Effects of High-intensity Static Stretching on Range of Motion, Performance, Muscle Activation and Architecture

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Abstract

The acute effects of static stretching on strength and power are conflicting as research has shown that it can reduce strength and power or have no effect. A variable of static stretching that has received little attention is the intensity of static stretching.

The first study within this thesis was a systematic review of 18 studies which examined the effects of different intensities of static stretching on ROM, strength and power. The findings revealed conflicting results. ROM increased no matter the intensity, some studies showed that strength and power decreased regardless of static stretch intensity, and some showed that high intensities led to a greater decrease. It was also revealed that there were methodological inconsistencies between the studies on how they measure the intensity of the static stretches.

The following study within this thesis was a questionnaire to examine the current practices athletes and coaches participating in sport in the UK on their use of static stretching and specifically static stretching intensity. Results from the questionnaire of 147 athletes and 19 coaches revealed that static stretching prior to sport performance is still undertaken despite recommendations from previous research (78%). In addition, to the author's knowledge this is the first study to investigate if the intensity of static stretching is considered within sport in the UK. It was shown that athletes are less likely to consider the intensity of stretches (68%) whereas coaches are more likely to consider it when programming static stretching exercises for their athletes (70%). This study also showed that there is a variety of methods of measuring the intensity of static stretches and is often not considered by athletes due to this reason.

The following study presented in this thesis aimed to examine the reliability of a 120% point of discomfort static stretch of the hamstrings as a high-intensity static stretch. Results showed that this was a reliable method of generating a high-intensity static stretch when compared to subjective discomfort ratings. In addition, knee extension ROM increased pre to post ($p=0.043$) and knee flexion MVIC was decreased following the high-intensity static stretch intervention ($p=0.02$), however, hamstring passive stiffness and single leg jump power remained unchanged.

The final study within this thesis aimed to build on the findings from the previous study and compare different durations and intensities of static stretching (100%*30s, 120%*30s, 120%*60s) on hamstring range of motion, strength, power, muscle architecture and muscle activation via surface electrical myography (EMG). The results showed that all three conditions led to increases in knee extension ROM with a greater increase occurring following the 120%*60s condition ($p=0.024$). None of the conditions led to changes to knee flexion MVIC or single leg jump power. Furthermore, there were no changes following any of the stretch conditions on EMG and muscle architecture.

In conclusion, performing a 120% static stretch of the hamstring is a reliable method of generating a high-intensity static stretch and is also a reliable method of increasing knee extension ROM. No conclusions can be made on the effects of high-intensity static stretching on strength, power, EMG, fascicle length and angles results have differed across the studies presented within this thesis.

List of Publications

The following manuscripts have been published in peer-reviewed journals:

Bryant, J., Cooper, D.J., Peters, D.M. and Cook, M.D. (2023). The Effects of Static Stretching Intensity on Range of Motion and Strength: A Systematic Review. J Funct Morphol Kinesiol. 8(2):37. doi: 10.3390/jfmk8020037.

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Manuscripts in preparation

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Bryant, J., Cooper, D.J., Peters, D.M. and Cook, M.D. A survey on the static stretching practices of coaches and athletes of different sports and competition levels within the UK.

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Declaration of Authorship

I, Joseph Bryant, declare that the thesis entitled:

Effects of High-intensity Static Stretching on Range of Motion, Performance, Muscle Activation and Architecture

and the work presented in the thesis are both my own and have been generated by me as the result of my own original research. I confirm that:

- this work was done wholly or mainly while in candidature for a research degree at this University;
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- parts of this work have been published as journal articles and conferences abstracts which are listed above.

Signed:

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Abbreviations

1RM	One Repetition Maximum
ACSM	American College of Sports Medicine
ADP	Adenosine Diphosphate
ATP	Adenosine Triphosphate
Ca^{2+}	Calcium Ion
CMJ	Countermovement Jump
DCER	Dynamic Constant External Resistance
ECC	Excitation-Contraction Coupling
ECSS	European College of Sport Science
EMG	Electromyography
GTO	Golgi Tendon Organ
ITT	Interpolated Twitch Technique
MEP	Motor Evoked Potential
MTJ	Musculotendinous Junction
MTU	Musculotendon Unit
MVC	Maximal Voluntary Contraction
MVCC	Maximal Voluntary Concentric Contraction
MVIC	Maximal Voluntary Isometric Contraction
NCAA	National Collegiate Athletics Association
NRS	Numerical Rating Scale
PEDRO	The Physiotherapy Evidence Database
PIC	Persistent Inward Currents
PICOS	Participants, Interventions, Comparisons, Outcomes and Study design
PNF	Proprioceptive Neuromuscular Facilitation
PoD	Point of Discomfort
PoP	Point of Pain
PRISMA	Preferred Reporting Items for Systematic Review and Meta-analysis
RFE	Residual Force Enhancement
RMS	Root Mean Squared
ROM	Range of Motion
RPE	Rate of Perceived Exertion
VAS	Visual Analog Scale

1 Introduction

Stretching is a common activity performed across the spectrum of performance from recreationally active people to elite athletes. Coaches and fitness professionals also prescribe stretching to improve flexibility, sports performance, reduce muscle soreness or prevent or rehabilitate an injury (Page, 2012).

Stretching practices have been used for millennia, some yoga stretches are believed to be around 5000 years old, warriors in ancient Greece were said to perform stretch-like exercises before going into battle (Kunitz, 2016) and martial artists have been observed performing stretching exercises to be able to reach extreme ranges of motion for kicks (Draeger & Smith, 1969; Behm, 2018). During the Second World War, soldiers were instructed to stretch to improve flexibility which would 'reduce resistance to movement' thus improving the performance of the muscles (Delorme, 1945; Delorme *et al.* 1952).

Stretching is primarily used to increase flexibility and joint range of motion; these terms are often used interchangeably yet have different definitions. Flexibility is the ability of the soft tissue structures such as muscles, tendons and connective tissue to elongate through the range of motion of the joint (Zachazewski, 1989; Konin *et al.* 2012). ROM on the other hand, is the degree of movement that can occur at a particular joint (Haff and Triplett, 2016; Keogh *et al*. 2019), this has been defined further to include functional ROM which is the required ROM needed for individuals to carry out movements and activities of daily life (Doğan *et al.* 2019). Improving flexibility and ROM is believed to enhance aspects of muscle performance such as strength and power because it improves "muscle compliance" which aids in force absorption (Noonan *et al.* 1993; Magnusson and Renström, 2006). However, Ingraham, (2003) suggested that athletes only need the range of motion required for their sport.

There are several types of stretching, the main three are static, dynamic and proprioceptive neuromuscular facilitation (PNF) stretching (Thomas *et al.* 2021). Static stretching and its effects on strength and power will be the focus of this PhD thesis. Static stretching has been shown to be a successful method of increasing flexibility and ROM (Medeiros *et al*. 2016) however, its effects on strength and power are currently conflicting and contradictory. Static stretching immediately before strength and power exercises such as maximal voluntary contractions (MVC), sprinting and vertical jump has had varied research results. Many have shown that static stretching may lead to a decrease in strength or power, known as the stretch-induced force loss (Simic, Sarabon and Markovic, 2013). Further research has examined the duration of the static stretching on subsequent strength and power performance has shown that static stretches held for shorter durations (<30 seconds) do not lead to the stretch-induced force loss (Behm *et al.* 2015a). Further contradiction arises when static stretching is performed with a full dynamic warm-up which has been shown to attenuate any possible negative effects following static stretching (Stevanovic *et al.* 2019). In addition, the effects of static stretching before strength and power performances may vary between different levels of training status of individuals, for example, those who are already flexible, such as gymnasts and dancers, may not experience decreases in strength and power following static stretching (Dalrymple *et al.* 2010).

Some variation in results in studies that have examined the effects of static stretching on strength and power could be due to the proximity the performance measures take place following the static stretch intervention. The term used is 'acute effects' however, studies have used different times between the stretch intervention and the post stretch performance measures. Ryan *et al.* (2008) and Mizuno *et al.* (2014) both found that plantar flexion strength decreases immediately following static stretching but recovers within ten minutes. Nakamura *et al.* (2022) demonstrated similar findings for the hamstrings, observing that knee flexion MVIC decreases immediately following static stretching and trends towards recovering after ten minutes and fully recovering after 20 minutes. Furthermore, Haddad et al (2014) found that power could be impaired for up to 24 hours following static stretching. Studies within this thesis will aim to undertake post stretch performance measures immediately following the static stretching interventions.

A variable of static stretching which has seldom been researched is the intensity of the stretch, static stretching intensity currently has two definitions, Jacobs and Sciascia, (2011) defined stretch intensity as: "*the magnitude of force or torque applied to the joint during a stretching exercise*." Freitas *et al.* (2015) defined it as: "*the degree of muscle-tendon lengthening induced by a change in joint range of motion*." This is the definition that will be used throughout this thesis. Static stretching to different levels of intensity may lead to different responses, acute static stretching to a higher intensity has been shown to lead to greater increases in ROM, however, high-intensity static stretching on strength and power has shown negative results Kataura *et al*. 2017, or a positive effect (Takeuchi and Nakamura, 2020). Kataura *et al.* (2017) examined different static stretching intensities on hamstring isometric muscle force, results showed that the highest intensity used (120% of ROM measurement) resulted in a greater decrease in isometric muscle force compared to lower intensities of 80% and 100% of ROM measurement. Conversely, Takeuchi & Nakamura (2020) examined high-intensity stretching on hamstring peak torque during knee flexion and found that the high-intensity stretch did not affect the peak torque. With regards to chronic effects of different intensities of static stretching studies have shown no difference on strength and power (Muanjai *et al.* 2017; Melo, 2021).

Only a small amount of research has currently been undertaken on the effects of different static stretching intensities on strength and power, this is possibly due to a lack of a universal method of measuring the stretch intensity. For example, some studies have achieved a specific stretch intensity by using a percentage of the participants' pre-stretch ROM score (Kataura *et al.*, 2017, Takeuchi *et al.* 2020), some have used numerical rating scales from 0 to 10 (Rodriques *et al.* 2017, Santos *et al.* 2020), requiring participants to assess the stretch themselves to a given number and one study had participants simply stretch to a self-assessed point of discomfort (PoD) or point of pain (PoP) (Muanjai *et al.* 2017). It is difficult to identify a universal method of measuring the intensity of a static stretch due to the subjective nature of ROM and individuals' subjective pain thresholds. Furthermore, research examining the effects of static stretching intensity is relatively recent, with the first investigation occurring from 2007, therefore, it is likely that there have not been enough investigations to identify a reliable or universal method for measuring or reporting of static stretching intensity.

Static stretching has been theorised to affect muscle architecture, which is the physical structure of the muscles, consisting of the total muscle length, muscle fascicle length, pennation angle and cross-sectional area (Wickiewicz *et al.* 1983). For example, longer fascicle lengths and smaller pennation angles of the Vastus Lateralis of female sprinters are associated with greater power output (Wakahara *et al.* 2013). Alterations to muscle architecture are often achieved through resistance training, however, it is theorised that static stretching may lead to similar changes to the muscle that are observed following resistance training (Mohamed *et al.* 2011). Results are currently varied, Mizuno (2019) observed an increase in plantar flexion strength and an increase in muscle thickness following an eight-week static stretching programme and Panidi *et al.* (2021) observed an increase in unilateral countermovement jump height and an increase in gastrocnemius cross-sectional area. Alternatively, recent studies have shown that static stretching programmes of varying durations on the plantar flexor muscles did not lead to increases in strength or changes to muscle architecture (Sato *et al.* 2020, Yahata *et al.* 2021, Longo *et al.* 2021; Sato *et al.* 2020) also suggested that static stretching to a higher intensity may lead to changes in muscle architecture and thus increases in strength.

Numerous studies have shown that static stretching is utilised in sport and fitness (Judge *et al.* 2013, Babault *et al.* 2021), however, it is unknown if the intensity of static stretching is considered by sports coaches, strength and conditioning coaches and athletes.

1.1 Aims of Thesis Chapters

The aims of this thesis included investigating the acute effects of high-intensity static stretching on performance measures of range of motion, strength and power. This thesis also aimed to investigate current static stretching practices amongst athletes and coaches, to examine the reliability of a high-intensity static stretch protocol and to compare two stretch intensities on ROM, strength and power to investigate the relationship between stretch intensity and stretch duration. The aims of each study chapter of this thesis are:

1. To systematically review the current literature on the effects of different static stretching intensities on ROM, strength and power (Chapter 4).

2. To explore static stretching practices amongst athletes and coaches, and if these groups consider static stretching intensity when undertaking static stretching (Chapter 5).

3. To examine the reliability of 120% point of discomfort as a high-intensity static stretching and the effects on ROM, strength and power (Chapter 6).

4. To compare higher and lower intensity static stretches on ROM, strength and power, and to investigate a possible relationship between stretch intensity and duration. In addition, this study examined the effects of stretching on muscle architecture and muscle activation (Chapter 7).

2 Literature review

2.1 Physiology of muscle contractile elements during stretching

Muscle is made up of muscle fibres, each muscle fibre is composed of bundles of myofibrils, which are made up of sarcomeres arranged in series (Mukund and Subramaniam, 2020).

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Figure 2.1 Longitudinal sections of the human vastus lateralis (Hortobagyi et al. 1998).

The sarcomere comprises two main sets of alternating protein filaments, thin filaments known as actin and thick filaments called myosin, which run parallel to the muscle fibre axis. Each sarcomere is separated from the next by a dark line called the Z-line or Z-disk. In the middle of the sarcomere is the A-band which is the area in which the thin and thick filaments overlap, inside this is the H-zone which is an area of thick filaments with no thin filaments, at the centre of the H-zone runs a line called the M-line which indicates the centre of the sarcomere. On either side of the A-band are I-bands which are sections of thin filaments with no thick filament overlap (Huxley, 1957; Mukund and Subramaniam, 2020), this is presented in Figure 2.1 (Hortobagyi *et al.* 1998).

The primary role of sarcomeres is force generation which brings about contraction of the muscle and thus movement. Muscle contraction starts with the binding of Troponin-C with a calcium ion (Ca^{2+}) released during excitation-contraction coupling (ECC). This causes a conformational change in the troponin-tropomyosin complex which exposes myosin binding sites on the actin filament. This allows for the cross-bridge cycle to take place which is a sequence of enzymatic reactions that cause the movement of myosin heads on the actin filaments (Mukund and Subramaniam, 2020). The cross-bridge theory was first proposed by Huxley in 1957 who theorised that 'cross-bridges' extend from the myosin filaments towards the actin filaments. The theory can be broken down into several steps. Once the myosin binding sites on the actin filament have been exposed, the myosin heads "swing" out towards the actin filament at a 45º angle in a rigour (stiff) state. Available adenosine triphosphate (ATP) molecules bind to the myosin, briefly separating myosin from actin. The ATPase enzyme activity of myosin separates ATP into Adenosine Diphosphate (ADP) and a free phosphate molecule (Pi). This causes the myosin filament to rebind weakly to actin at the 90º angle relative to the actin, this is the cross-bridge. The release of the Pi molecule initiates what is called the power stroke. This involves the myosin heads rotating on its hinge which pushes the actin filament past it, towards the M-band in the middle of the sarcomere. At the end of the power stroke, myosin heads release ADP and regain its rigour state (Fitts, 2008). When several of these cross-bridges interact and slide actin filaments over the myosin filament in many sarcomeres at the same time, the myofibril bundles contract (shorten) which causes the muscle fibres as a whole contract and thus creates movement of the body (Rassier, 2017).

The cross-bridge and sliding filament theories help describe the process of muscle contraction through shortening, however, stretching involves lengthening of the muscle. This can be achieved in two ways. The first is through active tension or lengthening, sometimes referred to as active stretching, of the muscle through the interaction of actin and myosin filaments (Knudson, 2006), instead of contracting and overlapping to generate force, the filaments are stretched away, reducing any overlap between the filaments and thus reducing the amount of force a muscle can produce. The effect of a muscle being lengthened and reducing its force-generating capabilities is known as the length-tension relationship.

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Figure 2.2 Force-length relationship of frog skeletal muscle sarcomere as derived first by Gordon *et al.* (1966) (top) and schematic sarcomeres corresponding to crucial points (1-5) labelled on the force-length curve (bottom) (Rassier, Macintosh and Herzog, 1999).

Active tension is produced by an individual actively stretching a certain muscle. The second is passive tension or lengthening, sometimes referred to as passive stretching. This is without any activity of the actin and myosin filaments, passive lengthening is done through an interaction of something external to the body which causes the stretch, for example, another person pushing another's limb to force a stretch.

Furthennore, muscle fibres possess viscoelastic properties which means they display both viscous and elastic properties during defonnation or moving. If a constant force is applied to a muscle, the length will slowly but constantly increase, known as creep, when the muscle is sti·etched to a ce1iain length and held in that position, the force on the muscle gradually declines, once the force is removed completely the muscle will slowly return to its nonnal length, this whole sti·etching action is known as the sti·ess-sti·ain curve (Shrier and Gossal, 2000).

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Figure 2.3 Typical stress-su-ain cmve for desti11ctive tensile testing of skeletal soft tissues. Collagen fibril sti·aightening and failure, related to different regions of the sti·ess-sti·ain cmve (Korhonen. and Saarakkala, 2011).

When a muscle is lengthened passively, without any active conti·action, the sti·etch reflex (myotatic reflex) senses the change in length by automatically increasing the muscle conu-actility and keeping the muscle su-etched within the physiological limits (Bhatta.charyya, 2017). Specialised proprioceptors known as muscle spindles located within the muscle fibres are su-etched when the muscle is sti·etched, the neural firing of muscle spindle afferents is increased which increases alpha motor neuron activity causing the muscle fibres to conn-act and resist the su-etch. Another set of neurons directs the antagonistic muscles to relax through a mechanism called reciprocal inhibition, this helps maintain the muscle at a constant length. Gamma motor neurons then regulate the sensitivity of the sti·etch reflex (Bhattachaiyaa, 2017). Another proprioceptor involved in conu-olling muscle conti·action and lengthening is the Golgi tendon organ (GTO). As the naine suggests, these are located within the tendons, neai·to where it meets the muscle, an area termed the musculotendinous junction (MTJ). The GTO is a multiple-branched sensory ending enclosed in a connective tissue capsule.

