 20 s rest period after concentric hip flexion marked the end of one repetition {46}. Three repetitions of the CRAC stretch were performed for each leg by the principal investigator using standardised verbal instructions to ensure consistency and maximum co-operation from participants.

3.5 Testing procedure

Participants were tested individually and were required to attend three testing sessions at similar times on alternate days, over the course of one week. All tests were conducted on a non-slip, indoor track at the Groote Schuur Hospital Department of Physiotherapy, thereby ensuring a consistent testing environment. During the baseline testing session (Session 1) all participants were asked to complete an informed consent form (Appendix II) and a questionnaire (Appendix III) to determine any relevant medical and surgical history, injury history and current physical activity levels. Thereafter, body composition measurements were performed for all participants. Participants were then randomised into either the experimental or control group, and familiarised with all testing procedures. The experimental group was also familiarised with the CRAC stretch via a visual demonstration performed by the primary investigator. After being familiarised, participants' hamstring flexibility, agility and sprint performance were measured.

During the second session (Session 2), all participants had their pre-intervention hamstring flexibility recorded. Participants in the experimental and control groups performed a standardised warm-up. Participants in the experimental group received a CRAC stretch performed bilaterally by the primary investigator. Participants in the control group rested in supine for the same duration as was required for the CRAC stretch to be performed (6 min). After the CRAC stretch (experimental group) or rest period (control group), all participants had their hamstring flexibility measured using the AKE test. This was followed immediately by recording the better of two trials of agility and sprint performance tests measured using the Illinois agility and sprint tests, respectively.

At the third testing session (Session 3), the duration of effect of the CRAC stretch and the thixotropic effects of the CRAC stretch were assessed. For all participants, pre-intervention hamstring flexibility was recorded bilaterally and then followed by the standardised warm-up. Participants in the experimental group then received the CRAC stretch, performed on each leg, by the primary investigator. Participants in the control group rested in supine for the same duration as was required for the CRAC stretch to be performed. Participants then chose a slip of paper to randomly select the leg upon which multiple hamstring flexibility assessments were to be recorded, referred to as the “thixotropy” leg. The opposite leg would serve as the “control” leg.

Post-intervention hamstring flexibility was assessed at regular time intervals (0, 2, 4, 6, 8, 15, and 20 min) on the randomly selected “thixotropy” leg. In contrast, post-intervention hamstring flexibility was recorded at 0 and at 20 min only on the “control” leg. The effect of thixotropy was accounted for by muscular activity required for repeated flexibility measures in the “thixotropic” leg as compared to the “control” leg. There was a 100 % attendance rate as no participant withdrew from the study at any stage. The study design is summarised below in Figure 3.3.

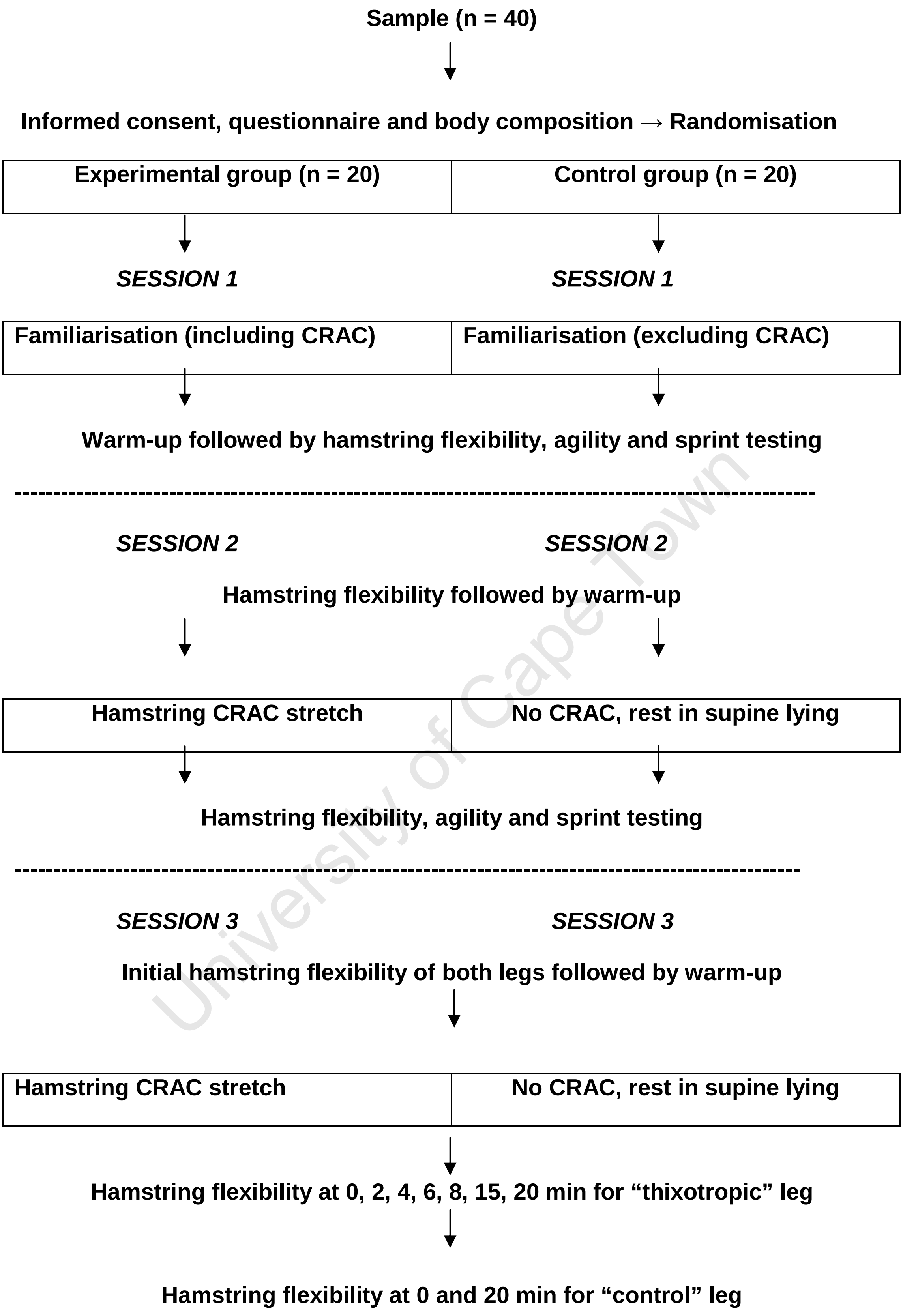


Figure 3-3*: A schematic diagram illustrating the flow of participants through each session of the testing procedure.*

3.6 Statistical analyses

Statistical analyses were performed using Statistica software [StatSoft, Inc. (2007). STATISTICA (data analysis software system), version 8.0. www.statsoft.com]. Normality was determined using the Kolmorogov Smirnov test. Differences in descriptive variables between the experimental and control groups were assessed using an independent t-test. Statistical significance for the two main effects of group and time, and the interaction (group x time) of all other variables were assessed using a two-way analysis of variance (ANOVA) with repeated measures. Tukey's HSD post hoc comparisons were performed where necessary. Differences in three dependent variables (flexibility, agility and speed) were compared at pre- and post-intervention periods within groups and were expressed as percentages (mean ± 5th and 95th percentile) of their respective pre-intervention values. All data are presented as the mean ± standard deviation (SD), unless otherwise stated. Statistical significance was accepted as $p \leq 0.05$.

3.7 Ethical considerations

The study was granted ethical clearance by the University of Cape Town Faculty of Health Sciences Human Ethics Research Committee (HREC REF: 200/2009) (Appendix I). This study was performed in accordance with the ethical principles outlined in the Declaration of Helsinki (Seoul version, 2008). Participants were required to complete an informed consent form prior to participating in the study. The informed consent form explained the purpose and procedure of the study, how confidentiality would be ensured and the right to withdraw from the study without reason or prejudice. Participants were not identified by name and were recorded as a number for statistical analyses. All data were recorded using a paper-based system and stored securely in a cabinet to which the primary investigator had sole access to. All participants in the study participated on a voluntary basis. All data was kept confidential and anonymous.