Unlike the muscle spindles that detect changes in muscle length, the GTO detects changes in muscle tension (Morimoto *et al.* 1993). Both the muscle spindles and the GTOs detect the changes, sending afferent signals to protect from over stretching and causing injury. The sliding filament cross-bridge theory does not account for eccentric or lengthening contractions or stretching beyond a certain resting length. Isometric steady-state force generated by an active muscle should be proportional to the number of cross-bridges that can form, which corresponds to the amount of overlap between thick and thin filaments (Huxley & Niedergerke, 1954), this was termed the force-sarcomere length relationship (Gordon, 1966). However, during eccentric or lengthening contraction, the isometric steady-state force produced at a given sarcomere length exceeds the predictions of the force-length relationship (Abbott and Aubert, 1952; Leonard and Herzog, 2010). This was termed the residual force enhancement (RFE), it has been suggested that RFE may be the result of a passive element becoming "engaged" during an active stretch (Edman, Elzinga and Noble, 1982; Herzog *et al.* 2012), this alludes to a passive force contribution in the sarcomeres. RFE increases with increased magnitude of stretch and is greater as the muscle is stretched further on the descending limb of the force-length relationship (Edman, Elzinga and Noble, 1982). A third muscle protein, titin, is responsible for RFE at longer muscle length (Wang *et al.* 1991). Titin was discovered in 1976 (Maruyama, 1976), it spans the half-sarcomere from the M-band to the Z-band. Titin's I-band structure allows for large elongations and passive force production and is described as a 'spring-like' molecule. Just before inserting into the Z-band, titin binds to actin along its most proximal point thereby establishing a "permanent" bridge between actin and myosin (Trombitás & Pollack, 1993): a bridge that is in parallel with the attached cross-bridge and in series with the myosin filament in the passive muscle. Titin is elastic because it contains a sequence of folded domains that can be progressively unfolded with the force of the muscle stretching. Energy stored in titin during stretching will aid during the next contraction of the muscle. The elasticity of titin can be modified naturally by isoform splicing and post-translational modifications at different stages of organism development. The titin-based force has been shown to increase during active compared to passive stretch of mouse Psoas muscle fibres, this modulation of titin-force allows the sarcomere to maintain its force-generating capability during active stretch to lengths beyond filament overlap and provides a protective mechanism within the sarcomere by which active stretch is limited. At sarcomere lengths beyond filament overlap (>4.0μm) cross-bridges cannot form and titin is the only contributor to myofibril force (Herzog *et al.* 2012).

2.2 Types of stretching

There are three main types of stretching that are commonly used which have all been shown to lead to an increase in range of motion (ROM) (Thomas *et al.*, 2018). The most frequently utilised stretching method is static stretching (Weldon *et al.* 2020; Babault *et al.* 2021). This involves taking one or multiple joints to their maximal ROM that the individual can reach as the muscle lengthens and is held in position for 15 seconds or more (Page, 2012; Behm and Chaouachi, 2011b). This type of stretching is common as it is easy to perform, and requires no equipment, however, the effects and benefits have been researched with changing views leading to confusion among strength and conditioning coaches and athletes (Chaabene *et al.* 2019). Static stretching can be further sub-divided into active where the individual performs the stretch themselves and passive which involves another person moving the individual into the stretched position. Previous research has shown that both passive and active static stretching increase ROM with no significant difference between the two types (Nakao et al., 2018), in addition, passive and active static stretching have been shown to reduce power in vertical jump exercises also without differences between them (Carvalho et al., 2012) Passive static stretching will be the focus of this thesis. This is to maintain validity and reliability of the static stretching interventions used with the studies within this thesis.

Dynamic stretching is mostly utilised before exercise as the dynamic movements are alleged to augment performance by raising muscle temperature and potentiating muscle (Hough, Ross and Howatson, 2009; Opplert and Babault, 2018). Dynamic stretching involves the movement of a joint and muscle group through a full ROM in a controlled manner, e.g., walking lunges with a torso twist. There is a sub-type to dynamic stretching known as ballistic stretching which consists of more rapid or bouncing movements, for example, walking lunges with a bouncing motion, these types are often used interchangeably. Previous research on the effects of dynamic and ballistic stretching on strength and power are varied but the majority show that they lead to an increase in strength and power (Herda et al., 2012, Su et al., 2016, Opplert & Babault, 2018).

Another common stretching method is proprioceptive neuromuscular facilitation (PNF) stretching. This method can be separated into three types, the first is contract-relax, which involves contracting the muscle in its lengthened position and then relaxing it while it is passively stretched even further, an example would be a supine straight leg raise to stretch the hamstring. The leg is lifted by another person or a using a band to the max ROM and held for five to 10 seconds, relaxed and then stretched again to a further ROM than the previous stretch. The next method is contract-relax-antagonist-contract which begins the same as contract-relax but then the antagonist's muscle is contracted while the agonist's muscle is being stretched, for example, during a straight leg raise stretch described above, while the hamstring is being stretched, the individual then contracts their hamstrings to try to push the leg back down. The third method is hold-relax which involves holding the stretch for 10-15 seconds, relaxing and then performing the stretch again (Hindle *et al.* 2012).

For this thesis, the effect of static stretching is chosen to be investigated over other types as intensity is easier to control and manipulate and has fewer variables.

2.3 Static Stretching and Range of motion

One of the main reasons for undertaking static stretching is to improve flexibility and range of motion (Weldon *et al.* 2020; Babault *et al.* 2021). Flexibility is defined as the ability of the muscles, tendons and connective tissues to lengthen through the ROM (Zachazewski, 1989), ROM is the available amount of movement around a joint measured in degrees. These terms are often used interchangeably despite having different definitions. Improving flexibility and range of motion is believed to reduce the risk of muscle pulls and strains (Verrall *et al.* 2007) and improve muscle compliance to aid in force absorption which could then improve speed and power (Noonan *et al.* 1993, Magnusson and Renström, 2006). Research has shown that any type of stretching, either static, dynamic or PNF stretching, will lead to an increase in ROM (Medeiros *et al.* 2016).

There are two mechanisms to explain stretching-induced changes in ROM. The first is an increase in stretch tolerance by a neural inhibition effect on the spinal motoneurons. Stretch tolerance is the ability to cope with discomfort and pain experienced during a stretch (Weppler & Magnusson, 2010), if an individual can tolerate a greater stretch this will result in a larger ROM. A neural inhibition on the spinal motor neurons following static stretching is supported by Killen *et al.* (2019). This study examined the effects of 10 sets of 30 seconds (1st set at PoD and sets 2-10 at maximal bearable discomfort) unilateral hamstring passive static stretching of the dominant limb on the hip flexion ROM of the contralateral, unstretched limb, and found a 13.63% increase in the hip flexion ROM of the unstretched limb (pre vs post (mean±SE): 64.7±4.0 vs. 73.5±4.7°, $p<0.001$, $d = 0.42$). The main methods to measure stretch tolerance are to measure passive torque alongside ROM during passive joint movement using an isokinetic dynamometer or to measure a participant's pain experienced during a stretch using a numerical rating system (NRS) or visual analogue scale (VAS).

The second possible mechanism for an increase in ROM from static stretching is increased compliance of the musculotendinous unit (MTU) to lengthen under mechanical tension. For example, Morse *et al.* (2008) found increased compliance of the gastrocnemius muscle complex following dorsiflexion static stretching through a 47% reduction in passive stiffness from 16.0 ± 3.6 to 10.2 ± 2.0 Nm deg^{-1} and a 17% (+4.6±1.5°) increase in dorsiflexion ROM.

Research on how ROM may affect sport performance has suggested that it is sport dependent, for example, dancers and gymnasts require a greater level of flexibility and ROM compared to athletes in other sports (Gleim & McHugh, 1997). Required ROM can also be position-specific, for example, football goal keepers have been found to possess greater ROM of hip and knee flexion and ankle dorsiflexion than players in other positions (Oberg *et al.* 1984). It has been suggested that an athlete only needs to have a functional ROM to be successful in their sport and it is unnecessary to spend too much time stretching and should spend more time practicing the sport-specific movements and skills (Ingraham, 2003).

2.4 Acute effects on strength

Static stretching used to be recommended to perform before exercise within a warm-up to reduce muscle tension and increase 'freedom of movement' which was thought to increase strength and power (Smith *et al.* 1994; Young *et al.* 2007). Muscular strength is the ability to produce force against an external resistance (Siff, 2008). Various methods can be used to measure strength including maximal voluntary isometric contractions (MVIC) in a laboratory or a one-repetition maximum (1RM) in an applied setting.

Static stretching has repeatedly been shown to negatively affect strength acutely (Simic *et al.* 2013, Walsh *et al.* 2017). Kokkonen *et al.* (1998) were the first to demonstrate negative responses from static stretching. Participants completed a stretching protocol of five different stretches for three repetitions of 15 seconds prior to 1 repetition maximum of a prone knee flexion and a seated knee extension exercise, results showed a decrease in muscle strength by 7.3% ($p<0.05$) for knee flexion and by 8.1% ($p<0.05$) for knee extension. Power *et al.* (2004) examined the effects of static stretching of the quadriceps, plantar flexors and hamstrings on knee extension and plantarflexion maximal voluntary isometric contraction (MVIC), they found that two stretches to the point of discomfort each held for three repetitions of 45 seconds for a total of 270 seconds of stretching per muscle lead to a 9.5% decrease ($p<0.05$) in quadricep MVIC when tested immediately following the stretching. The post-stretch performance tests were then repeated 30 minutes, 60 minutes, 90 minutes and 120 minutes following the stretching, the quadricep MVIC remained decreased by up to 10.4% 120 minutes after stretch intervention, however, plantarflexion MVIC strength remained unaffected by the static stretching. A recent study also found static stretching to not affect plantarflexion MVIC strength (Gesel *et al.* 2022). These findings suggest that there could be differences in force loss between different muscle groups following acute static stretching.

Other stretching methods have been shown to not lead to as great a decrease in strength, for example, Walsh *et al.* (2017) examined the effects of 90-second static stretches of the quadriceps and hamstrings to the point of mild discomfort on knee extension and flexion strength compared to a dynamic stretching protocol group and a no-stretch control group. The results showed that the static stretching decreased both knee extension ($p<0.001$) and flexion strength ($p=0.002$) and knee extension strength was significantly reduced more than the dynamic stretching protocol ($p=0.025$) and the control group ($p=0.036$). In a systematic review and meta-analysis of 61 studies, Simic *et al.* (2013) found that acute static stretching decreased maximal strength by -5.4% (95% CI: -6.6% to -4.2%).

The type of contraction used to measure strength, either isometric, concentric or eccentric has been shown to be different following static stretching. A systematic review has shown that studies which examined isometric strength experienced a slightly greater decrease following static stretching than concentric or eccentric, -6.3%, -4.4% and –4.2% respectively (Behm *et al.* 2016). Furthermore, a study has shown that 30-second and 60-second static stretching of the quadriceps leads to a small magnitude but significant impairment to isometric strength and no effect on concentric strength (Kasahara *et al.* 2023). Authors suggested that isometric strength decreased following the static stretching due to two underlying mechanisms; a neurological mechanism involving a reduction in Persistent Inward Currents (PICs) which amplify synaptic input and play an essential role in normal motor unit behaviour and their ability to produce force (Trajano *et al.* 2017) and a morphological mechanism which was a reduction in passive stiffness (Behm *et al.* 2016). However, it is unclear as to why isometric strength is affected by static stretching, but concentric strength is not.

The methods of measuring strength outputs in these studies only measure the strength of a single muscle group or specific joint movement at a time such as knee extension to examine the strength of the quadriceps and knee flexion to measure hamstring strength. Further research is needed to examine the effects of strength on compound exercises which involve multiple muscle groups and joint movements such as squats. Heisey *et al.* (2016) compared the effects of a static stretching group and a no-stretch control group on total volume and maximum repetitions of the back squat at 80% of 1RM of female collegiate athletes. The static stretching protocol lasted for a total duration of 7 minutes and 50 seconds from three different stretches to target the gluteals, quadriceps and hamstrings. Each stretch was held for 30 seconds on each side with 10 seconds rest between each stretch. Results revealed no significant difference between groups for either total volume (p=0.27) or total repetitions (p=0.12). Research strongly suggests that acute static stretching is likely to reduce strength output, however, there are caveats to that such as the duration of the stretch, the intensity of the stretch, the muscle groups stretched, and the types of movement used to assess strength.

2.5 Acute effects on power

Another indicator for the performance of a muscle or muscle group is power which is required for success in many sports defined as the maximum amount of force generated in a short period (Kawamori *et al.* 2004). Power is often assessed using vertical jump tests on force plates, sprinting tests and peak force output on an isokinetic dynamometer. A systematic review and meta-analysis of 12 studies that examined the effect of acute static stretching on different measures of muscular power found a decrease of -1.9% (95% CI: -4.0% to 0.2%) (Simic *et al.* 2013).

The maximal vertical jump is often used to measure power due to ease of administration and ecological validity to multiple sports. Static stretching prior to a vertical jump test has been shown to lead to reductions in vertical jump and therefore, muscular power (Cornwell *et al.* 2001, Bradley *et al.* 2007).

Cornwell *et al.* (2001) examined 30 seconds of hip and knee flexor static stretches to the participants' pain threshold on vertical jump height in two different vertical jump techniques; static jump and countermovement jump, and peak power output during these jumps. Results showed that jump height for both techniques was diminished by 4.4% and 4.3% respectively following the stretching protocol and peak power in both jumps was decreased by 3.2% and 2.17% following the stretching, these findings show that static stretching can reduce power in movements that utilise the stretch-shortening cycle (countermovement jump) and those that do not (static jump). The data collected from this study was not sufficient to show which mechanisms may potentially cause the reduction in power and jump height, however, authors suggested that the static stretching may have altered the knee and hip extensors from operating in the most advantageous part of their force-length and force-velocity curves. The authors went on to suggest that the significance of the reduction in vertical jump may depend on the activity in which it is performed, for example, a 1cm reduction in jump height may not be meaningful in sports like basketball or volleyball but it could have more of an impact in a sport like high jump. Cornwell *et al.* (2001) tested participants immediately following the static stretching and suggested that different durations between the stretches and the performance tests may lead to different outcomes. Bradley *et al.* (2007) also required participants to hold static stretches to the point of mild discomfort of the quadriceps, hamstrings and plantar flexors for 30 seconds and observed a 4.0% decrease in jump height ($p<0.05$), Bradley *et al.* (2007) observed this decrease in vertical jump height to persist for up to 15 minutes after the static stretching. Another study used a similar static stretching protocol but included hip extensor and flexor stretches, this study also found a 4.2% decrease in jump height (Hough *et al.* 2009). This study only examined the effects of a concentric-only vertical jump technique which reduces the ecological validity as jumping in sports usually requires the use of the stretch-shortening cycle (Turner *et al.* 2010).

A limitation found throughout these studies is that the number of participants is low, Cornwell *et al.* (2001) and Hough *et al.* (2009) used 10 and 11 participants respectively and Bradley *et* *al.* (2007) used 18. Furthermore, all the studies were performed using male participants in their 20s, this limits the scope of the investigation.

Short-distance sprints also provide an ecologically valid assessment of power, Fletcher & Jones (2004) compared passive static stretching and dynamic stretching on 20 metre sprinting performance of male rugby players. The static stretching procedure consisted of stretching the gluteals, quadriceps, hamstrings, adductors, hip flexors, gastrocnemius and soleus, each muscle was stretched for 20 seconds at the point of 'mild discomfort.' Passive static stretching resulted in an increase in 20-metre sprint time (Pre: 3.23±0.17 vs. Post: 3.27±0.17 s, $p<0.05$), whereas the dynamic stretching resulted in a decrease in sprint time (Pre: 3.25±0.17 vs. Post: 3.18±0.18 s, $p<0.05$). Similar findings were found by Winchester *et al.* (2008) who examined static stretching on 40 metre sprinting times on collegiate track and field athletes. The static stretching protocol consisted of 3 repetitions of 30 second stretches to the 'point of discomfort' for the hamstrings, quadriceps, gluteals and calf muscles. When compared to a no-stretching group, this stretching protocol significantly increased sprint times over 20 metres (Stretch: 2.41±0.21 s, no stretch: 2.33±0.35 s, $p<0.05$) and 40 metres (stretch: 5.72±0.42 s, no stretch: 5.62±0.42 s, $p<0.05$).

Just like measuring strength, power can also be measured using single muscle or joint movement such as leg extension power to assesses power in the quadriceps using an isokinetic dynamometer. Yamaguchi *et al.* (2006) examined 4 sets of 30 seconds of quadricep static stretching on peak power output during concentric dynamic constant external resistance (DCER) on a leg extension machine at three different loads; light load (%5 of MVC), moderate load (30% of MVC) and heavy load (60% of MVC). Results showed that power output was significantly decreased for all loads following static stretching compared to no stretching (-12% for 5%MVC, -6% for 30%MVC, -9% for 60%MVC). Another study also examined the effects of quadricep static stretching on peak torque and mean power output during a leg extension exercise at different angular velocities of 60°s and 300°s rather than at different loads (Marek *et al.* 2005). This study consisted of four different quadricep static stretches each held for 30 seconds at the 'point of discomfort but not pain.' The results showed a decrease in both peak torque and mean power output during both leg extension velocities following the static stretching protocol. For slow velocity leg extension (i.e., 60°s), static stretching reduced peak torque from 180.7±14.8 nm to 180.4±15.7 nm ($p=0.051$) and mean power output from 162.8±13.1W to 162.2±13.3W. For the fast velocity (i.e., 300°s), static stretching reduced peak torque from 113.0±11.8 nm to 111.1±12.8 nm ($p < 0.001$) and reduced mean power output from 511.3±49.8 W to 497.9±52.9 W ($p=0.041$).

A recent study of thirteen males and nine females examined four sets of 30 second static stretches of the quadriceps, hamstring, gluteals and plantar flexors on MTU stiffness, MVC torque, peak power of the plantar flexion and jump height, peak power, peak force and peak rate of force development (RFD) during a counter movement jump (CMJ) (Gesel *et al.* 2022) The results showed significant reductions to plantar flexor MTU stiffness (-7.6%), MVC torque (-1.5%) and peak power (-7.7%) but no significant changes to jump height, peak power, peak force and peak RFD during CMJ. The decrease in plantar flexion measures were theorised to be due to the decrease in MTU stiffness, however, the plantar flexion measures were taken immediately following the stretching whereas the CMJ was measured 20 minutes later. It was suggested that this 20-minute gap allowed the MTU stiffness to return to baseline thus no significant changes to CMJ performances. Furthermore, this study showed gender differences in response to static stretching, females' plantar flexion peak power was reduced by 2% whereas the male's reduced by 10%, this finding suggests that males may be more susceptible to reductions in power following static stretching, this was theorised to be due to males having a higher baseline level of MTU stiffness (Gesel *et al.* 2020). Power output is likely to be reduced following static stretching protocols no matter the power measure used (Simic *et al.* 2013). Yet, like with strength output, there are caveats to this such as stretch duration, the time between stretch and power exercise and intensity of stretch.

2.6 Variables of static stretching

Several variables can be manipulated to potentially lead to different outcomes from static stretching. These are the duration of stretch (how long a single stretch is held), volume (the sum of several single stretches within one stretching session or over the course of a static stretching programme) and frequency (the number of stretching sessions per week). The next is the intensity of the stretch which is defined as "*the degree of muscle-tendon lengthening induced by a change in joint ROM that is controlled by an individual's subjective tolerance to stretch*" (Freitas *et al.* 2015), this is the hardest variable to measure and is the least researched among the different variables.

2.6.1 Duration

The effects of the duration of a static stretch can be easy to examine as the duration of a stretch is easy to implement, therefore effects of static stretching duration are observed acutely. As previously discussed, acute static stretching can lead to impairments in strength and power (Walsh *et al.* 2017; Gesel *et al.* 2022) due to reductions in MTU stiffness which slows force transmission from the muscle to the bone. However, research on the duration of static stretching on strength and power has suggested that short-duration stretches (<30 seconds) have trivial or no effects on strength and power, and that longer durations (>30 seconds) would lead to the stretch-induced force impairment (Behm & Chaouchi, 2011; Behm *et al.* 2016). A systematic review of 83 studies revealed that maximum strength is decreased following static stretches for more than 60 seconds (Warneke *et al.* 2024). The theory that a longer stretch duration is more likely to lead to force impairments was first observed by Knudson & Noffal (2005) who found that 40 seconds of wrist flexor static stretching would lead to a greater decrease in grip strength compared to a 10-second stretch ($p<0.05$). Kay & Blazevich (2008) examined the effects of different static stretching durations on plantar flexor peak moment. The findings showed that all static stretching durations lead to a reduction in peak ankle moment (-16.7%) and showed that reductions in peak moment were correlated with stretching duration in that the longer the stretch then the greater the decrease in peak moment. This decrease was attributed to the reduction in MTU stiffness.