3.7.1 Risks to participants

There are no risks associated with the use of the inclinometer. Participants adhered strictly to the specific warm-up protocol used in this study. The purpose of the warm-up protocol was to decrease the risk of injury associated with performance tests and stretch intervention {33, 111, 120}. Similar warm-up protocols have reported no adverse effects on participants in previous studies {6, 7, 65}.

The Illinois agility test was performed before the sprint test. This procedure minimised the risk of strain injury during sprinting by allowing the hamstring muscle group to actively warm-up by starting with a lower intensity exercise. For the sprint test, participants were given a distance of 25 m to slow down gradually after passing the final timing gate. The gradual deceleration after sprinting limited the risk of eccentric hamstring strain, which is usually associated with rapid deceleration. The primary investigator, experienced in the application of the CRAC technique, conducted all interventions to reduce the risk of over-stretching the target muscle {69}. Standardised verbal instructions were used by the primary investigator during CRAC stretching and performance tests to ensure consistency and result reliability. Participants were familiarised with CRAC stretching and performance tests during baseline testing to reduce the risk of hamstring injury.

3.7.2 Benefits to participants

Benefits might have included short term increased muscle flexibility following the CRAC stretch {123} which is associated with decreased risk of hamstring muscle strain {61}. Although there was no remuneration for participation in this study, participants were reimbursed for travelling expenses. As an incentive, all participants received a cap upon completion of the study. Participants received information regarding their performance during the course of the study. Results of the study were presented to participants by electronic mail or via cellular communication.

4 RESULTS

4.1 Participants

The descriptive characteristics of participants are shown in Table 4.1. There was a significant difference between groups in body mass (p = 0.02, t = 2.35), with participants in the experimental group having a significantly higher body mass, compared to participants in the control group. There were no significant differences between groups for any other descriptive variables.

Table 4-1: ***Descriptive characteristics of participants in the experimental (n = 20) and control (n = 20) groups. Data are expressed as mean ± standard deviation.***

VARIABLE	**EXPERIMENTAL**	**CONTROL**
Age (years)	24.10 ± 4.06	24.45 ± 3.92
Stature (m)	1.76 ± 0.06	1.75 ± 0.06
Body mass (kg)	79.04 ± 11.11	71.98 ± 7.51*
Body mass index (BMI)	25.31 ± 3.41	23.40 ± 2.87

** p = 0.02*

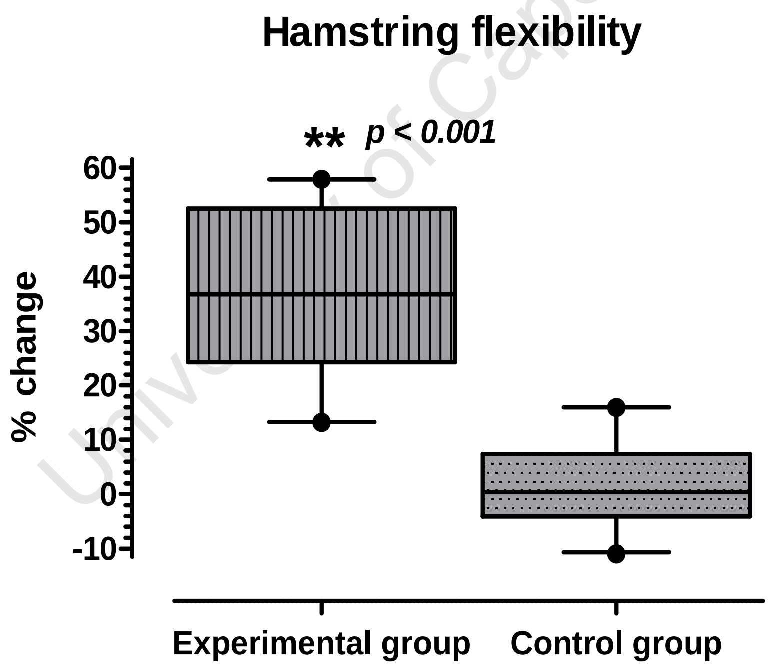
4.2 Flexibility

The difference in hamstring flexibility (measured as degrees of active knee extension) prior to and immediately following CRAC stretching in the experimental group as compared to the control group (no intervention) are shown in Table 4.2. Note that an increase in AKE indicates increased hamstring flexibility.

Table 4-2: ***Pre- and post-intervention hamstring flexibility of participants in the experimental (n = 20) and control (n = 20) groups. Data are expressed as mean ± standard deviation.***

HAMSTRING FLEXIBILITY	EXPERIMENTAL	CONTROL
Pre-intervention (°)	48.18 ± 8.46	56.91± 13.38
Post-intervention (°)	65.90 ± 8.59	57.95 ± 13.19

There was a significant difference in pre- and post- intervention hamstring flexibility between groups (Figure 4.1), with an increased percentage change in hamstring flexibility of the experimental group, compared to the control group ($p < .001$). Based on the mean results for pre- and post-CRAC intervention, there was an increase of 36.7% in AKE within the experimental group following hamstring CRAC stretching.



Significant differences: ** Post-CRAC intervention ($p < 0.001$)

Figure 4-1: ***Percentage change in hamstring flexibility for participants in the experimental (n = 20) and control (n = 20) groups. Data are expressed as mean ± 5th and 95th percentile. Note a positive change indicates an improvement in hamstring flexibility.***

4.3 Agility

The agility scores (measured in seconds) prior to and following CRAC stretching in the experimental group as compared to the control group are shown in Table 4.3.

Table 4-3: ***Pre- and post-intervention Illinois agility test scores of participants in the experimental (n=20) and control (n=20) groups***

AGILITY SCORE (sec)	EXPERIMENTAL	CONTROL
Pre-intervention	16.86 ± 0.83	17.06 ± 1.81
Post-intervention	16.35 ± 0.80	16.69 ± 1.55

There were no significant differences in the percentage change of agility between groups (Figure 4.2).

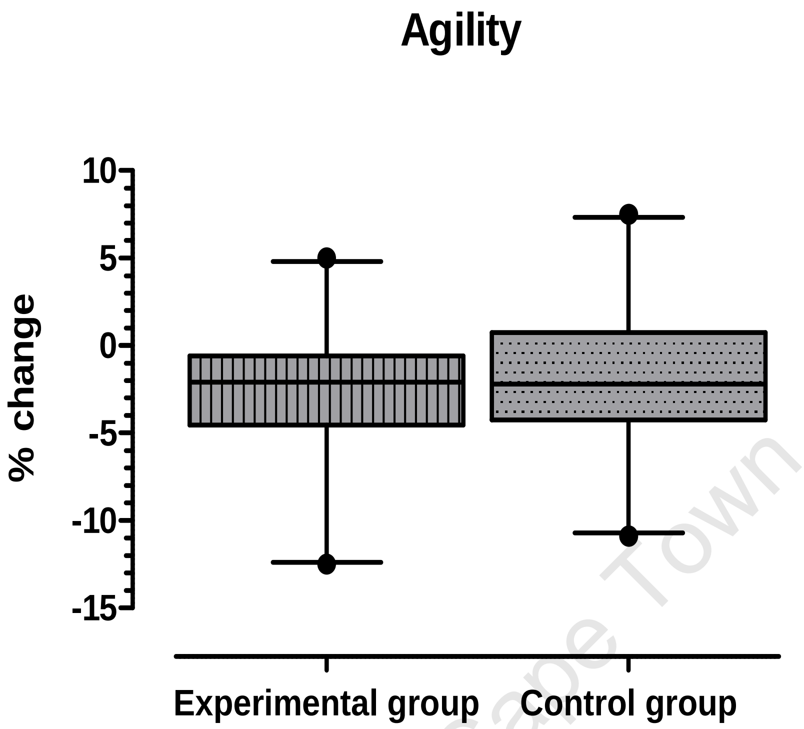


Figure 4-2: ***Percentage change in agility for participants in the experimental (n=20) and control (n=20) groups Data are expressed as mean ± 5th and 95th percentile. Note a negative change indicates an improvement in agility.***

4.4 Best 10 m sprint

The best 10 m sprint times (measured in seconds) prior to and following CRAC stretching in the experimental as compared to the control group are shown in Table 4.4.

Table 4-4: ***Best 10 m sprint times for pre- and post-intervention of participants in the experimental (n = 20) and control (n = 20) groups. Data are expressed as mean ± standard deviation.***

BEST 10 m SPRINT (sec)	EXPERIMENTAL	CONTROL
Pre-intervention	2.01 ± 0.11	2.02 ± 0.26
Post-intervention	2.01 ± 0.13	1.99 ± 0.17

There were no significant differences in the percentage change of best 10 m sprint performance between groups (Figure 4.3).

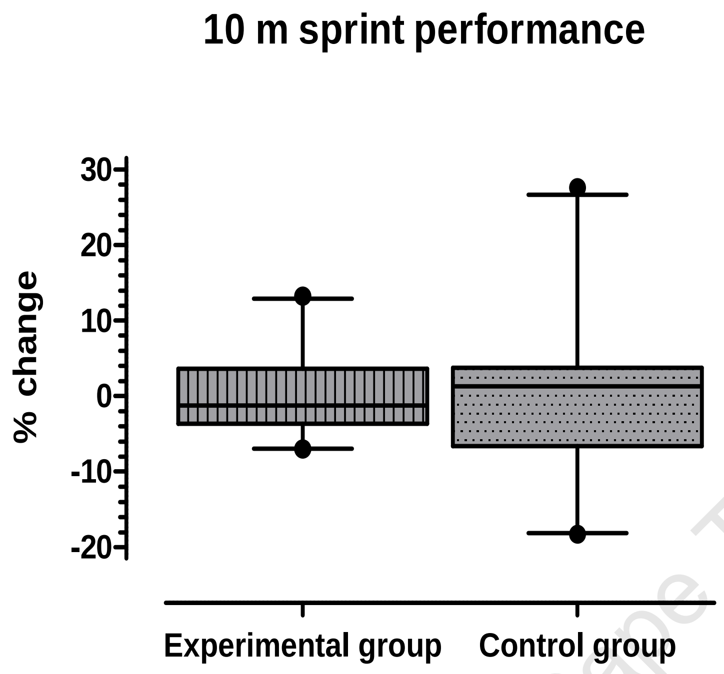


Figure 4-3: ***Percentage change in best 10 m sprint performance for participants in the experimental (n = 20) and control (n = 20) groups. Data are expressed as mean ± 5th and 95th percentile. Note a negative change indicates an improvement in 10 m sprint performance.***

4.5 Best 25 m sprint

The best 25 m sprint times (s) prior to and following CRAC stretching in the experimental as compared to the control group are shown in Table 4.5

Table 4-5: ***Best 25 m sprint times for pre- and post-intervention of participants in the experimental (n = 20) and control (n = 20) groups. Data are expressed as mean ± standard deviation.***

Data are expressed as mean ± standard deviation.

BEST 25 m SPRINT (sec)	EXPERIMENTAL	CONTROL
Pre-intervention	4.30 ± 0.19	4.39 ± 0.34
Post-intervention	4.26 ± 0.23	4.40 ± 0.38

There were no significant differences in the percentage change of best 25 m sprint performance between groups (Figure 4.4).

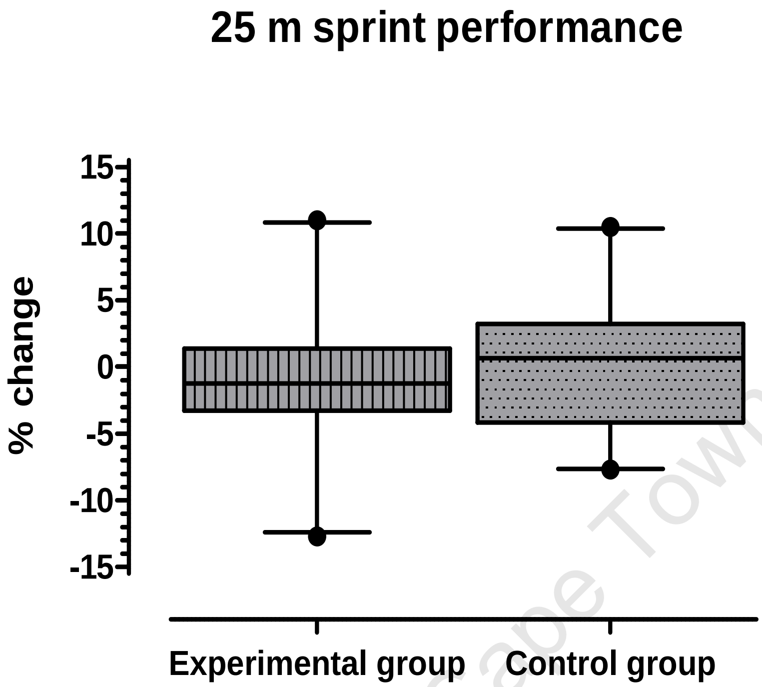
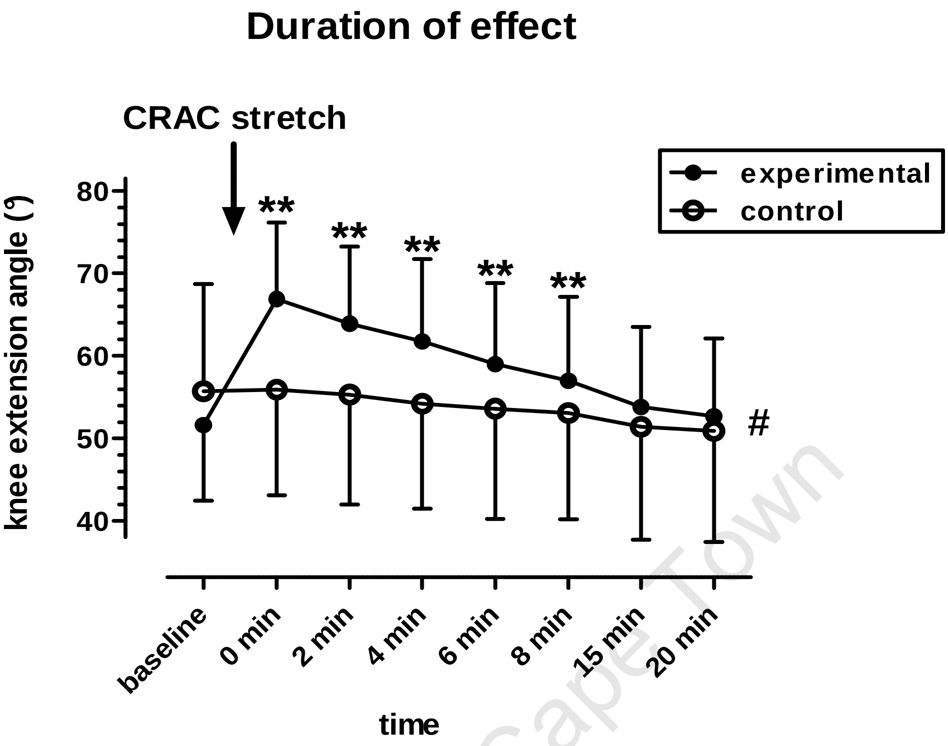


Figure 4-4: ***Percentage change in best 25 m sprint performance for participants in the experimental (n = 20) and control (n = 20) groups. Data are expressed as mean ± 5th and 95th percentile. Note a negative change indicates an improvement in 25 m sprint performance.***

4.6 Duration of CRAC effect

There was a significant interaction between groups over time ($F_{(7,\ 266)} = 38.95$; $p < 0.001$) with an increase in active knee extension angle of the experimental group post-CRAC stretch, compared to the control group. Experimental group knee extension angle, immediately post-CRAC intervention, remained significantly increased for the duration of 8 min compared to the experimental and control group baseline knee extension angle ($p < 0.00003$).