Ogura *et al.* (2007) compared the effects of 30 seconds versus 60 seconds of hamstring static stretching on knee flexion MVC. Results showed that the MVC was significantly lowered with 60 seconds of static stretching compared to the control and 30 seconds of the stretching conditions, control: 287.6 ±24.0 N, 30 seconds: 281.8 ± 24.2 N, 60 seconds: 262.4 ±36.2 N. This was attributed to a possible change in viscoelasticity of the hamstrings as it has been shown that the viscoelastic property of the muscles increases as total stretch time increases (Magnusson *et al.* 1996). The larger decrease after 60 seconds of static stretching was also suggested to be due to impaired excitability of the alpha motor neurons (Avela *et al.* 1999) or inhibited central nervous system (Cramer *et al.* 2005). Pinto *et al.* (2014) built on the findings of Ogura *et al.* (2007) by comparing 30 seconds to 60 seconds of static stretching on vertical jump performances. Instead of only stretching one muscle group, this study had participants hold a 30-second stretch on the plantar flexors, hamstrings, quadriceps and gluteus maximus. The results from this study showed that 60-second static stretching condition led to a decrease in countermovement jump height (-3.4%), peak (-2.0%) and average (-2.7%) power output when compared to the no-stretch condition. There were slight decreases in countermovement jump height, peak and average power output between 30-second stretch condition and no-stretch condition and between 30-second stretch and 60-second stretch conditions however, these decreases were statistically different, ($p>0.05$).

Most of the studies that observed the stretch-induced force loss used long-duration stretches or a high volume. In Walsh *et al.* (2017), participants held stretches for 90 seconds and observed a decrease in knee extension and flexion, Gesel *et al.* (2022) had participants stretch hold single stretches for 30 seconds but did this four times taking the total volume up to 120 seconds per muscle group, this lead to a decrease peak power output. From research on stretch duration, just one set of 30 seconds of stretching may not lead to the stretch-induced force loss.

Sato *et al.* (2020) examined the effects of a 20-second static stretch of the gastrocnemius on concentric and eccentric strength. Results showed no change to strength, this was speculated to be due to no neurological and mechanical changes due to the short duration of stretch. In addition, it has been theorised that short-duration static stretches may improve speed and power performances, Avloniti *et al.* (2016) compared different durations of static stretching on speed and agility performances. The findings showed that static stretches shorter than 20 seconds lead to an improvement of 2.8-3.2% in 10 and 20-metre sprint performances and agility remained unaffected after all stretch durations. The authors suggested that short-duration static stretches may not change the viscoelastic properties and stiffness of the MTU or sarcomere cross-bridge kinetics. Further research on short-duration static stretching and possible acute improvements to speed and other measures of performance such as vertical jump or strength is needed.

The mechanisms underlying force loss following longer static stretching durations have been researched extensively (Trajano *et al.* 2013), however, mechanisms following short-duration static stretching are less clear It is theorised that short-duration static stretches (<60 seconds) are not of sufficient duration to lead to a decrease in MTU stiffness which in turn leads to the stretch-induced force loss (Matsuo *et al.* 2013; Stafilidis & Tilp, 2015), the MTU will maintain its ability to generate force to the bone. It is also possible that shorter durations of static stretching do not affect the rate of muscle activation and thus not reduce the rate of force development (Palmer *et al.* 2019).

2.6.2 Static stretching intensity

A variable of static stretching that has received little attention is the intensity of a stretch. There are two definitions used to describe static stretching intensity, Jacobs & Sciascia (2011) defined stretch intensity as: "*The magnitude of force or torque applied to the joint during a stretching exercise"*, whereas Freitas *et al.* (2015) defined it as: "*The degree of muscle-tendon lengthening induced by a change in joint range of motion that is controlled by an individual's subjective tolerance to stretch*." These two are independent definitions for the same variable, and as a result, it can make comparison of studies difficult. The definition used throughout this thesis will be the definition from Freitas *et al.* (2015).

Too little force during a static stretch may not elicit any changes in ROM or MTU stiffness and too much force could lead to strain of the tissue or an inflammatory response (Jacobs & Sciascia, 2011). Within most studies examining the effects of static stretching, participants are instructed to stretch to a 'point of discomfort' (POD), however, it is possible that a higher intensity of stretch may lead to different outcomes such as alterations to muscle architecture which would subsequently lead to improvements in strength and power measures (Sato *et al.* 2020; Yahata *et al.* 2021).

With regard to different levels of static stretching intensity on ROM, research has shown that any level of static stretch intensity will lead to an acute increase in ROM and that a higher intensity would lead to a greater increase (Fukaya *et al.*, 2021; Kataura *et al.* 2017), this was due to both an increase in stretch tolerance potentially due to experiencing more pain during high-intensity stretching, and with a greater decrease in MTU stiffness following a higher intensity protocol.

The first study to investigate the effects of different static stretching intensities examined the acute effects on jump performance, hypothesizing that lower intensities would increase ROM without the stretch-induced force loss causing a decrease in jump performance (Behm & Kibele; 2007). In this study, participants performed 4 sets of 30 second stretches of the quadriceps, hamstrings and plantar flexors to either 50%, 75% and 100% of the point of discomfort. The percentage was based of force reading at the point of discomfort, so 50%PoD was 50% of the amount of force from 100%PoD. Results showed that all three intensities of stretch-induced impairments to jump performance suggesting that static stretching above

50%PoD should not be done prior to explosive movements. The authors attributed the jumping performance impairments to a decrease in MTU stiffness no matter the level of intensity used. Another study examined low versus high-intensity hamstring static stretching on peak hamstring force and only observed a decrease in peak force following the high-intensity condition (Marchetti *et al.* 2019). The authors speculated that the higher intensity placed greater tension on the MTU which led to central drive inhibition or a reduced contractile capacity.

There are few studies on static stretching intensities on strength measures, Kataura *et al.* (2017) showed that static stretching to 120% of ROM led to a greater acute decrease in hamstring isometric muscle force when compared to stretches to 80 and 100%, Rodriques *et al.* 2017 found that static stretching to a '10' on a visual analogue scale (VAS) lead to a greater decrease in quadricep concentric peak moment than when stretching to a '7.' The reduction was thought to be due to the decrease in MTU stiffness commonly given as the reason for a decrease in strength and power. Rodrigues *et al.* (2017) suggested that the high-intensity stretched reduced neural activation by the Golgi tendon reflex.

One recent study examined 20 seconds of hamstring static stretching to three different intensities, PoD, 120%PoD and maxPoD, on hamstring peak torque during MVIC and MTU stiffness (Takeuchi *et al.* 2020). It was hypothesised that the high-intensity would lead to a decrease in MTU stiffness and thus a decrease in hamstring strength. Results from the study showed that the high-intensity stretching led to a decrease in MTU stiffness yet hamstring peak torque was unaffected. This was theorised to be either due to the 20-second duration of the stretching was not sufficient to reduce MTU stiffness enough to negatively affect strength (Behm *et al.* 2016). It was also theorised that the high-intensity nature of the stretching led to an increase in muscle activation, however, no measure of muscle activity was taken in this study.

The conflicting results from the literature on the effects of static stretching intensity could well be attributed to the variety of methods in which the intensity of a static stretch is measured. Behm *et al.* (2007) used a percentage of point of discomfort, this percentage was based on the amount of force that occurred at the point of discomfort during the stretch. Other studies used a percentage of maximum ROM that was taken in pre-intervention testing, Kataura *et al.* (2017) and Takeuchi *et al.* (2020) set 100% intensity as the maximum ROM and then 120% intensity was set to 1.2 times the ROM at 100%. A method that is common within the literature is a purely subjective method using a visual analogue scale or a numerical rating system (Takeuchi *et al.* 2021) with 10 being unbearable pain and 1 being no pain at all. For example, Muanjai *et al.* (2017) simply used PoD and PoP as the intensity participants were to stretch to. Static stretching intensity could be viewed as highly subjective as individuals all have different pain thresholds. Stretch tolerance is one of the main mechanisms attributed to increased ROM therefore individuals with high baseline ROM are likely to have a higher stretch tolerance than less flexible individuals, thus stretching to a certain ROM could be very low intensity on a visual analogue scale for highly flexible individuals and very high for someone with less flexibility.

Attempts have been made to create a universal method of measuring the intensity of a stretch. Dantas *et al.* (2008) developed the scale of Perceived Exertion in Flexibility (PERFLEX) which used a numerical rating scale from 0 to 110 with verbal descriptors used to describe how each numerical section should feel and then terms to describe what may occur in the muscle, to the author's knowledge, this method has only been used by Melo *et al.* (2021). Freitas *et al.* (2015) developed the stretching intensity scale (SIS) using a visual analogue scale (VAS), an absolute magnitude estimation (AME) score and verbal stretching intensity symptom descriptors. Freitas *et al.* (2015) described maximal intensity as the maximal range of motion without pain which coincided with 100 on the numerical component of the VAS, they included a submaximal range which was stretch intensities from 0 to 100 and then a supramaximal range for stretches exceeding the maximal ROM without pain. This method is said to have high reliability for measuring stretching intensity, as this method allows participants to gauge stretching intensity below and above their maximum ROM without pain (Freitas *et al.* 2015). Neither of these methods are universal, if a reliable and valid method of measuring static stretching intensity can be found then it may reduce discrepancies in results. No studies have tested the reliability of static stretching to a high-intensity over multiple visits.

2.7 Effects of static stretching on different populations

Most research on the effects of static stretching is commonly conducted on a convenience sample of participants from the university population, who are recreationally active (Lima *et al.* 2019). The effects of static stretching may differ between different populations. For example, athletes with a high degree of flexibility (i.e., gymnasts or dancers) may respond differently to static stretching than less flexible individuals (Lima *et al.* 2016). Furthermore, these athletes will regularly undertake stretching and flexibility training therefore, their trainability and sensitivity to change are likely to be lower than an untrained sample. Morrin and Redding (2013) examined the acute effects of static stretching to the point where participants could "*feel tension, but not pain*" on vertical jump and ROM in female dancers and showed no subsequent decrease in vertical jump (No stretch: 37.76±4.2 Vs. Static Stretching: 38.01±5.1 cm), however, there was an increase in hamstring ΔROM (No stretch: 0.85±4.1 Vs. Static Stretching: 4.55±3.3). It was suggested that the acute static stretching did not negatively impact vertical jump because this study examined female participants and females have been shown to have a lower baseline level of MTU stiffness (Kubo *et al.* 2003). An MTU that is compliant prior to the static stretching bout may mean that the MTU is not mechanically affected by the stretching (Dalrymple *et al.* 2010). Another potential explanation for the usually observed decrease in power measurements following static stretching is a decrease in muscle activation (Power *et al.* 2004), it was suggested that individuals who have trained their flexibility may have dampened the sensitivity of their sensory receptors and thus do not experience a decrease in muscle activation. Another study supported the findings by Morrin & Redding (2013) which showed that static stretching prior to jumping performance did not have a negative effect on elite-level gymnasts, both male and female. The authors suggested that gymnasts are likely to be accustomed to static stretching for substantially longer than the duration used in this study thus not long enough to affect the MTU negatively (Donti *et al.* 2014).

Some studies have used college-aged participants, but these participants have been American collegiate athletes competing in the National Collegiate Athletic Association (NCAA) competition which is a high level of sport in which division one athletes are ranked as "elite level' athletes and athletes in division two and three are ranked as "highly trained" athletes. (Mckay *et al.* 2021).

Egan *et al.* (2006) examined the acute effects of quadriceps static stretching on leg extension peak torque and MVIC in female NCAA Division 1 basketball players. The results showed no adverse effects of static stretching on these outcome measures. The authors suggest that the training status of the participants affects the results in that the chronic MTU adaptations from strength and conditioning training throughout the basketball season minimised MTU length-tension relationship changes. A limitation of this study is that the outcome measures were laboratory-based, and research on more sport-specific movements such as vertical jump would be more ecologically valid to this population. This limitation was built on by Dalrymple *et al.* (2010) except on NCAA Division 2 volleyball players. In this study, participants stretched plantar flexors, hamstrings, quadriceps and hip extensors. The results of this study found that peak jump height during a countermovement jump of volleyball players was unaffected by the static stretching intervention. Several reasons for this finding were given, the first was that as the participants played volleyball and were accustomed to performing a vertical jump and trained at jumping therefore a greater stimulus could have been needed to impact the jump height. Next, the static stretching intervention used was three 15-second stretches for each muscle which some studies have shown to not be a sufficient volume to lead to the stretch-induced force impairment (Behm *et al.* 2016). The last reason suggested was due to the sex of the participants, the participants in this study were female and had a lower level of baseline MTU stiffness which would mean the static stretching may not negatively affect the MTU stiffness.

Molacek *et al.* (2010) investigated the effect of acute static stretching of the Triceps and Pectoral muscles on bench press 1RM of NCAA American football players. Results again showed that acute static stretching did not cause any changes to the strength of highly trained athletes. The authors suggested that the lack of decrements in strength following the static stretching intervention was perhaps due to trained athletes likely participating in some form of flexibility training which would allow them to recover from altered viscoelastic properties quicker than individuals who do not train flexibility on a regular basis.

It seems that trained athletes are likely to be unaffected by stretch-induced force impairments often observed following an acute bout of static stretching, further research could compare two groups, trained and untrained participants, using the same static stretching intervention on strength and power outcome measures.

One study has argued that highly trained athletes may be more susceptible to performance decrements of static stretching when compared to moderately trained participants. Avloniti *et al.* (2016) found that highly trained athletes had a greater decrease in speed performances over 10 and 20 metres than moderately trained participants, it was suggested that the elite sprinters would be more sensitive to changes in MTU stiffness and viscoelastic properties.

Static stretching may affect females differently than males as females have been shown to have lower baseline levels of MTU stiffness compared to males (Kubo *et al.* 2003, Cipriani *et al.* 2012). This is due to female connective tissues differing physiologically (Kjaer *et al.* 2008), the receptors of oestrogen, found in the fibroblasts of the tendons and ligaments, may impair collagen synthesis and affect tissue behaviour. Hormonal changes during the menstrual cycle could also influence MTU behaviour (Eiling *et al.* 2007). Hoge *et al.* (2010) compared the effects of a long-duration acute static stretching intervention of the Triceps Surae muscles on dorsiflexion ROM and MTU stiffness between males and females. Results showed that only the female participants significantly increased ROM following the stretching intervention from 109.39°±10.16° to 116.63°±9.63° ($p<0.05$), there were no significant decreases in MTU stiffness for either males or females following stretching, but males had higher level of MTU stiffness throughout the study. MTU stiffness has also been shown to be higher in males during a stretch than in females (Morse, 2011). Furthermore, Marshall & Siegler (2014) showed that females gave lower VAS scores than males, this indicated that females possess better stretch tolerance than males. which is an important mechanism for possessing good ROM and flexibility. This finding suggests that females would be able to tolerate higher stretching intensities than males.

Research on acute static stretching and power and strength measures such as vertical jump and squat strength in females have found that females do not tend to experience the stretch-induced force loss usually observed following a static stretch routine (Morrin & Redding, 2013; Heisey *et al.* 2016). Morrin & Redding (2013) examined acute static stretching "to the point of tension but not pain" on vertical jump of female gymnasts, results showed no effect on vertical jump height. Heisey *et al.* (2016) found that two 30-second stretches of the Gluteals, quadriceps and hamstrings did not negatively impact back squat strength in NCAA Division 1 female athletes from a variety of sports. This no effect was attributed to the participants being female and thus possessing an already compliant MTU therefore the stretching could not have any effect on stiffness. The no effect was also attributed to the training status of the participants as they were high-level athletes. Static stretching intensity may play a role in the differences between males and females. Females tend to possess higher levels of baseline flexibility and lower MTU stiffness (Kubo *et al.* 2003, Cipriani *et al.* 2012) than their male counterparts and may therefore require a much higher level of static stretch intensity to lead to the stretch-induced force loss. Further research is needed to directly compare the effects of acute static stretching between males and females, both trained and untrained participants.

2.8 Static stretching within a full warm-up

Within sport, recreationally or professional, athletes habitually undertake a full dynamic warm-up usually consisting of a light aerobic jog, some static stretching, dynamic stretching and then sport-specific movements. (Behm *et al.* 2015). The aim of a warm-up is to increase blood flow to the muscles and elevate muscular temperature, warm-ups also increase ATP turnover, which reinforces muscular function, muscle cross-bridge cycling rate and oxygen uptake kinetics which significantly affects exercise performance (McGown *et al.*2015; Park *et al.* 2018). In laboratory studies on static stretching on strength and power, participants may do a light aerobic jog prior to the static stretching intervention but nothing else and then exhibit reductions in strength and power. Research has suggested that a full warm-up would attenuate the possible negative effects of static stretching (Behm & Chaouachi, 2011).

Samson *et al.* (2012) examined the effects of static stretching when performed with two different warm-up protocols on countermovement jump performance and repeated sprint speed. The results showed that performing static stretching with either a general warm-up of a 5-minute jog at 70% max heart rate or a general warm-up with sport-specific activities did not lead to any decrements expected following static stretching. Blazevich *et al.* (2018) examined two static stretching durations within a full warm-up on flexibility, long jump, squat jump, countermovement jump, drop jump, agility and 20-metre sprint performances. The results found that neither the 5-second nor the 30-second static stretching interventions affected the performance measures. Stevanovic *et al.* (2019) examined static stretching within a sport-specific warm on vertical jump in male basketball players. Results showed that when performed in isolation, static stretching reduced vertical jump height but after a sport-specific warm-up up the vertical jump was increased. These studies theorise that when within a warm-up, the negative effects of static stretching are attenuated by an increase in muscle temperature, nerve conduction velocity and a decrease in muscle viscosity (Bishop, 2003) and possible post-activation potentiation (Behm & Chaouachi, 2011).

2.9 Underlying mechanisms for the stretch-induced force loss

There are multiple studies that have observed stretch-induced force loss following acute static stretching and have theorised several underlying mechanisms. The stretch-induced force loss following static stretching is resultant from multiple potential mechanisms. This includes neural responses such as decreased muscle activity and alterations to motor neuron excitability, and morphological changes such as reduced MTU stiffness altering the length-tension relationship (Chaabene *et al.* 2019). There can also be psychological responses such as placebo or nocebo effects. It is unclear which of these mechanisms is responsible (Behm *et al.* 2020) and it is possible that they occur in combination.

2.9.1 *Neurological mechanisms*

Neural responses affect the activation of the muscles (Trajano *et al.* 2017) and are commonly measured using electromyography (EMG). EMG measures the electrical activity that is produced by the muscles and is influenced by central and peripheral components of the neuromuscular system, including muscle conduction velocity, motor unit recruitment, synchronisation and firing frequency (Farina *et al.* 2002).