Significant differences:

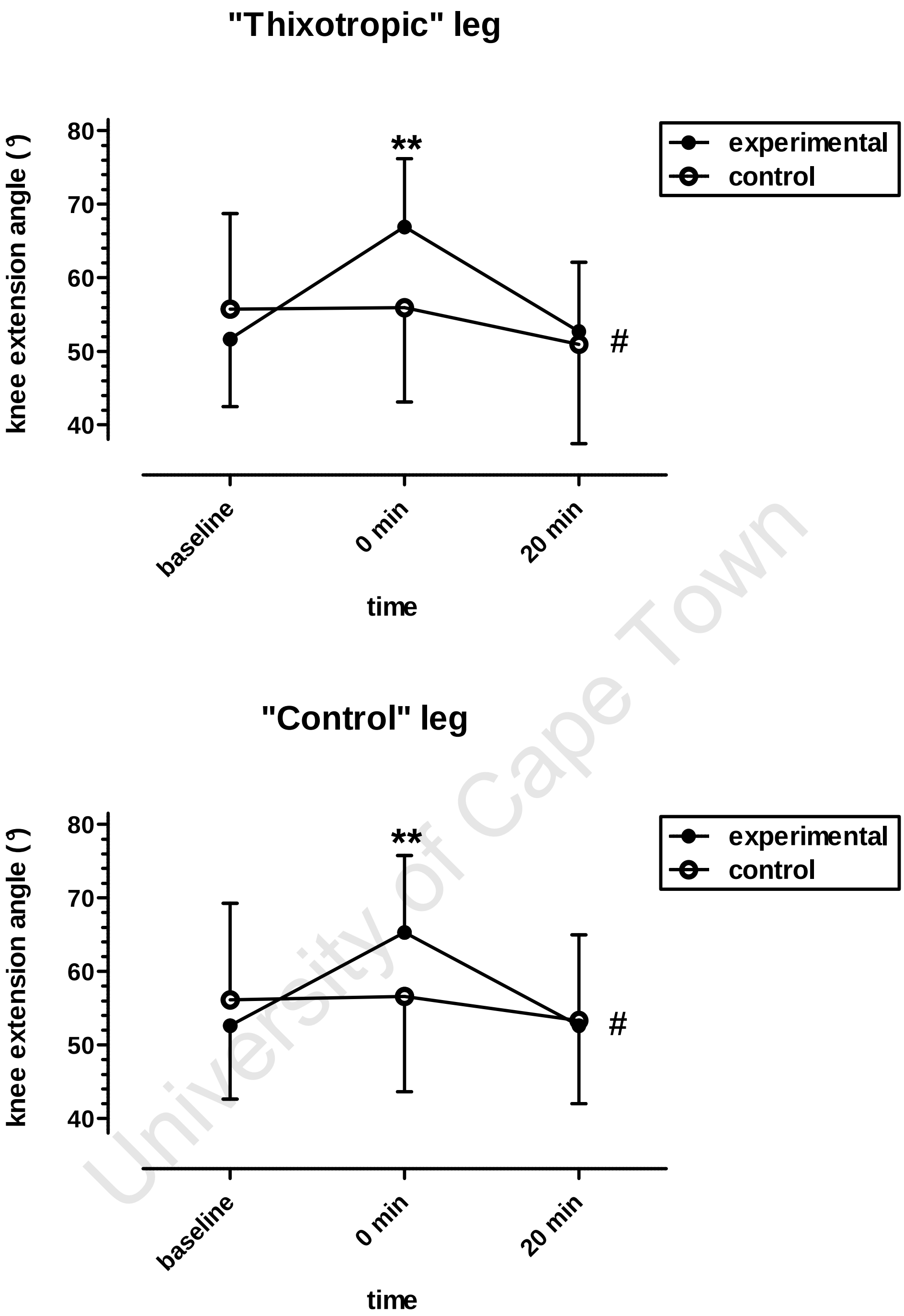
** experimental baseline vs. experimental 0, 2, 4, 6, and 8 min ($p < .001$)

interaction of group x time ($p < .001$)

Figure 4-5: ***Differences in duration of effect for participants in the experimental group (n = 20) and control group (n = 20). Data are presented as mean ± standard deviation.***

4.7 Thixotropy

There was a significant interaction between groups over time ($F_{(2, 76)} = 79.72$, $p<.001$), with an increase in knee extension angle immediately post-CRAC stretching in the experimental group (0 min). There were no significant differences between the knee extension angles of the “thixotropic” and ”control” leg in the experimental and control groups at the 20 minute interval when compared to baseline knee extension angles within each group.



Significant differences: ** 0 minutes vs. baseline ($p < 0.001$); # main effect over time ($p < 0.0001$)

Figure 4-6***: Differences in knee extension angle of the "thixotropic" leg (above) and "control" leg (below) of participants in the experimental group (n = 20) and control group (n = 20) at baseline, 0 minutes and 20 minutes. Data are expressed as mean ± standard deviation.***

5 DISCUSSION

To date, to the knowledge of the author, there have been no studies that have examined the effects of hamstring CRAC stretching on agility and sprint performance. Considering this lack of evidence, the testing protocol required careful planning. Previous studies investigating other forms of PNF stretching have focused on isolated effects such as flexibility {28, 33, 79, 97, 106} and peak torque and EMG activity {47, 65, 131}. Currently, only one previous study has examined the effect of hamstring CRAC stretching on postural stability {93}. Agility and sprint performance were used as functional measures of muscle performance in this study as compared to the isolated measures of muscle performance described in previous studies. The hamstring CRAC intervention used in this study had no significant effect on agility or sprint times (both 10 m and 25 m) in moderately active males. However, the CRAC intervention was significantly effective in improving hamstring flexibility immediately post-application; and maintained significant hamstring flexibility for a total duration of 8 min thereafter.

5.1 Descriptive characteristics

There were no significant differences between groups in age or stature. There was a significant difference between groups in mass. Based on the stretch-induced strength deficit theory {7, 65, 71, 112} and the scientific laws of momentum {8, 78}, one would expect that participants of larger mass should exhibit a poor agility and sprint score following acute stretch intervention. While the participants in the experimental group had significantly greater body mass compared to the control group, there was no adverse effect on agility or sprint times. Further, the calculation of body mass index (BMI), which accounted for participants' height, produced non-significant differences between groups. In a previous study that investigated morphological differences after sprint training, Markovic et al {66} compared pre- and post-training anthropometric measurements in 150 physically active males. The anthropometric data usually associated with sprint performance assessments includes height, body mass, BMI, fat free mass, body fat percentage and thigh and calf muscle girth {66}.

In this study, body fat percentage and hence fat free mass, as a mathematical calculation based on body fat percentage, were not assessed. While BMI fails to distinguish between proportions of body fat and lean tissue, it may be used to describe the density of a person {113}. Since both height (a determinant of limb length) and body mass (a determinant of muscle mass and strength) impact on running speed, the interaction of body height and body mass, BMI, is an important anthropometric factor during sprint assessment {113}.. Based on the results of these studies, the use of BMI calculations in this study, which also investigated sprinting as a functional measure of muscle performance, is appropriate {66, 113}.

5.2 Flexibility

This study showed significant increases in hamstring flexibility in the experimental group post - CRAC intervention (Figure 4.1, page 86) compared to the control group. This illustrates the cause-effect relationship between stretching intervention and flexibility and is consistent with findings from numerous studies {22, 27, 29, 30, 33, 65, 94, 97, 106, 122}. DePino et al {22} investigated the effect of a hamstring static stretch protocol and found a significant increase of 6.8° and 5.6° in active knee extension ROM at one and 3 min post-stretching, respectively. Feland and Marin {29} demonstrated significant increases in mean change of passive knee extension after hamstring CR stretching. Using 20%, 60% and 100% isometric hamstring contraction strength, mean increases in post-CR stretch passive knee extension were 5.00°, 4.47° and 5.13°, respectively {29}. Ferber et al {3 0} also showed a significantly greater increase in passive knee extension after hamstring ACR (15.66 ± 0.95°) compared to CR (12.11 ± 0.66°) and SS (11.67 ± 0.82 °). A previous study used the AKE test to compare the effect of prior exercise on hamstring flexibility between groups that underwent 5 min of hamstring CR or static stretching {33}. Funk et al {33} observed significant increases in percentage change of hamstring flexibility within the PNF group after exercise compared with no exercise (7.8% increase) and baseline (9.6% increase). However, the data for the AKE measurements, including means and standard deviations were not presented {33}, which made the interpretation of the percentage change results for active knee extension difficult.

Marek et al {65} showed that CR stretching and static stretching of the quadriceps significantly increased active and passive knee flexion ROM. The increase in active knee flexion was 1.6° and 1.8° for CR and static qu adriceps stretching respectively {65}. There was no significant difference in active or passive knee flexion ROM between these interventions {65}. Schuback et al {97} compared the effect of self-applied slow-reversal-hold-relax PNF stretch and therapist-applied slow-reversal-hold-relax on hamstring flexibility, as measured by a passive straight leg raise test. Compared to the control group, there was a significant increase in mean change of passive right hip flexion of 9.6° and 12.6° in the self-applied and therapist-applied stretch groups respectively {97}. There was no significant difference in mean change of passive right hip flexion between self-applied and therapist-applied slow-reversal-hold-relax stretching groups {97}. Spernoga et al {106} showed that a modified CR hamstring stretch significantly improved mean active knee extension by 7.8° immediately post-stretch.

In light of the abovementioned evidence regarding the effect of stretching on flexibility, CRAC stretching has produced similar increases in flexibility compared to other forms of stretch intervention {27, 28, 94, 100}. Previous studies used static flexibility, such as passive knee extension {29, 30} and passive SLR {97}, as a measure of flexibility. Dynamic flexibility, which uses the participant's active ROM in the form of the AKE test was used as a measure of flexibility in this study. Further, hamstring CRAC stretching is an active stretch that emphasises contractile muscle work, as opposed to static stretching that involves the use of passive external force {65}. Despite the flexibility benefits of CRAC intervention, there are many variations in the overall stretch dosage. There are many components required to apply a CRAC stretch and due to inconsistencies in the literature with respect to CRAC dosage and method of application (Table 2.2), there is a lack of consensus of a standardised CRAC protocol. Overall CRAC stretch dosage is determined by the durations of: *a)* initial passive stretch; *b)* maximal isometric contraction; *c)* antagonist contraction; *d)* rest between isometric and antagonist contractions; *e)* rest between passive stretch and isometric contraction; and; *f)* rest between stretches. Furthermore, the frequency as determined by the number of repetitions per session, number of sessions per day/week and overall duration for which the protocol should be applied also influence overall CRAC dosage.

Joint flexibility is determined by a number of factors which include the MTU, joint capsule, adhesions, strength deficits, muscle hypertrophy and pain {38, 104}. There is no evidence to suggest that a higher body mass, as found in the control group of this study, may influence hamstring flexibility as measured using the AKE test. While the methodology and application of CRAC intervention employed in this study was similar to previous studies {97, 106} and was of a more acute nature, the common factors that modulate the effect of stretching interventions are intensity, duration and frequency {70}. Although it has been shown that the optimum duration for a passive static stretch is 30 s {5, 22, 77}, the optimum duration and frequency has not been determined for CRAC stretching, and this remains an area that warrants further research.

5.3 Agility and Speed

In this study, there were no significant differences between groups in agility and sprint performance (Figure 4.2, 43 and 4.4, pages 88-90). A previous study by Young et al {135} investigated potential beneficial transfer or carryover from sprinting to agility performance. The training protocols for both the speed and agility groups were conducted over six weeks at a frequency of two sessions per week, performed three to four days apart {135}. Young et al {135} included only those individuals who had completed a minimum of 10 sessions for statistical analysis. In comparison to Young et al {135}, the protocol in this study involved a total of four repetitions of the sprint and agility tests.

Young et al {135} showed that sprint training improved straight sprinting speed only and that the more complex the agility training task, the less likely that carryover from speed to agility will occur. Similarly, the use of a complex Illinois agility test in this study which involved 12 changes of running direction (Figure 3.2) may produce non-significant transfer to sprint speed. No specific sprint or agility training was performed in this study which was conducted over a shorter duration compared to previous studies {135}. Considering these differences, it would be safe to assume non-significant learning effect or carryover from speed to agility in this study.

The overlap in confidence intervals in these results (Figure 4.2, 4.3 and 4.4, page 88 – 90) may be due to morphological and functional differences within each group. Participants were not matched according to predominant training activities but in accordance with the overall duration of time per week (3-5 hours) which classified them as being moderately active. For example, there could be sport-specific adaptations in regular rugby players compared to adaptations in individuals that engaged in gym-based resistance training. Manning et al (1988) as cited by Baker and Davies {3} concluded that training specificity and the fibre type distribution within the muscle mass may make a greater contribution to force generation in activities requiring maximal effort over short periods. As previously discussed, fibre type distribution within a muscle is a direct result of innate characteristics and muscle adaptation due to the imposed training demand. Considering the short distance covered during the Illinois agility test and 25 m sprint used in this study, the findings by Manning et al (1988) further substantiate the link between training specificity and maximal force generation.

The results in this study are in contrast to those of previous studies {96, 107} that demonstrated significant negative effects (increased times) in sprint speed following static stretching. Sayers et al {96} found that static stretching after a standardised warm-up protocol (three repetitions of 30 s each on the hamstrings, calves and quadriceps) worsened acceleration, maximal-velocity sprint time and overall sprint time in elite female soccer players. Stewart et al {107} showed that two repetitions of 45 s static stretches on the hamstrings, calves, rectus femoris and quadriceps resulted in a mean disadvantage of 0.18 m over 40 m on the first sprint trial in elite under-19 year old rugby players. However, this effect became non-significant by the third trial, which could indicate the effect of thixotropy during the three minute rest period between trials. Furthermore, despite the significant wind assistance (mean headwind of 0.06 $m.s^{-1}$ during the stretching group sprint trials compared to that of the non-stretch group (mean headwind of 0.93 $m.s^{-1}$), there were no significant improvements in sprint times in the stretching group.

Previous studies have observed that static stretching reduces maximal voluntary isometric contraction and peak torque production as an acute effect {7, 120}. The overall force generated in maximal effort performance tests of short duration, such as sprinting and agility, seems to be dependent on these variables. The CRAC intervention used in this study had no detrimental effect on performance variables, as compared to static stretching. Within the context of exercise performance at the elite sport level, tests that investigate maximal functional performance, such as sprinting and agility, are very sensitive to timing. For example, differences between the personal best times of world-class sprinters can differ by 1%, which are milliseconds apart (Greene: 9.79 s, Bailey: 9.84 s, Christie: 9.87 s) {6}. A plausible explanation for not finding significant improvements in sprint or agility scores in this study could be due to limitations of the measuring equipment used. Previous studies have demonstrated that there is a latent period following a static stretch during which muscle function remains diminished for between 1 min and 120 min {7, 70}. This stretch-induced decrease in muscle strength has been linked to the acute effect of static stretching on neurological and biomechanical mechanisms {6, 24, 110}.

However, this latent period has not been determined for hamstring CRAC stretching. Due to this deficit in scientific evidence, it is possible that the participants began with agility and sprint testing during a period in which maximal muscle performance was compromised. A hypothesis for hamstring CRAC stretch not increasing agility and sprint times (a negative performance effect), as observed following static stretching, may be due to the active nature of CRAC stretch as compared to the passive nature of static stretching. The temporarily increased muscle compliance following stretching creates increased “*slack*” within the MTU, thereby delaying force production within the muscle and hence force transfer to the TPU {106}. With CRAC stretching, intrafusal fibre mismatch occurs during the isometric hamstring contraction {100}. It is hypothesised that the neurological and viscoelastic effects after intrafusal mismatch may be partially counteracted by the concentric quadriceps (agonist) contraction together with the simultaneously heightened eccentric hamstring activity during active agonist contraction {13, 104}. While this hypothesis is not relevant to static stretching due to the lack of active muscular contractions compared to CRAC stretching, it may substantiate static stretch-induced deficits in muscle performance.