Studies examining the effects of static stretching on EMG activity have found conflicting results, Trajano *et al.* (2013) examined a 5-minute passive stretch of the plantar flexors on peak torque and EMG activity measured within a minute of the static stretching. Results found decreases in both peak torque (15.7%) and EMG activity of the soleus (13.2%) and lateral gastrocnemius muscles (8.2%), these results suggest a strong correlation between EMG activity leading to the decrease in peak torque. Studies have also found that decreases in force and EMG activity can persist for up to 15 minutes following the static stretching, Behm *et al.* (2001) found that three 45-second quadricep static stretches lead to a 12.2% decrease in knee extension MVC, a 20.2% decrease in EMG activity and a 2.8% increase in Interpolated Twitch technique (ITT), when examined 10 minutes following the static stretching protocol and Fowles *et al.* (2000), found that the MVC and EMG activity of the plantar flexor muscles is still decreased for 15 minutes following static stretching by 12% and 15% respectively. These findings indicate that the stretch-induced force loss may be caused by changes to muscle activation than muscle elasticity. However, some studies have observed no significant reductions in muscle EMG activity, Palmer *et al.* (2019) examined different durations of hamstring static stretching on peak torque and EMG activity. Results showed no reduction in peak torque or EMG activity after 30, 60 or 120 seconds of static stretching. The authors suggested that the stretching duration was not long enough to cause a reduction in EMG or peak torque which is in accordance with previous studies that have examined the effects of different static stretching durations. Yet, other studies have examined longer stretch durations on EMG and observed no changes, Kay & Blazevich (2008) found 180 second total duration of plantar flexor static stretching to have no effect on EMG activity and Mizuno *et al.* (2014) examined a total duration of 5-minutes of plantar flexor static stretching on plantar flexor MVC and EMG activity, results showed a decrease in MVC but no decrease in EMG activity. From the literature, the extent of the role EMG activity plays on the stretch-induced force loss is unclear as muscle action potential wave readings (M-wave), which reflects changes in electrode recording volume, might be influenced by exercise-induced peripheral changes such as electrolyte balance and contraction-induced ischaemia (Dimitrova & Dimitrov, 2003). M-wave amplitudes could also change because of muscle length changes to the muscles as the position of the electrodes may change relative to the muscle fibres (Vieira *et al.* 2017). Recording conditions may also alter electrode position such as sweat on the skin causing the electrode to move, these can be counteracted by shaving the area of the participant's body where the electrodes are going to be placed and wiped with an alcohol swab to remove sweat and other skin surface oils. Furthermore, the EMG-force relationship is described as a curvilinear slope meaning that changes in EMG do not directly translate to changes in muscle force. Evidence suggests that EMG recordings may not be sensitive enough to be a consistent measure of neural mechanisms (Behm *et al.* 2020). However, when EMG is normalised to the M-wave, there is a consistent correlation with stretch-induced force loss. Differences in EMG activity results following static stretching may be due to the intensity of the static stretching protocols used. The intensity of the static stretching protocols on EMG activity has not been directly investigated, however, Behm *et al.* (2001) found a 20.2% decrease in the quadriceps following static stretches which 'stressed the subjects' ROM limits and Fowles *et al.* (2000) observed a 15% decrease in EMG of the plantar flexors following static stretching to 'the maximal tolerable stretch' which could be described as high-intensity, whereas Palmer *et al.* (2019) and Kay & Blazevich (2008) showed no reductions in EMG activity following static stretching to the point of discomfort. Further research is required to examine static stretching intensity on EMG activity.

Another potential neural mechanism for the stretch-induced force loss is the Hoffman's reflex (H-reflex). The H-reflex is a measure of afferent excitability of the spinal motoneuron (Zehr *et al.* 2002). It aims to replicate a stretch reflex by stimulating a peripheral sensory nerve which then reflects either the excitation or the inhibition of the reflex circuit affecting the ability to produce force. A decrease in H-reflex has been observed following a static stretching protocol, Avela *et al.* (1999) observed a 23.3% decrease in plantar flexor MVC along with a 43.8% decrease in H-reflex following a one-hour static stretching protocol. Avela *et al.* (1999) theorised that the reduction in H-reflex following the static stretching was due to a decrease in an excitatory drive from the Ia afferents due to reduced resting muscle spindle discharge, this is termed disfacilitation, resulting from an increase in compliance with the MTU. Guissard *et al.* (2001) observed a 25% decrease in H-reflex of the plantar flexors following a 10° dorsiflexion stretch and a 54% decrease in a 20° dorsiflexion stretch. The authors suggested that the H-reflex decrease was due to pre-synaptic inhibition which involves the release of inhibitory neurotransmitters which suppress Ca^{2+} channels and decreases glutamate, an excitatory neurotransmitter from nearby synapses (Guissard *et al.* 2001). However, these decreases observed in the H-reflex following static stretching are unlikely to be linked to performance decreases as Guissard *et al.* (2001) observed it to return to baseline within seconds of the stretching and Avela *et al.* (1999) observed the H-reflex to have returned to baseline 15 minutes later, they may have observed it sooner if a measure was taken closer to the termination of the stretching. These findings are supported by the proposal by Voigt and Sinkjær (1998) that depression in H-reflex goes through a rapid 2-step recovery, step one is the fastest which happens within 500ms due to pre-synaptic inhibition relief and step two is slightly slower and is related to post activation depression. Budini *et al.* (2018) found no reductions in H-reflex amplitude following 30 seconds of dorsiflexion static stretching which may have been due to the speed in which H-reflex recovers following a static stretch.

As previously mentioned, muscle spindles contain proprioceptors called Golgi tendon organs (GTO) which detect changes to muscle tension and send messages to the brain to prevent us from stretching too far. It has been suggested that static stretching to pain or discomfort leads to high muscle tension which could induce GTO inhibition, promoting muscle relaxation and interrupting a muscle contraction, this is known as autogenic inhibition, yet, similar to the H-reflexes, with regards to the stretch-induced force loss, GTO effects only last for 60-100 milliseconds following a stretch thus are unlikely to contribute to force loss (Trajano *et al.* 2017).

Corticospinal pathway excitability and inhibition have also been speculated to play a role in the stretch-induced force loss (Trajano *et al.* 2017), the corticospinal pathway is the primary channel for voluntary motor control in humans which relays neural signals from the brain to the muscles and is dependent on alterations to the muscle during exercise (Weavil *et al.* 2018). It is theorised that desensitisation of the muscle spindle stretch receptors from static stretching may inhibit the corticospinal pathway which may cause reduced force loss (Trajano *et al.* 2017). However, research has not found any evidence supporting this hypothesis, studies have measured motor-evoked potential (MEP) of muscles, a measure of corticospinal excitability, following a static stretching protocol and found no significant changes thus no corticospinal inhibition (Budini *et al.* 2019, Pulverenti *et al.* 2019).

Another neurological factor that is thought to be involved in the stretch-induced force loss is a reduction in PICs (Trajano *et al.* 2020, Behm *et al.* 2021). PICs are depolarising currents generated by voltage-sensitive sodium and calcium channels located on the motoneuron dendrites (Heckman *et al.* 2005). PICs augment and prolong synaptic input producing sustained depolarization of the cell which causes motoneurons to continue to fire without the need for more input. This makes PICs a fundamental component of normal motor output observed in humans and decreases in PIC amplitude can significantly affect the force produced by the muscle (Heckman *et al.* 2008). Passive inward currents are measured using a paired-motor unit technique, this measures the differences between (Δf) the discharge rate of a lower-threshold motor unit (control unit) as a surrogate for the level of the excitatory drive at the time of recruitment and de-recruitment of a higher-threshold unit (test unit). Trajano *et al.* (2020) observed a 26% decrease in Soleus muscle PIC amplitude following five repetitions of 60-second plantar flexor static stretches at the maximal tolerable stretch. This study did not measure strength following the static stretching, so this is currently just early evidence that PICs might be involved in the stretch-induced force loss, future studies of more robust PICs measure techniques are required (Behm *et al.* 2021)

2.9.2 Morphological responses

Morphological (also termed peripheral or mechanical) alterations from static stretching can also result in subsequent force loss. This includes altered MTU stiffness, changes to the length-tension relationship and architectural changes to the muscle (Behm *et al.* 2021).

Decreases in muscle and/or tendon stiffness are commonly given as the underpinning mechanism for force decrements following static stretching protocols (Behm *et al.* 2016). It is hypothesised that alterations to the stiffness of contractile or passive elastic elements within the MTU may compromise force transmission to the bone and thus reduce the external force produced (Behm *et al.* 2021). Research has found that static stretching will reduce whole MTU stiffness, however, only longer duration (3-5 minutes) stretches lead to decreases in muscle force output, this has been shown in studies examining the knee flexor muscles (Hatano *et al.* 2019; Matsuo *et al.* 2019) and the plantar flexors (Bouvier *et al.* 2017; Konrad *et al.* 2019). Due to these findings, it can be suggested that the reduction in MTU stiffness may not be fully responsible for decreases in muscle force output. In addition, studies examining the effects of static stretching on MTU stiffness tend to measure passive stiffness when the muscle is not producing force, rather than active stiffness, when the muscle is producing force, which are not related, reductions in passive stiffness can be observed without changes to active stiffness (Hunter *et al.* 2001; Behm *et al.* 2020). Changes to muscles' parallel elastic components may influence muscle force but this is yet to be researched directly. Another morphological mechanism associated with the stretch-induced force loss is changes in the length-tension relationship, studies have observed a rightward shift in the length-tension curve following static stretching indicating reduced muscle force (Cramer *et al.* 2007; Weir *et al.* 2005). The reduced force from changes to the length-tension relationship is theorised to be due to changes in the length of the sarcomere which disrupts the overlap of actin and myosin filaments away from the 'optimal overlap' for force production (Rassier, 1999). There are several possible mechanisms underpinning this shift but have currently received little attention (Behm *et al.* 2020). The first is a possible reduction in PIC strength, as this is joint-angle dependent and thus muscle-length dependent (Gorassini *et al.* 2002; Kim, 2017). Longer muscle lengths may also lead to greater inhibition of the H-reflex (Blazevich *et al.* 2012). Finally, reduced force production from altered muscle lengths may be triggered by changes in calcium sensitivity of the actin and myosin complex within the sarcomere, this can bring about a 'fatigue-like' effect (Behm *et al.* 2020).

Alterations to muscle architecture properties have been suggested to be partly responsible for stretch-induced force loss, for example, an increase in fascicle pennation angle may reduce muscle force (Eng *et al.* 2018). To date, no study has observed changes in muscle architecture and reductions in force output following acute static stretching. Muscle architecture is the physical structure of the muscles, consisting of the total muscle length, muscle fascicle length, pennation angle and cross-sectional area (Wickiewicz *et al.* 1983). These are the common components of muscle architecture observed in studies examining the effects of static sti·etching on muscle architecture. Fascicle length is the length of the fascicle between the superficial aponeurosis and the deep aponeurosis, and pennation angle is the internal angle of the fascicle and the deep aponeurosis (Fukutani *et al.* 2015). Cross-sectional area is the area of the muscle pe1pendicular to its fibres (Maughan *et al.* 1983). Changes in muscle architecture are associated with improvements in muscle sti·ength and power (Nimphius *et al.* 2012), for example, in female sprinters compared to age, height and body mass matched confrols, the fascicle length of the vastus lateralis (sp1inters 8.40±1.24cm vs conti·ols 5.98±1.03cm, $p<0.01$), gasti·ocnemius medialis (sprinters 5.92±0.77cm vs confrols 5.52±0.60cm, $p<0.05$) and gasti·ocnemius lateralis (sprinters 7.44±1.07cm vs controls 6.26±0.87cm, $p<0.01$) was longer, and a smaller pennation angle can have a positive impact on power output (Wakahara *et al.* 2013). Cross-sectional area (CSA) is a measme of muscle size, which is used to estimate muscle hypertrophy and ati·ophy and can be used to detennine force production (Franchi *et al.* 2018).

Figure 2.4 The effect of longer fascicle length on a muscle-joint torque generating system and sarcomeres force-velocity relationship. For a given tendon excursion at a muscle fascicle sho1tening 1cm per second, fascicle (B) would need to sho1ten its single sarcomere 1.0µm while fascicle (A) could share the sho1tening distance between its sarcomeres and each sarcomere would need to sho1ten only 0.5µm. The physiological implication is that fascicle (A) could sho1ten at a slower velocity (0.5□mi/sec) than fascicle (B) (1.0µm/sec) and be at a sti·onger poition of the sarcomeres force-velocity curve (Abe *et al.* 2001).

Mechanical loading of skeletal muscle and time under tension (TUT) is what causes alterations in muscle architecture, it triggers molecular and structural changes that alter the physiology (Ferraro *et al.* 2014) and the contractile properties of the muscle fibres (Franchi *et al.* 2014). Mechanical loading is usually achieved through resistance training which increases the muscles' "time under tension" (TUT) placing stress on the muscles inducing muscle hypertrophy and increasing muscle strength (Toigo & Boutellier, 2006), stretching could be viewed as a method of mechanically loading the muscles (Mohamed *et al.* 2011). An area of muscle architecture which has been theorised to be partly responsible for the stretch-induced force loss is titin. Titin is a spring-like protein filament found within the sarcomere which is responsible for almost all passive force within the myofibril (Herzog *et al.* 2012), static stretching may affect its role on muscle stiffness and force production (Brynnel *et al.* 2018). Titin contributes to active force during eccentric contractions by calcium binding to the titin and the titin binding to actin filaments, this then increases the titin's stiffness (Rassier *et al.* 2015). This implies that titin's stiffness and thus contribution to force production is influenced by muscle length during contraction or by passive stretch (Herzog, 2014). During contractions started at shorter muscle lengths, titin is theorised to bind to the actin filament further from the Z-band which would increase titin stiffness, however, when a passive stretch occurs, titin cannot bind to actin which decreases stiffness. In addition, titin's stiffness is decreased further as during a passive stretch, no contraction occurs meaning no calcium is available to bind to the titin (Herzog *et al.* 2012). Future research is required to investigate the role of titin on reduced force loss following acute static stretching.

2.10 Psychological effects

An effect which has not been explored is possible psychological effects leading to stretch-induced force loss, first mentioned by Behm *et al.* (2016) who briefly suggested a possible placebo or nocebo effect if participants in studies are familiar with the literature on static stretching. Janes *et al.* (2016) examined the effects of three 30-second static stretches to the point of discomfort of the hamstring on knee flexion strength assessed using a four-second isometric MVC test, this study used two groups of participants, one of which was knowledgeable about the potential negative effects of static stretching on force output and the other were deceived and informed that static stretching will provide increased force outputs. The authors hypothesised that the deceived group would not experience force decrements as much as the knowledgeable group. However, the deception group did experience trivial and small magnitude decreases in knee flexion MVC force (1-minute post-test: -3.6%, 5 minutes post-test: -10.4%) and MVC force during the first 200ms of the movement (1 minute post-test:-7.0%, 5 minutes post-test: -12.2%) whereas the biased group showed no change to MVC force and only small decreases to force during the first 200ms (1 minute post-test: -19.6%, 5 minute post-test: -14.9%). Another study showed that psychological effects may not play a role in static stretching on strength-endurance performance, Bertolacini *et al.* (2021) assessed a quadricep static stretching routine of three separate quadricep stretching exercises each performed for three sets of 30 seconds for a total of nine minutes of static stretching to the point of discomfort on two groups of participants. One of the groups was informed that static stretching of the quadriceps prior to a knee extension strength-endurance test would be beneficial and the other was informed that static stretching would negatively impact strength-endurance. The study went on to show that the biases of the participants did not interfere with the total number of repetitions and the total volume of the exercise. Findings from these studies suggest participant bias or deception effects are generally trivial. Furthermore, they also suggest that stretch-induced force loss is a result of physiological rather than psychological mechanisms.

Blazevich *et al.* (2018) suggested that the inclusion of static stretching may increase confidence in some athletes that their physical performance will be improved. Research on this topic is relatively recent, the importance of psychology in athletic performance cannot be underestimated, therefore further research in this area would be highly beneficial.

There are many theories surrounding the potential underlying mechanisms of stretch-induced force loss following an acute bout of static stretching that have been put forward throughout the years and is possibly a combination of several different mechanisms. Some mechanisms are highly likely to be involved such as reduced Persistent Inward Currents and changes to muscle stiffness, some that were once thought to play a significant role may not be as important such as the Hoffman reflex or Golgi tendon inhibition. Others are currently unclear as there is limited research on the theory, for instance, the role of Titin proteins and reduced calcium sensitivity.

2.11 Summary

To summarise, the acute effects of static stretching on performance outcomes like strength and power are varied due to several factors and variables from the duration of the stretching to the intensity at which the stretches are held. Further research is required to find a reliable method of inducing a high-intensity static stretch and then observe the effects on strength and power.

3 General Methods

3.1 Introduction

Specific methods and protocols for each study are described in the corresponding Chapters. The purpose of this Chapter is to describe the main methods used in multiple studies within this thesis.

3.2 Laboratory and procedures

All experiments were conducted in a British Association of Sport and Exercise Science (BASES) accredited laboratory at the University of Worcester. The laboratory was air-conditioned to 19±1 °C.

3.3 Participants

All participants that took part in the studies were volunteers. Participants read the participant information sheet and gave informed consent prior to their first laboratory visit. Participants were health screened with the laboratory health history questionnaire and exclusion criteria include not currently be taking any nutritional supplements, having injuries that would be exasperated by the testing, muscular or soft tissue injuries to the legs, cardiovascular disease or hyper/hypo tension, or any other serious medical condition that would influence the safety of participants to undertake exercise. If participants are taking medication this may exclude them from the study if the medication controls for cardiovascular conditions, cholesterol or hyper/hypo tension.

All participants were males between 18 and 35 years old. This inclusion criteria was used to give a homogenous sample within the experiments. Furthermore, it aligns to the studies used in the systematic review in chapter 4 of this thesis. Lastly, this sample was also a convenience sample.

The studies also use solely male participants with women excluded from participation as oestrogen increases connective tissue stiffness and therefore would be an extraneous variable which could influence results (Chidi-Ogbolu & Baar, 2019). The studies also excluded participants who have hyperflexibility (self-reported) or injuries that would be made worse by the testing. Using a power of 80%, an alpha error of 0.05 and effect size of 0.8 using G*Power software Version 3.1.9.7 (Heinrich Heine University Düsseldorf, Düsseldorf, Germany) demonstrated that 15 participants would be required for this study.

Within this thesis, 2 experimental studies were conducted, these are presented as 2 experimental Chapters (Chapters 6 and 7). Some of the participants took part in both studies.

3.4 Anthropometric measurements

3.4.1 Body mass

Participants were weighed while wearing minimal clothing (shorts, T-shirt and socks). Body mass was measured at the beginning of the participants first laboratory visit (Secca 887, Seca, Hamburg, Germany) to the nearest 0.1 kg.

3.4.2 Height

A stadiometer (Seca 213 portable stadiometer, Seca, Hamburg, Germany) was used to measure participants height to the nearest 10 mm. Participants wore shorts, T-shirt and socks and stood with their back against the stadiometer. Participants heels were against the rest plate and they looked straight ahead with the head in Frankfort horizontal plane.

3.5 Protocol

The University of Worcester Research ethics committee approved all protocols and procedures used all studies of this thesis.