5.4 Duration of effect

There was a significant increase in the post-CRAC intervention knee extension angles of the experimental group compared to the control group for a total duration of 8 min when compared to the pre-CRAC intervention knee extension angle measurements between groups. Very few studies have specifically investigated the duration of effect of acute stretch intervention such as static {22} and PNF {106}. While DePino et al {22} reported a maximum duration of effect of 3 min, caution must be used when interpreting their results due to methodological flaws such as non-randomisation of the limb receiving intervention (right limb selected as default) and poor control of the thixotropic property of muscle (experimental group participants were allowed to flex the knee between stretches). Spernoga et al {106} effectively isolated the cause and effect relationship of the PNF stretch. This was achieved by having participants lie still in supine for the duration of the repeated flexibility measurements, with the control group lying supine for 5 min longer (the approximate time it took to complete the stretching protocol for the experimental group).

Spernoga et al {106} maintained significantly improved flexibility up to 6 min post-stretch whilst indirectly demonstrating the thixotropic property of muscle as both groups tended towards baseline flexibility after 6 min. There was a significantly greater decrease in hamstring flexibility (measured by degrees of active knee extension) (i.e. beyond baseline flexibility of 40.53° ± 10.97°) noted in the control group after 2 min of inactivity (43.33° ± 11.42°) { 106}. In comparison to the duration of effect results of the abovementioned studies {22, 106}, the duration of stretch effect in this study yielded improved results of 8 min.

The practical relevance of the duration of hamstring CRAC stretch employed in this study means that three repetitions of the stretch (which would take 3 min to perform on a patient/participant) would result in increased flexibility for a minimum time of 8 min. Importantly, this maintained increase in flexibility would occur on a randomly selected leg and in the absence of physical exercise (such as running).

These findings also provide evidence-based clinical application for sports physiotherapists. Due to the limited time allocated for pre-match warm-ups in a variety of sporting codes, the sports Physiotherapist may use the CRAC stretch to effectively increase flexibility in a short period of time (3 min) for a period of 8 min. Similarly, the application of this CRAC stretch during the half-time interval (such as in football or rugby) may be used to increase hamstring flexibility, if deemed necessary by the physiotherapist's assessment. Considering the nature of running-based sports such as football, rugby or field hockey, it is postulated that the duration of effect of hamstring CRAC may be prolonged (i.e. longer than 8 min) as players are rarely required to be inactive for 8 min during pre-match warm-up as compared to the study design (Session 3). This hypothesis is based on the thixotropic properties of muscle tissue discussed below. However, as this is a hypothesis, further studies are required to compare the effects of this hamstring CRAC protocol on flexibility during pre-match and post-match warm-up. The use of active knee extension in this study as a measure of flexibility lends credibility for the use of this stretch protocol in sport, as measures of active flexibility are more relevant than passive flexibility on the field of play.

5.5 Thixotropy

There were significant increases immediately post-intervention in knee extension angles of both the "control" and "thixotropic" leg within the experimental group compared to those within the control group (Figure 4.6, page 92). To prevent possible bias or confounding effect, the leg chosen for repeated measures ("thixotropic" leg) was randomly selected. Knee extension angle was recorded at specifically timed intervals (at 0, 2, 4, 6, 8, 15 and 20 min). There was no significant main effect over time within and between groups. Therefore, the effect of hamstring CRAC stretch on flexibility tended towards baseline flexibility values over time for both groups. The subsiding flexibility effect occurred despite the initial significant increase in knee extension angle in the experimental group for both the "control" and "thixotropic" leg. This effect was credited to the limitation imposed on muscular activity (supine lying) during the repeated measurement intervals.

These results demonstrated the effect of thixotropy during which insufficient muscular activity post-intervention causes the muscle to return to a stiffer gel-like state as compared to its initial liquid-like state following motion {106}. The results of this study are consistent with findings regarding the phenomenon of thixotropy in previous studies {22, 106, 122}.

The findings regarding hamstring thixotropy after CRAC stretching are clinically relevant to physiotherapists involved in various sporting codes. Considering the effect of flexibility subsiding to baseline values over 20 min, the hamstring CRAC stretch should be followed by warm-up procedures within 20 min of stretch application. Similarly, the use of specific exercises as selected by the physiotherapist to maximise the benefit of the increased active ROM following hamstring CRAC stretching should be performed within 20 min of stretch application. Based on the duration of effect of hamstring CRAC results discussed above, optimal timing of performance for such warm-up or therapeutic exercises would be within 8 min of stretch application.

6 SUMMARY AND CONCLUSION

Human athletic performance consists of many broad components such as speed, power, endurance and agility. In the context of sport, the combination of these components is common in sport-specific drills such as side-stepping in rugby (agility and speed) or beating a defender with a turn and breaking towards goal in football (speed, agility and endurance). Despite the complex nature of these sport-specific drills, muscle performance during these tasks is a common predictor of athletic ability. Previous studies have measured muscle performance by analysing properties such as flexibility, strength and power output {6, 31, 47, 65}. These measures are isolated to the primary muscle group used in a specific activity. In the context of sport, the hamstring muscle group has been extensively studied in a variety of codes such as rugby, football, cricket and basketball. The focus on the hamstring muscle is especially important to sports physiotherapy and sports medicine professionals considering the high rate of strain recurrence and time taken for the athlete to recover from injury {18, 80}. One of the predisposing factors of hamstring strain is a lack of flexibility, for which stretching is usually prescribed {61}. The relationship between increased risk of hamstring strain and decreased flexibility has been documented {20, 49, 50, 126}. Furthermore, the nature and risk of hamstring strains in a variety of sporting codes has also been described {9, 10, 26, 114, 128}. Despite the evidence provided in the abovementioned studies, there is scarce scientific knowledge regarding the effect of a CRAC stretch on speed and agility as components of athletic performance. Previous studies using static stretch interventions have produced negative results on measures of exercise performance {96, 107}.

Thus, considering the lack of evidence, the primary aim of this study was to investigate the effects of a hamstring CRAC intervention on sprint and agility performance in moderately active males. The specific objectives as described in Section 1.3.2 (page 3), may be answered as follows:

To determine differences in hamstring flexibility, agility and sprint performance between an experimental group that performed a CRAC stretch and a control group that received no intervention.

In this study, there was a significant improvement in the percentage change of hamstring flexibility post-CRAC intervention in the experimental group compared to the control group. This further illustrates the cause-effect relationship between stretching and flexibility (as measured by active range of motion in this study). There were no significant differences in the percentage change of agility, 10 m and 25 m sprint times between groups. These findings are in contrast to previous studies by Sayers et al {96} and Stewart et al {107}, who found the effect of an acute static stretching protocol on speed to be detrimental. While it may be inferred that CRAC intervention may not have a negative impact on these markers of athletic performance, it is recommended that further studies be conducted using electronic timing to ensure greater precision. Despite the sample size ensuring statistically significant results and adequate power in this study, it is recommended that the sample group in future studies should be further stratified according to predominant method of training (for example, rugby players only) to control the effect of training-specific adaptations.

To determine the duration of effect of a CRAC stretch on hamstring flexibility in the experimental group, compared to the control group that received no intervention.

In this study, there was an increase in hamstring flexibility which remained significantly elevated for a total duration of 8 min in the experimental group compared to the control group. The duration of effect of the CRAC stretch used in this study produced greater results compared to static stretching (3 min) {22} as well as hold-relax PNF stretching (6 min) {106}.

With regard to hamstring flexibility following the CRAC stretch used in this study, the clinical implication is that a set of three repetitions applied to either leg of a similar individual will result in an expected increase of up to 36.7% in active knee extension ROM. The practical recommendation for sports physiotherapists is the use of the CRAC stretch to increase hamstring flexibility of athletes both effectively and quickly, provided that it is deemed necessary and beneficial by an initial assessment.