Participants were sent the participant information sheet to read through before agreeing to participate. At the beginning of their first laboratory visit, participants were given the opportunity to read the participant information sheet again then signed an informed consent form. Participants were all volunteers and did not receive any payments for participating and were all aware they could withdraw from participation at any time and withdraw their data after completing the study if they so wished.

3.6 Sitting position

The sitting position used in Chapters 5 and 6 was the same sitting position used in Matsuo *et al.* (2013) which was shown to sufficiently stretch the hamstrings. Participants were seated on an isokinetic dynamometer (Humac Norm Isokinetic dynamometer CSMi), and the angle between the seat and the backrest was set to 60°. Each participant was securely stabilised using Velcro straps at the chest, knee and ankle. The lateral epicondyle of the knee was aligned with the axis of rotation of the lever arm of the isokinetic dynamometer. This position was used to perform the range of motion, passive stiffness and hamstring strength performance tests and static stretch of the hamstrings in Chapters 5 and 6. The reliability of this custom set up is not known, however, sitting position settings were recorded on the first visit, and exactly replicated for subsequent visits.

3.7 Range of motion

Both studies within Chapters examined knee extension range of motion in the seated position described above. Anatomical 0° was set at the angle where the participants' tibia was vertical, the researcher would then move the participant's testing leg into knee extension and the participants indicated when they first felt discomfort in the hamstrings. The angle achieved was recorded on the participant's laboratory sheet. The reliability of this method of measuring ROM is not known, however, the measurement was performed by the same researcher everytime.

3.8 Passive stiffness

The passive stiffness (Nm/°) of the hamstrings was taken by the isokinetic dynamometer lever arm passively extending the participants' test leg into knee extension to the same angle achieved in the ROM test and back to anatomical 0° at a speed of $5°\cdot s^{-1}$. Before commencing this movement, participants were given standardised instructions, they were instructed to relax and not resist the lever arm. The highest amount of force produced during this test displayed the participants' passive stiffness.

3.9 Maximal Voluntary Isometric Contraction (MVIC)

A 6-second MVIC (N.m) was used to assess hamstring strength in the same sitting position. The lever arm passively extended the participants' leg into knee extension to half the ROM angle achieved; participants were then instructed to flex their knee as hard as they could for 6 seconds. Participants were encouraged by the researcher during the 6 seconds. The peak force produced during the 6 seconds was recorded. Data was exported and analysed in Microsoft Excel to allow the peak force produced to be identified. This method was selected based on similarities to previous research (Matsuo et al., 2013, Kataura et al., 2017) which showed it is a reliable method of isolating the hamstring muscles, including the Bicep Femoris due to the angle of the hip and a simple task for participants to complete with an ICC of 0.91 (Pereira De Carvalho Froufe Andrade *et al.*, 2013).

3.10 Static stretching protocol

The static stretching protocol was performed in the same sitting position; the researcher would extend the participants' testing leg to the angle required for the stretch and held for the time required. In Chapter 6, the stretch performed was 120% of the ROM test score and held for 30 seconds. In Chapter 7, the stretch was held for 100% or 120% for 30 seconds in the second and third visits to the laboratory in a randomised order and 120% for 60 seconds in the fourth visit to the laboratory.

Figure 3.1 Isokinetic dynamometer with adapted seat.

Figure 3.2 Participant seated in isokinetic dynamometer performing static stretch at 120%PoD.

3.11 Stretch sensation

To assess the participants' subjective rating of the stretch intensity, immediately following the stretch, participants were asked to draw a line on a visual analogue scale, which was a 100mm line from "no pain at all" to "worse pain imaginable." For data interpretation, the participant's mark was measured from 0 to 100 mm, with the interpretation that the higher the score, the larger the participant's rated intensity of the stretch.

3.12 Power

To measure power, participants performed two single-leg jumps on a force plate (AMTI BP600900 force plate with MSA-6 amplifier, AMTI, Watertown MA, USA). Firstly, single leg drop jump from a 20cm box, participants were instructed to drop onto their testing leg and jump as high as they could. The second was a single-leg pogo jump test during which participants performed three small hops and a fourth maximal jump on their testing leg. Data was acquired at 1000Hz using Vicon Lock Lab a-to-d unit and Vicon Nexus software (Vicon, Oxford UK).

3.13 Peak Passive torque

Peak passive torque was measured during the stretch protocol, all time points during the 30-second stretch were put onto an Excel spreadsheet and the greatest number was the peak passive torque produced by hamstrings during the stretch (N.m).

3.14 Warm-up

Prior to all laboratory visits, participants completed a 5-minute warm-up on a Monark stationary bike (Ergomedic 874E, Monark Sports and Medical, Vansbro, Sweden) at ~60 RPM. Participants were instructed to not undertake any stretching routines or movements as part of their warm-up.

3.15 Data Presentation and sample sizes

Data was collected in the laboratory and transferred to Microsoft Excel and then SPSS 29.01.0 (IBM SPSS Statistics, Armonk, NY: IBM Corp) for analysis. Data visualisation and presentation was performed in Graph Pad Prism 10.3.1 (GraphPad Software LLC, Boston, MA, Dotmatics). Sample sizes for experimental chapters were performed using G*Power software (Heinrich Heine University Düsseldorf, Düsseldorf, Germany).

4 The Effects of Static Stretching Intensity on Range of Motion, Strength, and Power: A Systematic Review

Data from this Chapter has been published – **Bryant, J**., Cooper, D.J., Peters, D.M., Cook, M.D. (2023) The Effects of Static Stretching Intensity on Range of Motion and Strength: A Systematic Review. J Funct Morphol Kinesiol, 24;8(2):37. doi: 10.3390/jfmk8020037.

Abstract: The aim of this study was to systematically review the evidence on the outcomes of using different intensities of static stretching on range of motion (ROM) and strength. PubMed, Web of Science and Cochrane controlled trials databases were searched between October 2021 and February 2022 for studies that examined the effects of different static stretching intensities on the range of motion and strength. Out of 6285 identified records, 18 studies were included in the review. Sixteen studies examined outcomes on ROM and four on strength (two studies included outcomes on both ROM and strength). All studies demonstrated that static stretching increased ROM; however, eight studies demonstrated that higher static stretching intensities led to larger increases in ROM. Two of the four studies demonstrated that strength decreased more following higher intensity stretching versus lower-intensity stretching. It appears that higher-intensity static stretching above the point of discomfort and pain may lead to greater increases in ROM, but further research is needed to confirm this. It is unclear if high-intensity static stretching leads to a larger acute decrease in strength than lower-intensity static stretching.

4.1 Introduction

Stretching is a common method of improving range of motion (ROM) within sporting and rehabilitation settings and is a passive lengthening of a muscle and holding this for a sustained period of time (Magnusson *et al.*, 1995). The increase in ROM following a bout of static stretching results from an increase in stretch tolerance and a decrease in the passive stiffness of the muscle-tendon unit (Behm *et al.* 2016). Commonly performed in pre-exercise routines and "warmups" (Ebben *et al.* 2005), however, the effects on subsequent performance are unclear, with some studies observing positive effects (Young 2007) and others impaired performance (Behm and Chaouachi 2011). As a result, the European College of Sports Science (Magnusson & Renström., 2006), the American College of Sports Medicine (Garber *et al.* 2011) and the Canadian Society for Exercise Physiology (Behm *et al.* 2016) do not recommend the use of static stretching and instead promote dynamic stretching. Despite these recommendations, surveys have found that static stretching is still used prior to exercise (Judge *et al.* 2013, Popp *et al.* 2017).

Good ROM (i.e., flexibility) is important for performance and activities of daily living as it allows full usage of the functional range. There are also suggestions that associate less flexibility (Witvrouw *et al.* 2003) and higher stiffness (Watsford *et al.* 2010) with a greater risk of muscular injury. This occurs because during movements the demands in energy absorption and release may rapidly exceed the capacity of the muscle-tendon unit (Lorimer *et al.* 2016). As a result, there may be a balance between, increasing ROM and reducing stiffness to decrease injury risk, against the force decrements and performance in dynamic movements after static stretching. Furthermore, this balance of considerations is made following limited research on the intensity of stretching as a variable.

There are four variables that can impact upon the effectiveness of stretching; frequency of stretching, duration of the stretch, the stretch position held and the stretch intensity (Marschall, 1999; Wyon *et al.* 2009). Whilst the duration and frequency of stretching are simple for participants to understand and implement, the intensity of stretch and position held for each stretch are far more subjective. Due to their inherently subjective nature, the effects of different stretch intensities and positions on ROM and exercise performance are harder to control and research.

Stretching intensity does not have a single definition. Jacobs & Sciascia (2011) defined it as; "*The magnitude of force or torque applied to the joint during a stretching exercise*.", however, Freitas *et al.* (2015) defined it as: "*The degree of muscle-tendon lengthening induced by a change in joint range of motion*." Historical recommendations for stretching intensity were to elicit the maximal ROM without pain or discomfort (Anderson and Anderson 1980). Subsequent investigations have examined the influence of stretching intensity on ROM and observed that stretching to a higher intensity (120% of point of pain) compared to a lower intensity (80% with no pain) elicited a greater change in ROM (Kataura *et al.* 2017). Therefore, the intensity of a static stretch may be important for eliciting greater changes in ROM.

Static stretching has been shown to reduce strength immediately following the stretching bout (Behm *et al.* 2001, Kay *et al.* 2008), this is likely due to a reduction in MTU stiffness and an increase in MTU compliance (Rubini *et al.* 2007) and reduced motor unit activation (Trajano *et al.* 2013). Furthermore, the effects of static stretch intensity have been shown to reduce strength performances (Kataura *et al.* 2017, Rodrigues *et al.* 2017) and have no effect on strength (Apostolopoulos *et al.* 2018, Takeuchi *et al.* 2020), therefore stretch intensity may be important on subsequent strength performance, however, the overall finding is not clear.

Stretching intensity is subjective with studies investigating stretching intensity using the participants' perception of the intensity, often using the terms 'point of pain' or 'point of discomfort' (Kataura *et al.* 2017) or a numerical rating scale (NRS) for pain or discomfort (0= no pain, 10= worst imaginable discomfort or pain) (Takeuchi *et al.* 2021). As a result, this variability in methods makes stretching at different intensities difficult to define and to implement within an applied setting. Furthermore, the outcomes are unclear and therefore it is difficult to determine if high-intensity stretching is more beneficial to increase ROM and strength. Multiple studies have examined the effects of intensity of static stretching on ROM and to the authors' knowledge, no previous studies have systematically collated these together to identify if the intensity of static stretching is important for eliciting changes in ROM and strength. There is also a lack of systematic reviews on this topic and practical recommendations that contribute to the understanding of the effects of intensity on static stretching on subsequent range of motion and strength. Therefore, the aim of this study was to systematically review the acute effects of different static stretching intensities on the range of motion, strength and power.

4.2 Methods

4.2.1 Ethical approval

Ethical approval was granted for the study by University of Worcester's College of Business, Psychology and Sport Ethics Panel (CBPS21220019).

4.2.2 Search strategy

An electronic database search was conducted of the PubMed, Web of Science and Cochrane controlled trials databases between October 2021 to February 2022. The population, intervention, comparison, outcomes and study design (PICOS) eligibility criteria are described in Table 4.1. Studies were excluded if they used injured participants or looked at the effects on injury prevention, intensity was not an independent variable, and no performance measures were used such as ROM or muscle force. No systematic reviews or meta-analyses were included in this study. The search terms are presented in Table 4.2 and then described in Table 4.3. The data extracted from the studies was number of participants, participant age, static stretching intervention, specifically the muscles stretched, the duration and repetitions of static stretch, how static stretch was administered and the intensities of the static stretches and how these were measured. And finally, the performance measures used. The current study utilized PRISMA (Preferred Reporting Items for Systematic Review and Meta-Analyses) guidelines (Figure 4.1) (Page *et al.* 2021)

Table 4.1 The PICOS (participants, intervention, comparisons, outcomes, and study design) described for inclusion criteria within this systematic review.

PICOS components	**Details**
Participants	Adults aged 18-50 with no history of serious injury or on-going injury. General population and athlete population
Intervention	Static stretching
Comparisons	Pre- or post- intervention or comparison of experimental conditions (e.g., high-intensity versus low intensity), acute effects (within an hour of static stretch intervention)
Outcomes	Range of motion Flexibility Muscular strength Muscular power
Study design	Randomised controlled trials, non-randomised controlled trials, single or double blinded to outcomes.

Table 4.2 Keywords included in the database search strategy.

Stretching	Outcomes
Static Stretching	Exercise Performance
Static Stretching intensity	Range of motion
	Muscular power
	Flexibility
	Strength

Table 4.3 Definition of terms of static stretching, objective and subjective stretch intensity, range of motion, muscular strength and power and flexibility

Term	Definition of variables
Static Stretching	Involves taking one or multiple joints to the max range of motion the individual can reach as the muscle lengthens and held in that position for 30 seconds or more.
Static Stretching intensity	Magnitude of force or torque applied to the joint during a stretching exercise (Jacobs & Sciascia, 2011) The degree of muscle-tendon lengthening induced by a change in joint range of motion that is controlled by an individual's subjective tolerance to stretch (Freitas *et al.* 2015)
Range of motion	The availability of movement around a joint measured in degrees
Muscular power	Generation of force over a short period of time (Kawamori *et al.* 2004)
Flexibility	The ability of the muscles, tendons and connective tissues to lengthen through the range of motion
Strength	The ability to produce force against an external resistance (Siff., 2008)

4.2.3 Study Selection

Immediately following exclusion of duplicates, study titles and abstracts were independently screened by two authors to determine relevant studies. The studies had to meet the following criteria 1) used static stretching; 2) manipulated stretching intensity as an independent variable;

and 3) had an outcome measure of range of motion, power, or strength in the stretched muscle. Disagreements between the authors (JB and MC) were discussed and mediated by a third author (DC).

4.2.4 Data Extraction

The studies then underwent detailed analysis by the lead author to be included into the review. Studies with no data available, clinical trial registration, or data presented within a conference proceeding were excluded from the review. The lead author extracted the following information from the included studies: authors, date of publication, sample size (*n*), study design, participant characteristics (age, training status), stretching intervention, outcome measures (range of motion, power, strength) and results. Changes in flexibility, ROM, 1RM, muscular power were converted to percentages if not provided by the paper.

4.2.5 Quality Assessment

Risk of bias was assessed using the PEDro (https:/ /pedro.org.au/english/resources/pedro-scale/) tool for assessing bias on the items; 1. eligibility criteria, 2. Random allocation, 3. Concealed allocation, 4. Similar baseline characteristics, 5. Blinding of all subjects, 6. Blinding of researchers, 7. Blinding of assessors measuring a key outcome, 8. Outcome measures were collected from a minimum of 85% of participants, 9. Participants were tested as planned within the study design, 10. Results of between-group statistical comparisons are reported for at least one key outcome, 11. The study provides both point measures and measures of variability for at least one key outcome. The PEDro scale was chosen as it has been used in previous sport and exercise science systematic review studies (Simic et al., 2013) and has been shown to be a reliable method to use in sport and exercise science systematic reviews (Rico-Gonzales et al., 2022) Furthermore, the PEDro scale assesses the internal validity of studies, and not the external validity, which helps to determine if there is a casual link between the interventions of stretching and the outcomes.

4.3 Results

Figure 4.1 demonstrates the systematic review flow chart following the PRISMA guidelines. The database searches yielded 6,285 articles of which 352 were then removed due to duplication. A subsequent 5878 articles were then excluded based on their titles and abstracts alone.

The full texts of 52 articles were subsequently retrieved of which 18 studies were included in the review for meeting the inclusion criteria.

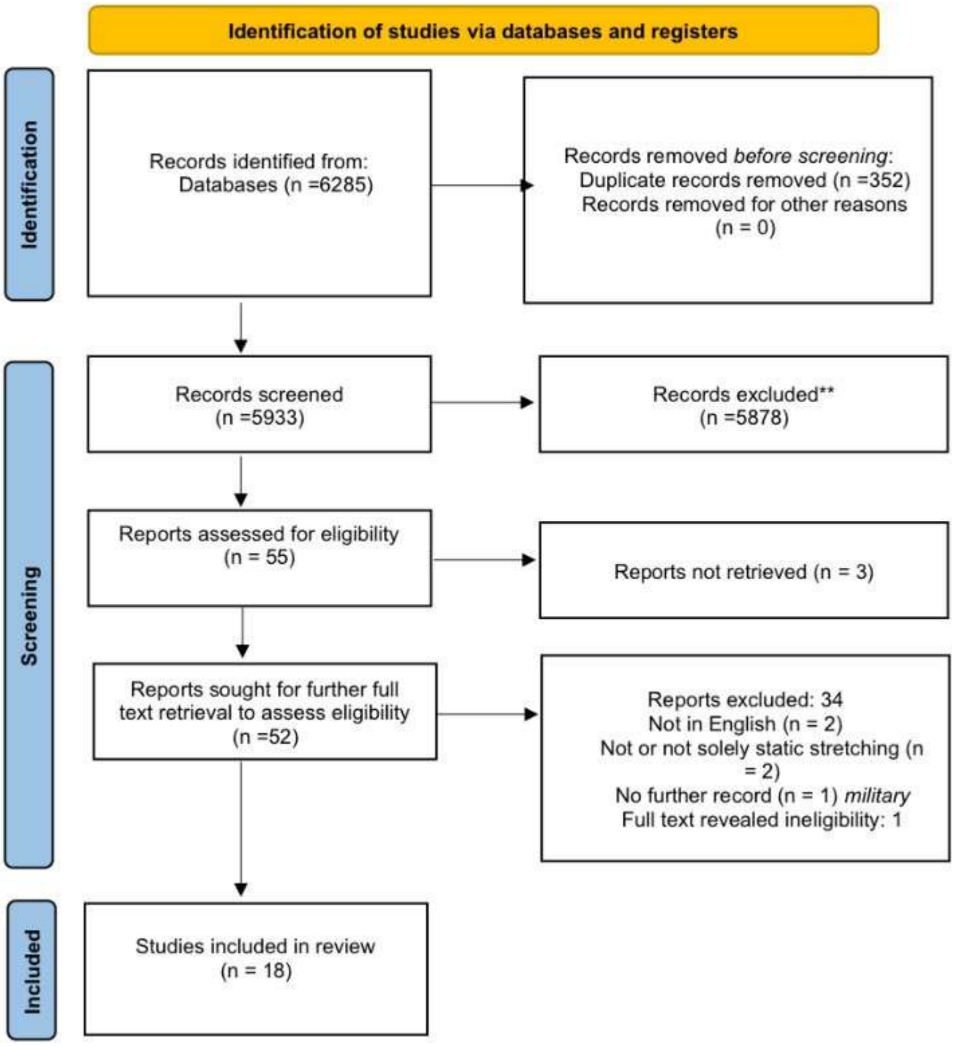

Figure 4.1 Systematic flowchart of the selected studies

4.3.1 Selected Study Characteristics

The studies examining acute effects of different stretching intensities on ROM, strength and power are reported in Table 4.4, 4.5, 4.6 respectively. For acute effects of different stretching intensities, there were 18 studies. The participant sample size ranged from 10 to 41 participants, with all the studies using men, five using a combination of men and women and no studies using women only.