The thixotropic property of muscle tissue refers to the ability of muscle to become more liquid-like after motion and the ability to return to a stiffer, gel-like condition after rest. In the context of this study, the stationary cycle warm-up and CRAC stretch protocol affected the thixotropic property of the hamstring muscle group. In contrast, rest in supine lying after these interventions served as a method of returning the muscle to a stiffer state as a form of thixotropic control. The clinical implication of the sustained duration of CRAC effect is that even with thixotropic control, such as rest in supine lying, the individual upon which the CRAC intervention is applied will sustain an increased active knee ROM and hamstring flexibility for a maximum duration of 8 min. Due to the limited time allocated for pre-match warm-ups in a variety of sporting codes, a practical recommendation for the sports physiotherapist is the use the CRAC stretch to effectively increase flexibility in a short period of time (3 min) for a period of 8 min. Similarly, the use of this CRAC stretch during the half-time interval (such as in football or rugby) can be used to increase or maintain increased hamstring flexibility, as deemed necessary by the physiotherapist's assessment.

The practical recommendation for sports physiotherapists regarding hamstring thixotropy after CRAC stretching is to follow stretch application with warm-up procedures within 20 min. Similarly, the use of specific exercises as selected by the physiotherapist to maximise the benefit of the increased active ROM following hamstring CRAC stretching should be performed within 20 min of stretch application. Based on the duration of effect of hamstring CRAC results discussed above, optimal timing of performance for such warm-up or therapeutic exercises would be within 8 min of stretch application.

While the effect of CRAC stretching did not produce detrimental effects on agility and sprint performance, the credibility for its use in performance enhancement in sport cannot be made from this study due to inconclusive evidence. It is recommended that future studies re-evaluate the effect of hamstring CRAC on functional measures of exercise performance such as agility and sprinting. Future studies should also investigate chronic adaptations following regular, long-term hamstring CRAC stretching and examine these effects on sprinting and agility tests in comparison to the effects of acute CRAC applications, such as the intervention used in this study.

Further studies are required to investigate the possible sports-specific changes in pre- and post-match warm-up flexibility following hamstring CRAC stretch performed before warm-up. In addition, it is recommended that future studies investigate the specific duration of possible stretch-induced deficits in muscle performance following hamstring CRAC stretching compared to other forms of PNF stretching. These studies would add much needed scientific evidence in the field of exercise performance enhancement using PNF stretching. Considering the effect of sport-specific adaptation, it is recommended that for future studies, participants recruited should be from a specific sporting code and matched according to body mass and competitive level within the sport. This will control potential variability in exercise performance between participants, especially in study protocols that require maximal voluntary effort over short durations such as sprinting and agility testing.

Based on the results of this study, should greater hamstring flexibility be required, CRAC should be the method of choice as it is an effective, time-efficient method that does not have a detrimental effect on exercise performance.

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8 APPENDICES

APPENDIX I: INFORMED CONSENT FORMS

Dear Participant,

The U.C.T Division of Physiotherapy will be conducting a study to determine the effect of a stretch called a CRAC (contract-relax-agonist-contract) on hamstring length – how long the effect lasts and its effect on athletic performance. Information gained from this study will be used by the M.Phil Sports Physiotherapy student for the final year thesis. You will be asked to attend a total of 3 appointments (on alternate days) over the course of 1 week. Note that participation in this study is voluntary (there will be no remuneration for participating) and all information given as well as the results of the study will remain confidential. Please take time to read this form thoroughly before signing.

On the first appointment:

1. You will to be asked to complete a 4 page questionnaire regarding your physical activity levels as well as sport, injury and health history and will then be randomly assigned to a testing group.
2. Hamstring flexibility will also be measured using an inclinometer.
3. You will be required to rest for 30 minutes, during which the hamstring stretch technique and a summary of the testing procedure, will be taught via a video demonstration, verbal discussion and an information pamphlet.
4. This will be followed by a 5 minute warm-up on a cycle ergometer and then the Illinois agility test and sprint test, which you will be asked to perform twice.
5. The session ends with a hamstring flexibility measurement. The total time required for this first visit is approximately 50 minutes.

On subsequent appointments: (Total duration-approximately 45 minutes)

6. Hamstring flexibility will be measured again.
7. You will be taken through the warm-up.
9. Participants placed in the experiment group will then be given the hamstring stretch, whilst those in the control group will rest for 5 – 6 minutes.
10. Performance testing which involves the Illinois agility test and sprint test will commence and each participant will be required to perform 2 repetitions of each test, the best time of the 2 trials will be recorded and the session ends with a hamstring length measurement.
11. Duration testing occurs on the final visit, which involves the exact same procedures (6 – 9) but substitutes (10) with repeating the hamstring length measurement 6 times on one leg over a period of 30 minutes.

Potential Risks:

1. It should be noted that your warm-up routine will be altered and this may not suit all the participants.
2. Any stretch technique that is performed incorrectly can predispose to injury. Therefore you will be supervised and facilitated by an individual experienced in this field to ensure that it is performed correctly.

Benefits:

You will receive a detailed pamphlet containing information about the stretch used in the study and advice regarding stretching. You will be given details regarding your performance on a regular basis. On completion of the study, the summarised results and recommendations will be formally presented to you. Through involvement in the study, you will have contributed to scientific knowledge and evidence in an area that is in need of much research.

Questions or Concerns:

If at any time you have any questions about the study please feel free to contact any of the individuals listed below. You are assured that all enquiries will remain confidential.

Timothy Vadachalam	084 378 0588
Theresa Burgess	021 406 6171
Prof. J. Jelsma	021 406 6595

Should you have any further queries, feel free to contact:

Ms. T. Burgess or Prof. J. Jelsma

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By placing your signature below it serves as confirmation that you have had adequate time to read through and have understood the consent form and that you are willing to participate in this study, aware of your right to withdraw at any time, that you may ask questions at any time during the study and that you are aware that all the information recorded is confidential. Your signature is further confirmation that you are aware of the possible risks involved in this study, and that there is no remuneration for participating in this study. Please note that UCT does offer a no-fault insurance that will cover all participants in the event that something may go wrong.

____________________	____________________________	____________
Signature of Volunteer	Name (Please Print)	Date
____________________	____________________________	____________
Signature of Witness	Name (Please Print)	Date
____________________	____________________________	____________
Signature of Investigator	Name (Please Print)	Date

APPENDIX II: DEMOGRAPHIC QUESTIONNAIRE

University of Cape Town Physiotherapy Study

Instructions:

- This questionnaire consists of 4 pages
- Note that your participation in this study is voluntary (there will be no remuneration for your participation).
- Please read each question carefully as it is important that we obtain accurate information.
- Please place information in the appropriate text box e.g. Date of Birth

  21/03/1983 Day/Month/Year

- If a question is asked, please place an **'x'** in the appropriate text box.

  For example: Which province do you live in?

  ☐ Limpopo ☒ Western Province ☐ Free State ☐ Kwa-Zulu Natal

- Please answer all questions as truthfully as possible. The information gathered will be used in the study but will remain strictly anonymous.
- If you have any questions do not hesitate to phone or e-mail any of the individuals below:

  Timothy Vadachalam 084 378 0588 / timv@vodamail.co.za

  Theresa Burgess 021 406 6171

  083 300 4991 / theresa.burgess@uct.ac.za

Prof. J. Jelsma 021 406 6595 / jennifer.jelsma@uct.ac.za

Name: ____

Surname: ____

Age: ____

Date of Birth: ___/____/_____

Have you been injured in the past 6 months?

____

____

If yes what type of injury? i.e.: muscle pulled, broken bone, ligament damage

____

____

Where was/is the injury? I.e.: Left leg, left hand, right knee

____

How did the injury occur? During your usual exercise routine or other activity

____

____

____

Have you had any physiotherapy or massage treatment in the last 6 months? If yes please specify.

____

____

____

Do you have any previous surgical history?

☐ Cardiac Surgery

☐ Spinal Surgery

☐ Other

☐ Fractures

Please specify where: ____

____

Have you been ill in the past 3 weeks? If so, what illness was/ is it? E.g. cold, flu, measles

____

____

If you answered “Yes” above, did you take any medication for the illness? What was it called?

____

____

____

____

Is there any medication that you take regularly to manage pain/injuries e.g.: paracetamol, anti-inflammatories?

____

Have you ever been diagnosed with any of these disorders?