14 of the 18 studies within this review examined the acute effects of different static stretching intensities on ROM, all of which observed an increase in ROM regardless of the intensity used. The main finding is that the higher the intensity of static stretching then the greater the acute increase in ROM, with seven of the 14 studies observing this finding. two studies only observed an increase in ROM after the highest stretch intensity. Three studies found no difference in ROM increases between intensities. 2 studies only observed high-intensity static stretching with no comparison to lower intensities.

6 of the 18 studies in this review examined the acute effects of static stretching intensities on strength. Similar to previous research, the results from these 6 studies are conflicting. Three of these studies observed a greater decrease in strength following higher intensity static stretching protocol when compared to a lower-intensity protocol (Apostolopoulos *et al.* 2018; Kataura *et al.* 2017; Rodrigues *et al.* 2017). One study only examined the effects of a high-intensity static stretching protocol on isometric muscle force and showed the high-intensity protocol led to a decrease in strength. One of the studies (Freitas *et al.* 2015) observed an increase in strength via peak torque measure after a high-intensity stretch condition, however, this finding was not expanded on. And finally, the remaining study (Takeuchi *et al.* 2020) did not observe a change in hamstring peak torque after any stretching intensities and thus no differences between intensities.

Table 4.4 Studies examining the acute effects of different static stretching intensities on Range of Motion

Study	n	Participants	Study design	Muscles stretched	Static stretching protocol	ROM measure	Results	Statistical results
Freitas *et al.* 2016b	17	Men (22.1±2.7) from a university population.	CO, B	Hamstrings Supine knee extension on isokinetic dynamometer on right side.	1. High-intensity at 100% of maximum tolerable passive torque with moderate duration (243.5±69.5 s). 2. Low intensity at 50% of tolerable passive torque for long duration of 900 s	Knee extension maximal ROM, peak passive torque, passive torque at a given angle, 1 min, 30-min and 60 min post stretching.	Average intensity for high-intensity stretching was 109.2±10.4% of initial peak torque and 107.3±7.6% of initial maximal ROM. Average intensity (peak torque and initial ROM) for low intensity not reported. Data reported within Figures. Low intensity and long duration stretching induced a higher acute decrease in passive torque. Stretch intensity was associated with greater ROM increases, whereas duration of the stretching was associated with acute passive torque decline.	Passive toque at baseline percentiles before and 1, 30 and 60 min following the high-intensity and low intensity demonstrated interaction effects, time effects and percentile effects (i.e., across the ROM) for both high and low intensity protocols (p<0.05). Maximal ROM and peak torque 1-min, 30-min and 60-min was higher following high-intensity and short duration versus low intensity and high duration (p<0.05).
Freitas *et al.* 2015a	10	Men (27.5±1.4yrs)	CO	Gastrocnemius Prone on ergometer	10 min stretching 3 intensities based on % of max dorsiflexion ROM: 40%, 60%, 80%	Ankle passive torque-angle response	Data reported within figures	Passive torque: a significant main effect observed for time at 65% (p=0.01), 70% (p=0.0001) & 75% of max ROM (p=0.02); protocol at 70% of ROM (p=0.03). Protocol x time at 70% of ROM (p=0.03).
Freitas *et al.* 2015b	17	Men (23.9±3.6yrs)	R, CO, B	Hamstrings Passive knee extension supine with 90° hip flexion on isokinetic dynamometer	3 separate laboratory visits: 180 s at 50% intensity 135 s at 75% 90 s at 100% Intensity determined as a percentage of maximum tolerated stretch torque 5 reps of each	Peak angle of knee extension while supine	Peak angle (°) 100%: 14.5±11.2, 75%: 4.0±7.6, 50%: 1.8±8.5	
Fukaya *et al.* 2020a	23	Men, (20.0±1.5 yrs)	RA, P	Hamstrings. Passive knee extension on isokinetic dynamometer with hip	60 seconds of static stretching for 3-days per week for 4 weeks at 100% (*n*12) or 120% (*n*11) intensity. 100% defined as maximum tolerable ROM without pain.	ROM of knee extension from the initial position.		

				and knee flexion starting at 110°				
Fukaya *et al.* 2020b	18	11 men, 7 women (21.5±0.5 yrs)	R, CO	Gastrocnemius Seated in isokinetic dynamometer	120% for 100 s and 50% for 240 s, 1-week apart. Intensity was based off 100% intensity as max dorsiflexion ROM to point of discomfort.	Dorsiflexion ROM	High-intensity: ROM % change: 25.7±19.9 Low intensity ROM % change: 16.0±11.8	Post hoc analysis revealed a significant increase in dorsiflexion ROM after static stretching at high-intensity and short duration protocol ($p<0.01$, ES=0.85)
Kataura *et al.* 2017	18	9 men, 9 women (20.6±1.2 yrs) Inactive	R, CO	Right hamstrings Sitting position on isokinetic dynamometer	180 secs at each intensity 80%, 100% & 120% of pre-intervention ROM value at onset of pain	Seated knee extension ROM	ROM mean change 80%: -0.17±3.75° 100%: 4.9±3.5° 120%: 5.9±4.4°	ROM increased significantly after stretching only for 100 & 120% intensities ($p<0.05$). ROM after stretching at 100 & 120% intensities were significantly greater than 80% (x^2=14.111, $p<0.05$).
Muanjai et al. 2017	22	Women (20 ± 1 years), physically active and not undertaking resistance, aerobic or flexibility exercise in the previous 6 months.	RA, P	Hamstrings. Passive knee extension on isokinetic dynamometer with hip flexion at 120◦ and lower leg at 50◦ below horizontal.	Stretching to the point of discomfort (POD) or point of pain (POP). Eight sets with 15 s between sets (total time of 4 min)	Absolute (◦) ROM change of angle during passive straight leg raise and absolute distance (cm) during sit and reach test, immediately following the stretching and 24-h post	Straight leg raise—median (interquartile range) increase POP 6◦ (2–11.5◦) * POD 4 (2–8.5◦) * POP 24-h post 5◦ (0.5–11◦) * POD 24-h post 3◦ (1–5.5◦) * * different to baseline, but not between conditions Sit and reach test POP 1.5 cm (0.25–2.5cm) * POD 2.5 cm (1–3.25cm) * POP 24-h post 2 cm (NR) * POD 24-h post 3◦ (NR) * * different to baseline, but not conditions	
Oba et al. 2021	14	Men (22.9 ± 1.0 years), with no history of lower-limb	R, CO	Right side, plantar flexors on	Control, 50%, 75%, 100% constant torque stretching at the	Absolute (◦) dorsiflexion	Pre vs. Post Control 36.8 ± 6.2◦ vs. 37.5 ± 5.4◦ 50% 37.3 ± 6.8◦ vs. 37.8	

		injury or neuromuscular disease.		isokinetic dyna-mometer.	maximum passive resistive torque measured in the first visit.	angle Pre and Post stretching.	± 6.5° 75% 35.2 ± 5.3.5° vs. 39.2 ± 6.7° * 100% 37.2 ± 6.2° vs. 43.3 ± 6.4° * * different to pre values	
Marchetti *et al.* 2019	15	Men (27.5±6.1yrs) Well trained	R, CO	Hamstrings Supine, passive hip flexion maintaining knee extension	50%PoD 6 sets of 40 secs 85%PoD 3 sets of 40 seconds	Passive hip flexion ROM	ROM change 50%PoD: pre: 98.5º±8.44, post: 103.4º±9.2 (+4.6%) 85%PoD: Pre: 96.9º±9.5, post: 109.3º±8.4 (+11.42%)	Hip flexion passive ROM: no interaction between static stretching protocols and time (p=0.773) Increase in both static stretching protocols from pre to post intervention:
Melo *et al.* 2021	41	Men Amateur soccer players	P, RA	Hamstrings Supine, passive stretch, hip flexion/knee extension	Comfort level stretching Mild discomfort level Pain level 3 sets of 30 seconds	Passive and active knee extensions	ROM: CLS; +2.4 MDLS; +4.1 PLS; +4.1	Intragroup analysis showed that athletes from all groups obtained an increase in active and passive knee extension ROM (p<0.05) Only PLS group exhibited a large effect size (ES=1.3, Δ=7.4º)
Nakamura *et al.* 2021	18	Men (22.7±2.8 yrs) Healthy, sedentary	R, CO	Quadriceps	120%, 100%, 80% intensities based on knee flexion ROM at PRE-testing. 3 sets of 60 seconds	Knee flexion ROM	Data shown within figures	Paired t test showed an increase in knee flexion ROM after 120% (p<0.01, *d*=1.33, 95% CI, 12.5-17.6) and 100% stretching intervention intensities (p<0.01, *d* = 0.75, 95% CI, 5.6-11.9) No significant change at 80% intensity (p=0.853, *d*=0.02, 95%CI, -2.0-2.4)
Santos *et al.* 2020	20	Men (21.7±2.48 yrs) Untrained	P, SB	Hamstrings Supine hip flexion	3 sets of 60 seconds Submaximal intensity or maximal intensity Intensity based on numerical rating scale of pain	Seated knee extension ROMinitial ROMmax	Greater relative change (%) in Low intensity stretching for both ROMinital and ROMmax Low intensity: ROMinital: +9.5%, ROMmax: +4.6% High-intensity: ROMinital: +8.5%, ROMmax: +2.2%	No ROM interaction or group main effect. A main effect for the time indicated a significant increase from pre- to post- intervention, regardless of the stretching intensity for both ROMinital ($F_{(1,18)}$=59.939, p=0.001) and ROMmax ($F_{(1,18)}$= 6.545, p=0.02). Effect size and relative change (%) suggested greater ROM increase for low intensity condition (ROMinital: +9.5%, ES=1.28; ROMmax: +4.6%, ES= 0.66) compared to high-intensity group (ROMinit: +8.5%, ES= 0.80, ROMmax: +2.2%, ES=0.14)

Takeuchi *et al.* 2021a	12	Men (21±0.8yrs) Recreationally active	R, CO	Hamstrings Sitting position in Isokinetic dynamometer	2 different intensities (100% point of discomfort (PoD), 120%PoD) 2 sets of 30 seconds	Knee extension ROM	Data reported within figures. Knee extension ROM increased in both intensities (p<0.01)	Knee extension ROM: a significant 2-way interaction (intervention x time, p<0.01)
Takeuchi *et al.* 2021b	14	Men (20.9±0.7 yrs) Healthy	R, CO	Hamstrings Seated in isokinetic dynamometer	Intensity: 100% point of discomfort (PoD) 120%PoD 2 sets of 30 seconds	Knee extension ROM	There was no significant difference between interactions in pre-stretching (p=0.37, 95%CI of -6.84-6.55), post stretching (p=0.21, 95%CI of -3.03-13.37), 10 minutes (p=0.43, 95%CI of -12.10-5.29), 20 minutes (p=0.40, 95%CI of -12.64-5.17)	A significant main effect for time (P<0.01, partial eta squared = 0.66, F= 50.47), but no main effect for intervention (p=0.44, particle eta squared = 0.02, F = 0.62) Significant 2-way interaction effect (intervention x time, p<0.01, partial eta squared = 0.14, F= 4.17)
Takeuchi *et al.* 2020	13	9 Men (21.2±0.4 yrs) 4 women (21.3±0.5 yrs) Healthy	R, CO	Hamstrings Seated on isokinetic dynamometer.	PoD, 100%PoD, 120%PoD 20 seconds	Seated knee extension ROM	ROM %change PoD: 113.5±10.4 100%PoD: 127.6±18.8 120%PoD: 135.6±18.5	ROM: significant 2-way interaction (intensity x time, p<0.01, partial eta squared = 0.73) Post hoc analysis indicated that ROM significantly increased at all intensities (p<0.01). At post measurement, ROM at maxPoD was higher than PoD intensity (p<0.01)
Takeuchi *et al.* 2021c	26	Exp 1: 11 men (23.8±3.4 yrs) Exp 2: 15 men (23.1±2.9 yrs) Healthy	R, CO SI	Quadriceps	Exp 1: 120% ROM 3 sets of 20 seconds 3 sets of 60 seconds Exp 2: 110% ROM 3 sets of 60 seconds Percentage intensity based on pre-intervention ROM value	Knee flexion ROM	ROM 1 min: PRE 128.2±9.2° Post: 145.9±6.5° 3 Min PRE: 123.4±11.4° POST: 136.8±9.8°	Knee flexion ROM: Significant 2-way interaction (p=0.18, partial eta squared = 0.09) but no main effect for intervention (p=0.08, partial eta squared = 0.15). Significant main effect for time (p<0.01, partial eta squared = 0.84) ROM increased for both interventions, both p<0.01)
Nakamura et al. 2021	28	High-intensity: 14 men (20.9 ± 0.5	RA, P	Gastrocnemius, passive reclined at	Participants rated intensity on an 11-	Absolute (◦) dorsiflexion on the non-	ROM High-intensity Pre 16.5 ± 8.3◦ Post 21.9 ± 8.5◦ * Low intensity 20.1 ± 7.3◦ 21.5 ± 6.8◦ * Significant difference to pre	

	years). Low intensity: 14 men (21.4 ± 1.0 years), healthy, sedentary.		70◦ hip angle and 0◦ knee angle on isokinetic dynamometer	point verbal numerical scale of 1 to 11. High intensity at 6–7, Low intensity at 0–1 Three sets for 60 s with 30 s intervals. Three days per week for four weeks.	dominant leg.

ROM, Range of Motion; P, Parallel Groups; CO, crossover; B, Balanced order of experimental conditions; R, Randomised order of conditions; RA, Random allocation to experimental conditions/groups; MBI, magnitude-based inference; SB, single-blind where the data analysis and the delivery of the stretching performed by different researchers; SI, single intervention study design with all participants undertaking one condition; NR, Not-reported.

Table 4.5 Studies examining the acute effects of different static stretching intensities on strength.

Study	n	Participants	Study design	Muscles stretched	Static stretching protocol	Strength measure	Results	Statistical results
Apostolopoulos *et al.* 2018	30	Physically active men (25±6 yrs)	P	Hamstrings, Hip flexors, Quadriceps, passive static stretching bilaterally.	1. Control (no stretching), 2. Low intensity (30-40% max perceived stretch), 3. High-intensity (70-80%) following 60 eccentric contractions. 3 sets, 60 seconds.	Eccentric and isometric peak torque of right knee extensors 0, 24, 48 and 72 hr post.	Eccentric peak torque (Nm). **Low intensity** - 0 hr 247.5±62.0, 24 hr 229.6±62.8, 48 hr 244.3±55.3, 72hr 263.1±61.9. **High-intensity** – 0 hr 218.2±59.7, 24 hr 173.4±35.6, 48hr 208.0±44.7, 72 hr 195.9±31.9. **Control** – 0 hr 214.8±52.7, 24 hr 196.2±49.8, 48 hr 179.4±42.8 72 hr 200.6±65.6. Isometric peak torque (Nm). **Low intensity** – 0 hr 207.6±40.2, 24 hr 196.4±46.2, 48 hr 209.5±47.0, 72 hr 222.3±47.9. **High-intensity** – 0 hr 181.3±41.2, 24 hr 163.5±41.7, 48 hr 172.7±50.1, 72 hr 186.39.1. **Control** – 0 hr 185.1±55.2, 24 hr 161.5±49.5, 48 hr 169.6±50.6, 72 hr 172.8±55.4.	**Eccentric peak torque** Time X condition P=0.008 MBI - low intensity stretching had "most likely, very likely or likely beneficial" effects at 0 hr to 24 hr and 0 hr to 72 hr compared to high-intensity. **Isometric Peak Torque** Time X condition P=0.185, Time p<0.001 MBI - low intensity had possibly "trivial or beneficial" effects at 24 and 48 hr compared to high-intensity and "possibly beneficial or likely beneficial" at 48 and 72 hr compared to control. MBI was "unclear" comparing low versus high at all time points.
Freitas *et al.* 2016a	11	5 men, 6 women (27.2±6.5 yrs) Physically active	CO	Plantar flexors Dorsiflexion on isokinetic dynamometer	Non resting between repetitions (NRI) Stretched to end ROM (PoD) for 90 seconds then stretch further if they can	Maximum muscle isometric force	MVIC 1 min post intervention: -5.0±9.3% 10 min -6.7±8.7%	A significant effect was observed for time (P=0.022) for MVIC. A decrease was observed at 1 min (-5.0±9.3%, P=0.04) And at 10 min (-6.7±8.7%, p=0.02) No significant effects were observed for time (p=0.48) and protocols (p=0.47) in both stretching sessions.
Freitas *et al.* 2015b	17	Men (23.9±3.6yrs)	CO	Hamstrings Passive knee extension on isokinetic dynamometer	3 separate laboratory visits: 180 s at 50% intensity 135 s at 75% 90 s at 100% 5 reps of each Intensity was a percentage of maximum tolerated stretch torque	Peak torque	Peak torque (Nm) 100%: 19.8±27.6, 75%: -3.4±13.0, 50%: -5.6±15.9	Peak torque: p<0.05

Kataura *et al.* 2017	18	9 men, 9 women 20.6±1.2 yrs Inactive	R, CO	Right hamstrings Sitting position on isokinetic dynamometer	180 secs at each intensity 80%, 100% & 120% of pre-intervention ROM value at onset of pain	Isometric muscle force	Isometric muscle force mean change 80%: -1.2±3.7 Nm 100%: -3.3±5.1 Nm 120%: -2.9±5.9 Nm	Isometric muscle force decreased significantly after stretching compared with before stretching at 100% and 120% intensities (p<0.05)
Rodriques *et al.* 2017	22	Men (24±3 yrs) Recreationally active	CO	Quadriceps Stood upright, one leg pulled to full knee flexion	2 sets of 30 seconds	Knee extension MVC	Concentric peak moment of quadriceps following no stretching protocol (274.8±13.39 Nm) was significantly greater than maximal intensity stretching protocol (246.0±13.1 Nm)	Concentric peak moment of the quadriceps following no stretch protocol was significantly greater (p=0.014) than after maximal intensity stretching protocol.
Takeuchi *et al.* 2020	13	9 Men (21.2±0.4 yrs) 4 women (21.3±0.5 yrs) Healthy	CO	Hamstrings Seated on isokinetic dynamometer	PoD, 100%PoD, 120%PoD 20 seconds	Peak torque	Peak torque % change PoD: 99.1±14.0 100%PoD: 95.4±17.4 120%PoD: 98.4±20.1	Peak torque: no significant 2-way interaction (intensity x time, p=0.81, partial eta squared = 0.01). No main effect for intensity (p=0.17, partial eta squared = 0.11) and time (p=0.35, partial eta squared = 0.06)

Table 4.6 Studies examining the acute effects of different static stretching intensities on power

Study	n	Participants	Study design	Muscles stretched	Static stretching protocol	Power measure	Results	Statistical results
Behm *et al.* 2007	10	Convenience sample from student population 7 men (27.6±3.7 yes) 3 women (24.0±0.8)	CO	Quadriceps: Unilateral kneeling knee flexion. Hamstrings: Supine hip flexion with knee extended. Plantar flexors: ankle dorsiflexion on elevated surface	1.100% point of discomfort (PoD), 2. 75% PoD, 3. 50% PoD, for 4 sets of 30 seconds. 4. Control (5 seconds at maximal PoD).	Jump height (Squat jump, CMJ preferred, CMJ70°, CMJ short amplitude, drop jump)	Pre to post % decrease. **100% PoD -** drop jump 3.8%, squat jump 2.4%, CMJ 4.2%, CMJ70º 5.8%, short amplitude CMJ 4.4%. **75% PoD -** drop jump 6.1%, squat jump 3.7%, CMJ 3.9%, CMJ70° 3%, short amplitude CMJ 5.4%. **50% PoD** – drop jump 6.1%, squat jump 5.3%, CMJ 2.8%, CMJ70° 8.0%, short amplitude CMJ 4.0%. 3.5% mean decrease in all jumps (conditions combined).	Main effect for time with all stretching conditions combined (P=0.01). Drop jump 5.3% decrease (P=0.01), squat jump 3.8% decrease (p<0.0001), CMJ 5.6% decrease (p=0.002), CMJ70° 3.6% decrease (p=0.009), short amplitude CMJ 4.6% (p=0.008). Condition (Stretching versus control, p=0.01) Post-hoc comparisons indicated no differences between the intensities. Interaction effect (condition X time) no difference between 100, 75 and 50% POD stretching (p>0.05).
Marchetti *et al.* 2019	15	Men (27.5±6.1yrs) Well trained	CO	Hamstrings Supine, passive hip flexion maintaining knee extension	50%PoD 6 sets of 40 secs 85%PoD 3 sets of 40 seconds	Peak force	Peak force 85%PoD: pre: 41.0±9.2Kgf, post: 31.3±4.8Kgf	Knee flexion peak torque: a significant interaction for static stretching protocol and time from pre- to post- intervention only for 85%PoD (41.0±9.2 & 31.3±4.8) (p=0.004, *d*=1.37 (large), Δ% = 23.6%
Melo *et al.* 2021	41	Men Ages of groups Amateur soccer players	P	Hamstrings Supine, passive stretch, hip flexion/knee extension	Comfort level stretching Mild discomfort level Pain level 3 sets of 30 seconds	Modified shuttle run	Modified shuttle run: CLS; 0.0 sec MDLS; 0.1 sec PLS; 0.0 sec	No statistical difference between groups

Table 4.7 Pedro scale scores

	Eligibility criteria	Random allocation	Concealed allocation	Similar baseline characteristics	Blinding of all subjects	Blinding of researchers	Blinding of assessors measuring a key outcome	Outcome measures collected from a minimum of 85% of participants	Participants were tested as planned within the sudy design	Results of between groups statistical comparisons are reported for at least one key	Measures of variability for at least one key outcome	Total
Apostolopoulos 2018	1	1	0	1	0	0	0	1	1	1	0	6
Behm 2007	0	0	0	1	0	0	0	0	0	0	1	2
Freitas 2016a	0	0	0	0	0	0	0	1	1	0	1	3
Freitas 2016b	1	0	0	0	0	0	0	0	1	0	1	3
Freitas 2015a	0	0	0	0	0	0	0	0	1	0	1	2
Freitas 2015b	1	0	0	0	0	0	0	0	1	0	1	3
Fukaya 2020a	0	1	0	1	0	0	0	1	1	0	1	5
Fukaya 2020b	1	0	0	0	0	0	0	0	1	0	1	3
Kataura 2017	1	0	0	0	0	0	0	0	1	0	1	3
Marchetti 2019	1	0	0	0	0	0	0	0	1	0	1	3
Melo 2021	1	1	0	1	0	0	0	1	1	0	1	6
Nakamura 2021	1	0	0	0	0	0	0	0	1	0	1	3
Rodrigues 2017	1	0	0	0	0	0	0	0	1	0	1	3
Santos 2020	1	1	0	1	0	0	0	1	1	1	0	6
Takeuchi 2021a	1	0	0	0	0	0	0	0	1	0	1	3
Takeuchi 2021b	1	0	0	0	0	0	0	0	1	0	0	2
Takeuchi 2020	1	0	0	0	0	0	0	0	1	0	1	3
Takeuchi 2021c	1	0	0	0	0	0	0	0	1	0	1	3

4.4 Discussion

Within this review, 18 studies were included, with 16 examining acute effects on ROM, six studies examined a strength measure and three examined a power measure.

4.4.1 Acute effects on ROM

Acute increases in ROM after stretching are attributed to an increase in tolerance to the stretch (Brusco *et al.* 2019) and a decrease in MTU stiffness (Mizuno., 2017). Several of the studies within this review observed that ROM increased after any stretch intensity but had a greater increase after the highest intensity used, it was theorised that the increases after lower intensity stretching were due to an increase in stretch tolerance and the greater increase after higher intensity was due to both an increase in stretch tolerance and a decrease in MTU stiffness (Fukaya *et al.* 2021, Fukaya *et al.* 2020, Kataura *et al.* 2017, Takeuchi *et al.* 2020). Two of the studies in this review found that only the high-intensity stretching condition induced ROM increases, it was suggested that in order to increase ROM, stretching intensity should be between 50% and the maximum tolerable torque, and that if the stretching intensity is too low then physical stress will be insufficient to induce ROM increases (Freitas *et al.* 2016).

Three studies found no difference in ROM increases between different stretch intensities (Santos *et al.* 2020; Takeuchi *et al.* 2021; Takeuchi *et al.* 2021). One of these studies (Santos *et al.* 2020) suggested that their lower intensity condition had a slightly greater increase in ROM than the high-intensity condition but did not theorise as to why. The other two studies observed that ROM increased the same for both high and low intensity but found that higher intensity led to a decrease in MTU stiffness.

From the few studies investigating static stretching intensity on ROM, it seems that the higher the intensity of stretch then the greater the increase in ROM as it increases stretch tolerance and decreases MTU stiffness. Stretching to a high-intensity to improve ROM could be used to increase the ROM quicker and save time during a stretching session.

4.4.2 Acute effects on strength

Apostolopoulos *et al.* (2018) investigated the effects of different static stretching intensities on recovery of muscle function, eccentric and isometric peak torque, after eccentric exercise-induced muscle damage. The results suggested that low-intensity passive static stretch may improve eccentric and isometric peak torque to a better extent than high-intensity conditions however, no physiological mechanisms were suggested for this finding. Kataura *et al.* (2017) examined the isometric muscle force of the hamstrings, all static stretching intensities decreased isometric muscle force with a greater decrease after the higher intensity conditions, 100% and 120%. The decrease in isometric muscle force observed is in line with previous research which suggests that static stretching can reduce the force output of the muscle (Walsh *et al.* 2017, Gesel *et al.* 2022) which is theorised to be due to the reduced musculotendinous unit stiffness observed after static stretching as this reduces the force-generating capacity of the muscle. Rodrigues *et al.* (2017) examined the effects of high and low-intensity static stretching of the quadricep muscles on concentric peak moment (PM). High-intensity stretching, described in this study as stretching to the point of maximal discomfort, was observed to decrease quadriceps concentric PM more than submaximal discomfort stretching and no stretching. This decrease was also attributed to a reduced MTU stiffness along with reduced neural activation by the Golgi tendon reflex.

One of the few studies observed an increase in peak torque of the hamstring muscles after 100% static stretching intensity compared to lower intensities, which is not in line with current literature. However, the authors did not expand upon this finding. The remaining study (Takeuchi *et al.* 2020) used static stretching of the hamstring muscles at different intensities for 20 seconds. The study found that the peak torque of isokinetic knee flexion was not changed after all intensities. This study also examined the effects on ROM and MTU stiffness, the ROM increased and the MTU stiffness decreased more after the highest intensity protocol. According to previous research, a decrease in MTU stiffness should reduce the strength and force output of the muscle (Walsh *et al.* 2017) however this was not observed in this study. This suggests that high-intensity static stretching for just 20 seconds would increase ROM and reduce MTU stiffness without reducing the muscle force. This finding could be useful for athletes and recreationally active individuals as they will be able to increase ROM and reduce MTU stiffness which can reduce the risk of injury while not negatively impacting the strength of the muscle. The authors theorised that the high-intensity stretching activated the sympathetic nervous system and increased muscle activation which offset the negative effects of the decrease in MTU stiffness. In addition, research on the duration of static stretching has found that shorter duration static stretch has none or trivial effects on muscle strength (Behm *et al.* 2016, Kay & Blazevich, 2012). Further research on this finding is needed on different measures of strength or power such as vertical jump performance or sprint speed performance.

4.4.3 Acute effects on power

Only three studies within this review examined the effects of static stretching intensities on measures of power. Behm *et al.* (2007) examined the effects of different intensities of static stretching on jump performances using squat jump, different countermovement jumps and a drop jump. All intensities of stretching lead to a decrease in all the jump performance measures which is in accordance with previous research (Young & Behm, 2007) and recent research (Gesel *et al.* 2022). Furthermore, there was no significant difference in decrements between the different intensity conditions. Decrements observed were attributed to reductions in MTU stiffness thus decreasing force transmission (Behm *et al.* 2007). In addition, an interesting aspect of this study is the control condition, the control condition was maximal discomfort static stretching for just 5 seconds, participants in this group did not experience any decrement in jump performance. The main stretching protocol was four sets of 30-second stretching, which is a total of 2 minutes of static stretching, longer duration or great volume static stretching has been shown to lead to greater MTU stiffness and thus larger decrements in muscle force (Behm *et al.* 2016). This 5-second stretching protocol is similar to the findings from Takeuchi *et al.* (2020) that observed no peak torque impairments at high-intensity hamstring static stretching for just 20 seconds.

Marchetti *et al.* (2019) compared two different static stretching intensities with an inverse duration on the peak force of the hamstrings. The two conditions were 50% point of discomfort (PoD) for 240 total seconds and 85% PoD for 120 total seconds. A reduction of peak force was only observed in the high-intensity condition. The aim of this study was not to find the mechanisms underpinning this effect so authors could only speculate, they suggested that the reduction in peak force was due to higher MTU tension which led to central drive inhibition or a reduced contractile capacity (Marchetti *et al.* 2019).

Melo *et al.* (2021) investigated different static stretching intensities on 20-metre sprint performance of amateur football players, results showed no significant changes between intensities, no decreases or increases in performance. The authors concluded that as there are no changes, then individuals should just stretch to a mild discomfort level rather than to a pain level.

A further issue that arises within research on static stretch intensity is methodological inconsistencies in how a high or low-intensity static stretch is achieved. Many of the studies within this review use a method that uses a percentage of maximum ROM from pre-intervention measures or similar variations such as a percentage of angle at point of discomfort or maximum tolerable torque. Others use a solely subjective method such as a numerical rating scale of 0 to 10 where 0 is no pain or discomfort and 10 is either the point of discomfort or maximum tolerable pain. It is currently not clear if these methods are reliable in achieving the required stretch intensity.

This variation in methods of measuring intensity could explain the differences in findings from the studies because outcomes may not be reliable across time. This is especially important for the studies comparing high-intensity stretching at multiple visits. Subjectivity measures are common in this research, however, there are differences in these methods. Some of the 0-10 scale is 0 with no discomfort and 10 is the point of discomfort and then others that use a 0-10 scale, 10 is the point of pain which would be a greater stretching intensity than just the point of discomfort. There is no universal method of assessing a static stretch intensity, future research could investigate the reliability of stretching to a certain intensity to assess whether it correlates to a high or a low-intensity stretch. Overall, the general quality of the studies is low due to scoring 6 out of 11 on the PEDro scale. The PEDro scale was chosen as it has been used in previous studies sport science systematic reviews (Simic et al., 2013) and has been shown as a reliable method of assessing the quality of sport and exercise science systematic reviews (Rico-Gonzalez et al., 2022). Furthermore, as the stretching is delivered by an investigator, often using an isokinetic dynamometer in which they operate, investigators will also not be blinded, with all studies also scoring zero on item six of the PEDro scale (blinding of researchers). In addition, none of the studies scored zero on item five of the PEDro scale (blinding of subjects), this is likely due to humans' ability to perceive and rank sensation from mechanical stimuli, therefore, blinding them to a high or low-intensity stretch is difficult. All the studies scored for random allocation to study conditions; however, there was inadequate information provided by the studies on the process of participant randomisation to the study conditions. Therefore, future studies should use unblinded operators and then blinded data analysts. There is also scope for undertaking studies examining stretching intensity with participant deception to the intensity being used to prevent participants' preconceived conceptions of pain or discomfort. Studies using isokinetic dynamometers for the stretching intervention would be able to deceive participants on if they are stretching to a high or low-intensity stretch based on their pre-intervention ROM test. A meta-analysis was not conducted due to the relatively low number of studies included in the review and the low quality of research as shown by the PEDro scale. Furthermore, the studies have compared outcomes on different muscles (i.e. hamstrings, quadriceps and plantar flexors), therefore, meta-analysis could lead to misleading results due to anatomical and differences.

4.5 Conclusion

In conclusion, static stretching to a high-intensity is likely to lead to a greater increase in ROM compared to low intensity, suggested to be due to an increase in stretch tolerance and a greater decrease in MTU stiffness. For strength and power, no conclusion can yet be made due to a lack of research examining static stretch intensity on measures of strength and power. Findings are currently contradictory, some studies found no differences in strength or power as these decreased to the same extent no matter the level of intensity, and some found that high-intensity led to a greater decrease in strength and power, likely due to a greater decrease in MTU stiffness. In addition, higher-intensity static stretching for a shorter duration could potentially be beneficial for acute strength and power performances. Studies used in this systematic review scored low on the PEDro scale which limits the conclusions that can be drawn, due to many of the studies conducting the stretching protocols on isokinetic dynamometers it is not possible to blind the researchers as researchers need to input the stretch degrees required into the isokinetic dynamometer. However, future research could use deception of participants on the intensity of stretching undertaken. Furthermore, studies investigating static stretching intensity used a variety of methods for measuring the participants' intensity. Future research could investigate the reliability and validity of these methods.

5 A survey on the static stretching practices of coaches and athletes of different sports and competition levels within the UK.

The main finding from the previous study was that there are methodological inconsistencies among studies included in the review in how the intensity of a static stretch is generated. The studies included in the review were all completed in a laboratory environment. However, stretching will be performed by athletes and prescribed by coaches in an applied environment. Therefore, the next study decided to investigate if static stretching intensity is considered by athletes and coaches and how it might be defined and measured.

Abstract

Static stretching before sports performances has been shown to still be used despite recommendations from research, however, it is not clear if the intensity of static stretching intensity is considered. This investigation aimed to examine the static stretching practices of athletes and coaches within sports in the UK, and to investigate if the intensity of static stretching is considered. One-hundred and sixty-six responses were analysed: 147 athletes and 19 coaches. Results showed that 92% of athletes and 53% of coaches use static stretching with 94% of athletes and 70% of coaches using static stretching to improve ROM, 78% of athletes indicated using static stretching before training and 90% of coaches indicated using it after training. 31% of athletes and 70% of coaches consider the intensity of static stretching. In conclusion, static stretching is still used before sports performance, athletes do not consider the intensity whereas coaches are more likely to consider it. Definitions and measurements of static stretching intensity were varied.

5.1 Introduction

Static stretching is the most common modality of stretching used among recreational to international athletes and males and females (Babault *et al.* 2021) and is most often used to improve flexibility and joint range of motion (ROM). Static stretching has been demonstrated to be a successful method of achieving this (Medeiros *et al.* 2016), however, the effects of static stretching on other aspects of physical performance such as strength and power output have come under some scrutiny since the late 1990s. Several studies examining static stretching performed before exercise found subsequent reductions in strength and power, termed the stretch-induced force loss (Simic *et al.* 2013, Gesel *et al.* 2022). However, differences in static stretching protocols have been shown to lead to different outcomes, for example, the duration or the intensity of each stretch.

Short-duration stretches (<30 seconds) are less likely to lead to the stretch-induced force loss whereas longer duration stretches (>45 seconds) are more likely to lead to a decrease in force (Behm *et al.* 2016). With regards to stretch intensity, however, current literature is limited due to differences in how the intensity is defined. Current research suggests that higher-intensity static stretching leads to greater increases in ROM but greater decreases in force loss than lower-intensity static stretching as seen within Chapter 5 of this thesis.

Several questionnaire studies have investigated the stretching practices among coaches and athletes, Judge *et al.* (2013) conducted two surveys of the stretching practices used by 135 NCAA track and field and 111 NCAA cross-country coaches. A 33-item survey was used, 84.4% of track and field coaches and 85.2% of cross-country coaches reported using some form of stretching pre-activity, 11.1% of track and field coaches and 8.5% of cross-country coaches reported using static stretching pre-activity and most used a combination of static and dynamic stretching, 38.5% of track and field coaches and 44.7% of cross-country coaches. These results show a reluctance among coaches to discontinue static stretching before exercise despite most of the literature suggesting static stretching leads to stretch-induced force loss. Babault *et al.* (2021) electronically distributed a 32-item questionnaire, mainly in France. To be eligible to complete the questionnaire, participants were required to be active and practice sport or physical activity at least once per week for competition, recreation or health. The 32 questions were separated into five main themes. One: participant information; age, sex, training level and volume and subjective rating of flexibility level. Two: general stretching practices they utilise. Three: stretching education. Fourth, the stretching modalities used and why they are used. Five, the participant's injury history.

A total of 3546 responses were analysed, and results showed that most respondents felt the need to stretch and had conducted stretching exercises in the past two years and were mostly performed for improving flexibility and wellness. Out of all the modalities of stretching, static stretching was most used across gender and training levels, and was mainly used for improving ROM, aiding recovery and improving overall wellness. These studies show that static stretching is still commonly utilised for improving ROM and performance, however, more research is required to examine how the static stretching is conducted such as duration, frequency and intensity.

The aim of this study is to use a questionnaire to investigate the following 4 key areas; if coaches and athletes in sports in the UK use static stretching, when they use it, the purpose of the static stretching and if they consider the intensity of the stretching. Previous research has presented findings on coaches and athletes' use of static stretching within warm-up routines without exploring if they consider intensity within the stretching.

5.2 Methods

5.2.1 Ethical approval

Ethical approval was granted for the study by the University of Worcester's Health and Sciences Ethics Panel (HS22230016-R).

5.2.2 Data Collection

The data was collected from July 2023 to April 2024 using a questionnaire to identify stretching practices of those undertaking exercise and coaches. This questionnaire used a similar structure to that used by Judge *et al.* (2013a), Judge *et al.* (2013b) and Babault *et al.* (2021) which used both multiple choice and open-ended questions. In addition, the order of question topics was similar, for example, the first was questions on participant characteristics such as gender identity, age, sport and years of experience. Next was general stretching practices, e.g. which muscles, pre or post exercise, duration of stretches and how many times per week. The current questionnaire then went on to ask additional questions on static stretching intensity. The study was cross-sectional with athletes and coaches completing the questionnaire. The participants, all of whom volunteered for the study, remained anonymous when submitting their responses.

This questionnaire was distributed online via JISC (version 2) to athletes and coaches in the UK from all levels of sport through email, direct messages, and shared links on social media.

Participants were encouraged to share among their teammates and other colleagues within the sport. The first page of the questionnaire was the participant information sheet and participants were able to give informed consent on the second page.

The questionnaire first required participants to state whether they were a coach or an athlete and consisted of multiple-choice and open-ended questions. The number of questions each participant answered depended on responses to certain questions, for example, if athletes answered 'yes' to 'Do you consider static stretching?' then they would answer further questions, if they answered 'no' then they would be given an opportunity to discuss why and then the questionnaire would be finished for them. Multiple choice questions were used in accordance with previous research (Judge et al., 2013, Babault et al., 2021), open-ended questions were also used to give participants an opportunity to further expand on their answers.