☐ Coronary Heart Disease

☐ Diabetes

☐ Thyroid Disease

☐ Allergies:__________

☐ Tuberculosis

☐ Osteoarthritis

☐ High Cholesterol

☐ Asthma

☐ Rheumatoid Arthritis

☐ Renal Disease

☐ High Blood Pressure

☐ Osteoporosis

☐ Cancer

☐ Stroke

Other (please specify):

____

____

Please indicate, using the numbered sporting activity key, what physical, extra curricula activities you participate in, along with the amount of time and how often a week you participate in this activity. If none of the examples below is applicable please fill in your activity in the space provided.

Type of sport	Months per year (months/ year)	Number of sessions per week	Duration of each session (hour: min)	Total hours per week (hours/ week)

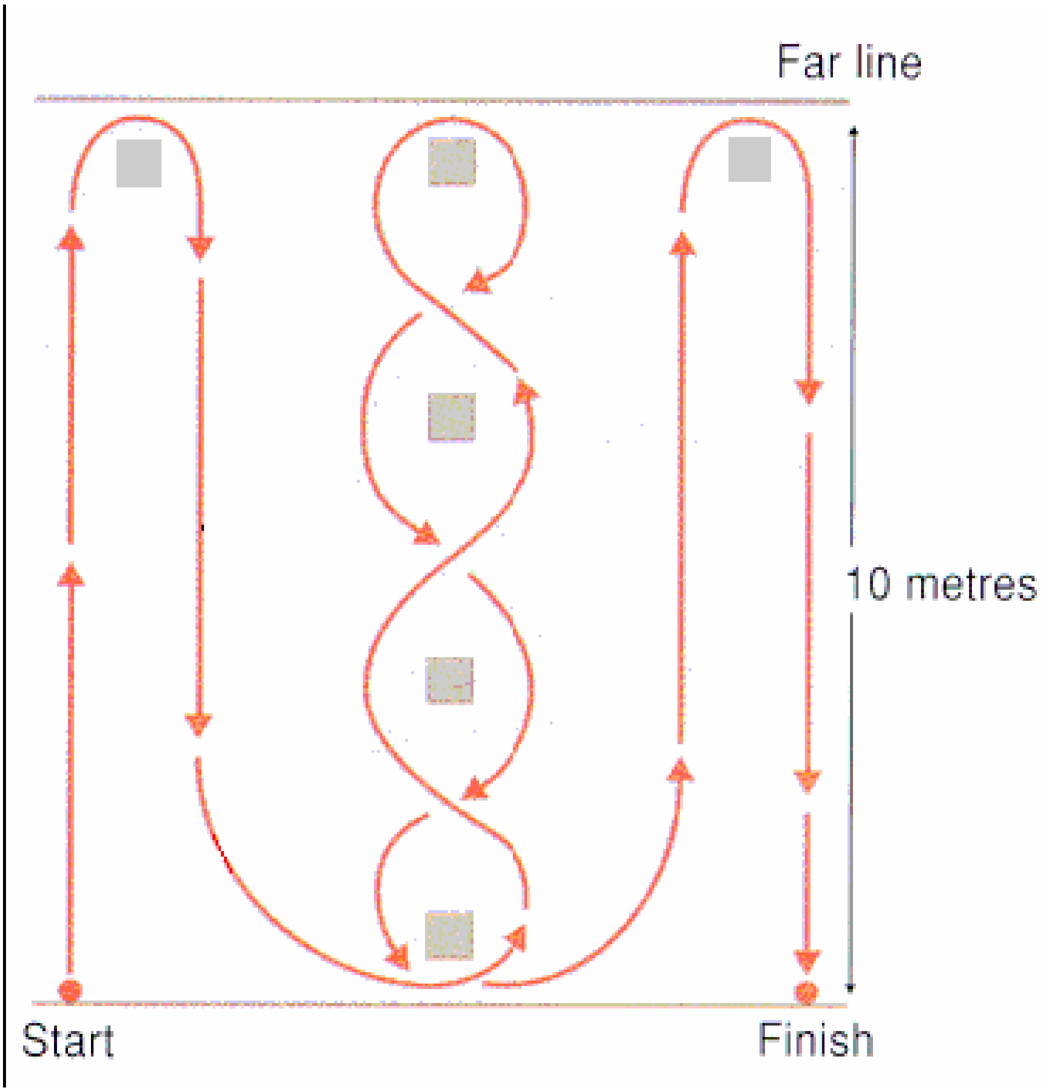
Examples of sporting activities:

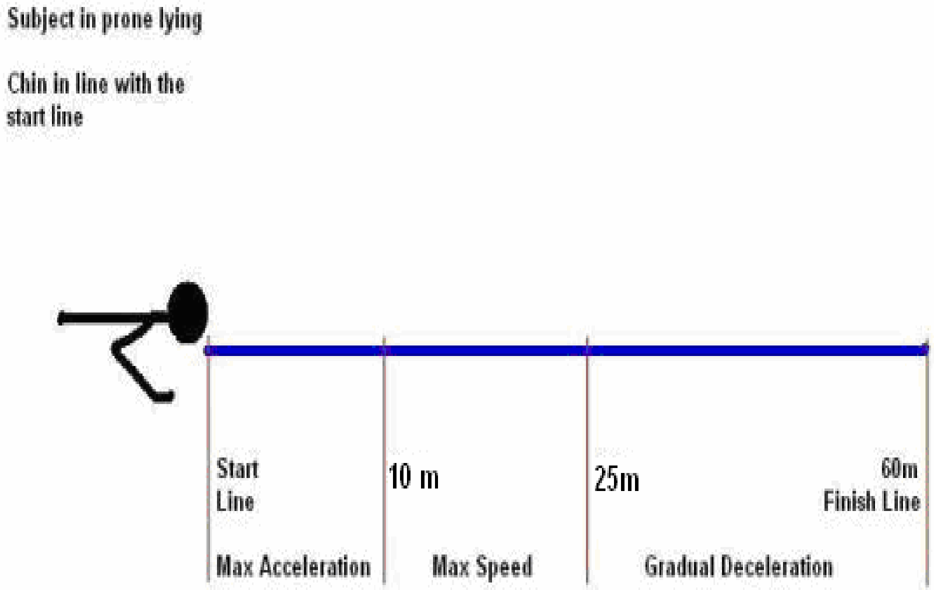
1. Hockey
2. Gym
3. Martial arts
4. Volleyball
5. Strength/ Resistance Training
6. Hiking
7. Golf
8. Canoeing
9. Dancing
10. Skating
11. Jogging
12. Squash
13. Tennis
14. Badminton
15. Horse riding
16. Swimming
17. Cycling
18. Walking
19. Basketball
20. Soccer
21. Athletics

Participants Signature:______________________________Date:_______________

Participants Contact Details:____

APPENDIX III: ILLINOIS TEST OF AGILITY AND SPRINT TEST




Subject in prone lying
Chin in line with the start line
Start Line
10 m
25m
60m Finish Line
Max Acceleration
Max Speed
Gradual Deceleration

APPENDIX IV: ETHICAL APPROVAL

UNIVERSITY OF CAPE TOWN

Health Sciences Faculty
Research Ethics Committee
Room E52-24 Groote Schuur Hospital Old Main Building
Observatory 7925
Telephone [021] 406 6338 • **Facsimile** [021] 406 6411
e-mail: sumayah.ariefdien@uct.ac.za

01 June 2009

REC REF: 200/2009

Mr T Vadachalam
Physiotherapy

Dear Mr Vadachalam

PROJECT TITLE: THE EFFECT OF A HAMSTRING CONTRACT RELAX AGONIST CONTRACT INTERVENTION ON SPRINT AND AGILITY PERFORMANCE IN MODERATELY ACTIVE MALES.

Thank you for submitting your study to the Research Ethics Committee for review.

Before formal approval is granted please could you address the following:-

- Please indicate in the consent and subject information sheets that participants will not receive any remuneration for taking part.
- Please note that the latest version of the Helsinki Declaration is 2008.

Please note that the ongoing ethical conduct of the study remains the responsibility of the principal investigator.

Please quote the REC. REF in all your correspondence.

Yours sincerely

PROFESSOR M BLOCKMAN
CHAIRPERSON, HSF HUMAN ETHICS

sariefdien