The questionnaire included both open, closed-ended and multiple-choice questions, participants were also given the opportunity to expand on responses to multiple-choice questions. On average, participants took between 5 and 10 minutes to complete the questionnaire.

Participants were anonymous and were able to withdraw their responses if they wished through a unique code that they would generate at the beginning. The questionnaire was trialled by being distributed to some of the primary author's (JB) basketball teammates. Four of whom completed the questionnaire and responses were included in the final data analysis. Feedback from this trial reported no issues. Once the survey was live, participants had as much time as they needed to complete it and were not given any prompts to complete it, this was since the questionnaire only took five to 10 minutes to complete.

5.2.3 Subjects

The inclusion criteria for this survey were kept wide to gain a broad view of static stretching practices in sports in the UK. Participants were eligible if they were over 18 years old and they played or coached any sport at any level in the UK. The sport had to be regular, organised and competitive. The term 'coach' encompassed head coaches, skills coaches, strength and conditioning coaches and sports therapists.

5.2.4 Data analysis

All questionnaire responses were downloaded from JISC to an Excel sheet. Descriptive statistics are reported as percentages, and responses from athletes and coaches were separated. Subgroup analyses of athlete respondents were conducted to compare responses between gender identities and competition level (recreational, regional, national, and international). The frequency rate was compared using two-tailed chi square analysis with significance set at $p<0.05$. Qualitative responses were input into the Marvin AI tool to perform a thematic analysis.

5.3 Results

5.3.1 Characteristics of participants

One-hundred and sixty-six responses were obtained, 147 athletes and 19 coaches. No participants were excluded as they had to meet the questionnaire requirements to complete it.

5.3.2 Athletes

Most respondents identified as male at 63% (*n=93*) and 35% (*n*=52) identified as female along with 0.68% (*n=1*) non-binary and 0.68% (*n=1*) unspecified. The characteristics of participants were similar between all gender identities; males were slightly older in the 20-29 age range and women were slightly younger in the 18-20 age range (see table 5.1). Competition levels were similar with the greatest number of participants for males and females competing in recreational sport. All competed in a variety of sports, with Rugby Union being the highest among all respondents, followed by Basketball for males and Netball for females. The years of experience for both males and females were the >8 years category.

Table 5.1 Participant characteristics

Gender	Total	Women	Men	Non-binary	Undisclosed
	147	35% (52)	63% (93)	<1% (1)	<1% (1)
Age range					
18-20	22% (32)	46% (24)	9% (8)		
20-29	44% (64)	40% (21)	44% (41)	100% (1)	100% (1)
30-39	17% (25)	2% (1)	26% (24)		
40-49	12% (17)	12% (6)	12% (11)		
50-59	3% (4)		4% (4)		
>60	3% (5)		5% (5)		
Competition level					
Recreational	45% (66)	40% (21)	48% (45)		
Regional	33% (49)	33% (17)	34% (32)		
National	14% (20)	19% (10)	10% (9)	100% (1)	
International	8% (12)	8% (4)	8% (7)		100% (1)
Sport					
Rugby (union or unspecified)	45% (66)	33% (17)	53% (49)		
Rugby league	3% (4)		3% (3)	100% (1)	
Basketball	8% (12)	6% (3)	10% (9)		
Football	7% (10)	8% (4)	6% (6)		
Netball	8% (11)	21% (11)			
Cricket	2% (3)		3% (3)		
Tennis	3% (4)		4% (4)		
Wheelchair basketball	1% (1)	2% (1)			
Running	8% (11)	8% (4)	8% (7)		
Athletics	2% (3)	4% (2)	1% (1)		
Cheerleading	1% (1)	2% (1)			
Field hockey	1% (2)	4% (2)			
Ice hockey	1% (1)		1% (1)		
Martial arts	4% (6)	8% (4)	2% (2)		
Bodybuilding	1% (1)		1% (1)		
Triathlon	1% (1)		1% (1)		
Cycling	2% (3)		3% (3)		
Olympic weightlifting	1% (1)		1% (1)		
Squash	1% (1)		1% (1)		
Badminton	1% (1)	2% (1)			
Unspecified	3% (4)	4% (2)	1% (1)		100% (1)
Years of experience					
<1 year	1% (1)		1% (1)		
1-4 years	13% (19)	21% (11)	8% (7)	100% (1)	
4-8 years	12% (18)	21% (11)	8% (7)		
>8 years	74% (109)	58% (30)	84% (78)		100% (1)

5.3.3 General Stretching Practices of Athletes

Almost all athletes across gender and competition levels indicated that they consider using static stretching (92%), with a slightly greater percentage of males static stretching than females, 94% and 88% respectively, but there was no association between gender and undertaking static stretching ($p>0.05$). The most common reason for using static stretching was 'To improve ROM/flexibility,' (94%), followed by 'To reduce muscle pain' (66%). Most respondents indicated that they use static stretching before (78%) and after (59%) every training session, whereas international athletes indicated performing static stretching every day. Static stretches are mostly held for 10-30 seconds (70%), followed by less than 10 seconds (20%).

The most common muscle group to stretch was the hamstrings with 74% of all respondents, this was followed by quadriceps for females (52%) and calves for males (68%). Static stretching was mostly self-prescribed except for national and international athletes who were prescribed it by strength and conditioning coaches and trainers.

Those who responded 'No' to 'Do you consider static stretching?' were given the opportunity to expand on why. The key themes that emerged from their responses were a preference for dynamic stretching, lack of perceived benefit of static stretching or lack of need and motivation.

Table 5.2 General Stretching Practices of Athletes

Do you consider Static stretching	Total	Women	Men	Non-binary	Undisclosed	Recreational (% of 66)	Regional (% of 49)	National (% of 20)	International (% of 12)
Yes	92% (135)	88% (46)	94% (87)	100% (1)	100% (1)	92% (61)	92% (45)	90% (18)	92% (11)
No	8% (12)	12% (6)	6% (6)			8% (5)	8% (4)	10% (2)	8% (1)

Reasons for Static stretching	Total (% of 135)	Women (% of 46)	Men (% of 87)	Non-binary	Undisclosed	Recreational (% of 61)	Regional (% of 45)	National (% of 18)	International (% of 11)
To reduce muscle pain	67% (90)	67% (31)	64% (56)	100%	100%	63% (38)	76% (34)	67% (12)	55% (7)
To reduce joint pain	29% (39)	33% (15)	28% (24)			31% (19)	31% (14)	33% (6)	0
To improve rom/flex	94% (127)	89% (41)	97% (84)	100%	100%	93% (57)	98% (44)	89% (16)	100% (11)
To improve strength	19% (26)	17% (8)	21% (18)			13% (8)	24% (11)	33% (6)	9% (1)
To improve power	14% (19)	11% (5)	16% (14)			8% (5)	20% (9)	22% (4)	9% (1)
To improve wellness	22% (29)	17% (8)	24% (21)	100%	100%	15% (9)	22% (10)	44% (8)	36% (4)
Other	8% (11)	9% (4)	8% (7)			8% (5)	9% (4)	6% (1)	9% (1)

Stretch duration	Total (% of 135)	Women (% of 46)	Men (% of 87)	Non-binary	Undisclosed	Recreational (% of 61)	Regional (% of 45)	National (% of 18)	International (% of 11)
<10 seconds	19% (26)	20% (9)	18% (16)	100%		15% (9)	27% (12)	17% (3)	18% (2)
10-30 seconds	70% (95)	74% (34)	69% (60)		100%	74% (45)	71% (32)	72% (13)	45% (5)
30-60 seconds	13% (18)	13% (6)	14% (12)			13% (8)	7% (3)	17% (3)	36% (4)
>60 seconds	5% (4)		5% (4)			2%(1)	2% (10)	6% (1)	9% (1)

Do you do static stretching in a warm-up?	Total (% of 135)	Women (% of 46)	Men (% of 87)	Non-binary	Undisclosed	Recreational (% of 61)	Regional (% of 45)	National (% of 18)	International (% of 11)
Yes	79% (106)	72% (34)	82% (71)	100%		85% (52)	78% (35)	72% (13)	55% (7)
No	20% (27)	24% (11)	17% (15)		100%	15% (9)	20% (9)	28% (5)	36% (4)
No response	2% (2)	2% (1)	1% (1)				2% (10)		9% (1)

Do you do Static stretching in a cool-down?		Women (% of 46)	Men (% of 87)	Non-binary	Undisclosed	Recreational (61)	Regional (45)	National (18)	International (11)
Yes	70% (95)	83% (38)	64% (56)		100%	75% (46)	58% (26)	78% (14)	82% (10)

No	30% (40)	17% (8)	36% (31)	100%		25% (15)	42% (19)	22% (4)	18% (2)
Are you supervised during Static stretching?	Total (% of 135)	Women (% of 46)	Men (% of 87)	Non-binary	Undisclosed	Recreational (61)	Regional (45)	National (18)	International (11)
Yes	11% (15)	15% (7)	8% (7)	100%		13% (8)	13% (6)	6% (1)	0
No	42% (57)	28% (13)	51% (44)			55% (33)	40% (18)	22% (4)	18% (2)
Sometimes	47% (63)	57% (26)	41% (36)		100%	33% (20)	47% (21)	72% (13)	82% (10)
Which muscle groups are stretched?	Total (% of 135)	Women (% of 46)	Men (% of 87)	Non-binary	Undisclosed	Recreational (61)	Regional (45)	National (18)	International (11)
Lower body	53% (72)	41% (19)	59% (51)	100%	100%	52% (32)	53% (24)	50% (9)	64% (8)
Upper body	28% (38)	24% (11)	30% (26)		100%	21% (13)	33% (15)	33% (6)	36% (4)
Both	42% (57)	50% (23)	39% (34)			38% (23)	49% (22)	56% (10)	18% (2)
Quadriceps	59% (79)	52% (24)	61% (53)	100%	100%	52% (32)	67% (30)	56% (10)	64% (8)
Hamstrings	74% (100)	65% (30)	78% (68)	100%	100%	70% (43)	76% (34)	72% (13)	90.91%
Glutes	40% (54)	39% (18)	39% (34)	100%	100%	34% (21)	40% (18)	50% (9)	55% (7)
Calves	61% (82)	46% (21)	68% (59)	100%	100%	59% (36)	62% (28)	50% (9)	82% (10)
Pectorals	24% (32)	33% (15)	18% (16)		100%	20% (12)	27% (12)	33% (6)	18% (2)
Shoulder	32% (43)	35% (16)	30% (26)		100%	28% (17)	36% (16)	39% (7)	27% (3)
Back	30% (40)	26% (12)	31% (27)	100%		31% (19)	29% (13)	22% (4)	36% (4)
Triceps	24% (32)	33% (15)	18% (16)		100%	20% (12)	27% (12)	33% (6)	18% (2)
Biceps	24% (32)	33% (15)	18% (16)		100%	20% (12)	27% (12)	33% (6)	18% (2)
Neck	30% (40)	28% (13)	30% (26)		100%	26% (16)	22% (10)	44% (8)	55% (7)
Abdominals	11% (15)	15% (7)	9% (8)			7% (14)	13% (6)	22% (4)	9% (1)
How often do you undertake Static stretching?	Total (% of 135)	Women (% of 46)	Men (% of 87)	Non-binary	Undisclosed	Recreational (61)	Regional (45)	National (18)	International (11)
Everyday	6% (8)	4% (2)	7% (6)			5% (3)	2% (10)	6% (1)	73% (9)
Every training session	61% (82)	65% (30)	57% (50)	100%	100%	61% (37)	60% (27)	56% (10)	27% (3)
1-5 times per week	33% (44)	30% (14)	34% (30)			34% (21)	40% (18)	28% (5)	
1-2 times per month	7% (9)	7% (3)	7% (6)			7% (14)	4% (2)	17% (3)	

When is Static stretching performed?	Total (% of 135)	Women (% of 46)	Men (% of 87)	Non-binary	Undisclosed	Recreational (61)	Regional (45)	National (18)	International (11)
Before training	78% (105)	72% (33)	82% (71)	100%		80% (49)	76% (34)	83% (15)	64% (8)
During training	17% (23)	13% (6)	20% (17)			21% (13)	13% (6)	17% (3)	9% (1)
After training	59% (80)	70% (32)	55% (48)		100%	67% (50)	47% (21)	67% (12)	64% (8)
Separate session	19% (26)	17% (8)	20% (17)			16% (10)	18% (8)	28% (5)	18% (2)
Who prescribes the Static stretching	Total (% of 135)	Women (% of 46)	Men (% of 87)	Non-binary	Undisclosed	Recreational (61)	Regional (45)	National (18)	International (11)
Myself	69% (93)	61% (28)	74% (64)		100%	77% (47)	71% (32)	50% (9)	55% (7)
Coach	46% (62)	61% (28)	39% (34)			33% (20)	60% (27)	67% (12)	36% (4)
Trainer	20% (27)	17% (8)	21% (18)			16% (10)	24% (11)	17% (3)	18% (2)
S&C coach	27% (36)	26% (12)	25% (22)	100%	100%	10% (6)	27% (12)	67% (12)	64% (8)
What other types of stretching do you perform?	Total (% of 135)	Women (% of 46)	Men (% of 87)	Non-binary	Undisclosed	Recreational (61)	Regional (45)	National (18)	International (11)
Active	64% (86)	70% (32)	60% (52)	100%	100%	56% (34)	62% (28)	89% (16)	73% (9)
Passive	20% (27)	20% (9)	21% (18)			21% (13)	16% (7)	17% (3)	27% (3)
Dynamic	73% (99)	80% (37)	69% (60)	100%	100%	67% (41)	78% (35)	89% (16)	64% (8)
Ballistic	10% (14)	15% (7)	8% (7)			7% (14)	18% (8)	11% (2)	0
PNF contract-relax	12% (16)	15% (7)	10% (9)			3% (2)	9% (4)	33% (6)	36% (4)
PNF Hold-relax	10% (13)	15% (7)	7% (6)			3% (2)	9% (4)	28% (5)	18% (2)
Oscillation	4% (5)	2% (1)	5% (4)			0	9% (4)	6% (1)	0

(* denotes multiple responses)

5.3.4 Static stretching intensity – athletes

Of all respondents, 31% indicated that they consider the intensity of static stretching, with a higher percentage of males than females, 37% and 20% respectively ($p<0.05$), with regards to competition level, international athletes had a higher response rate to consider intensity when static stretching with 36.36%, but this was not a significant association ($p>0.05$) (Table 5.3). Most respondents indicated that they consider the intensity of static stretching when stretching for performance (76%), recovery (81%) and flexibility (88%), in addition 88% also indicated that they believe the intensity of a static stretch is important to elicit improvements in flexibility and ROM.

Respondents were asked to define static stretch intensity and explain how they measure it. The key definition themes were discomfort and pain, depth and force of the stretch and how long the stretch is held. Three respondents indicated that they did not know how to define it. Similar themes emerged regarding measuring intensity, such as how it feels, discomfort and pain, range of motion and duration. Three indicated they did not know how to measure it or did not measure it as there is a lack of standardised measurement. Athletes who indicated that they do not consider the intensity of static stretching were asked to expand on their response, the main reasons given were a lack of need to consider it and a lack of knowledge on stretching.

Table 5.3 Static stretching intensity- Athlete

Do you consider static stretching intensity (in general)	Total (% of 135)	women (% of 46)	Men (% of 87)	Undisclosed	Non-binary		Recreational (61)	Regional (45)	National (18)	International (11)
Yes	31% (42)	19.57% (9)	36.782% (32)	100% (1)			33% (20)	29% (13)	28% (5)	36% (4)
No	69% (93)	80.435% (37)	63.218% (55)		100% (1)		67 (41)	71% (32)	72% (13)	64% (7)
Do you consider static stretching intensity when stretching for performance?	Total (% of 42)	Women (% of 9)	Men (% of 32)	Undisclosed	Non-binary	Undisclosed	Recreational (20)	Regional (13)	National (5)	International (4)
Yes	76% (32)	67% (6)	78.125% (25)	100% (1)			65% (13)	85% (11)	80% (4)	100% (4)
No	17% (7)	22% (2)	16% (5)				25% (5)	15% (2)		
Blank	7% (3)	11% (1)	6% (2)				10% (2)		20% (1)	
Do you consider static stretching intensity when stretching for recovery?		Women (% of 9)	Men (% of 32)	Undisclosed	Non-binary	Undisclosed	Recreational (20)	Regional (13)	National (5)	International (4)
Yes	81% (34)	78% (7)	81% (26)	100% (1)			75% (15)	85% (11)	80% (4)	100% (4)
No	13% (4)	0%	13% (4)				20% (4)	8% (1)		
Blank	10% (4)	22% (2)	6% (2)				5% (1)	8% (1)	20% (1)	
Do you consider static stretching intensity when stretching to improve flexibility?		Women (% of 9)	Men (% of 32)	Undisclosed	Non-binary	Undisclosed	Recreational (20)	Regional (13)	National (5)	International (4)
Yes	88% (37)	78% (7)	94% (30)				80% (16)	92% (12)	80% (4)	75% (3)
No	2% (1)	0%	0%	100% (1)			10% (2)			25% (1)
Blank	10% (4)	22% (2)	6% (2)				10% (2)	8% (1)	20% (1)	
Do you feel static stretching intensity is important to elicit improvements in flexibility?		Women (% of 9)	men (% of 32)	Undisclosed	Non-binary	Undisclosed	Recreational (20)	Regional (13)	National (5)	International (4)
Yes	88% (37)	78% (7)	94% (30)				90% (18)	92% (12)	80% (4)	75% (3)
No	2% (1)	0%	0%	100% (1)						25% (1)
Blank	10% (4)	22% (2)	6% (2)				10% (2)	8% (1)	20% (1)	

5.3.5 General stretching practices of coaches

Of the 19 coaches who took part in the survey, 53% indicated that they prescribe static stretching for their athletes (Table 5.4). Like athlete responses, the most common reason given for prescribing static stretching is 'To improve ROM/flexibility,' with 70%, different to the athletes, the coaches also prescribe static stretching 'To improve wellness' (20%). Coaches also prescribed athletes to hold each stretch for 10-30 seconds (80%). In addition, coaches who do not prescribe static stretching were given the opportunity to expand, themes included a preference for dynamic stretching, advice from governing body guidelines and not their area of expertise.

Table 5.4 General stretching practices of coaches

Do you prescribe static stretching?	
Yes	52.63% (10)
No	47.37% (9)
Reasons for Static stretching	% of 10
To reduce muscle pain	10.00%
To reduce joint pain	
To improve rom/flex	70.00%
To improve strength	
To improve power	
To improve wellness	20.00%
other	
Static stretching Duration	
<10 seconds	10%
10-30 seconds	80%
30-60 seconds	20%
>60 seconds	10%
Are your athletes supervised during Static stretching?	% of 10
Yes	50%
No	10%
Sometimes	40%
When do you prescribe for your athletes to do static stretching?	% of 10
Before training	30%
During training	20%
After training	90%
Separated, dedicated session	20%

5.3.6 Static stretching intensity – coaches

Seventy percent of coaches indicated that they take the intensity of static stretches into account (Table 5.5). 71% of these indicated that the intensity varies depending on when the static stretches are performed. Furthermore, most coaches consider the intensity when static stretching for performance, flexibility and recovery.

Table 5.5 Static stretching intensity - coaches

Do you consider the intensity of static stretching?	% of 10
Yes	70% (7)
No	30% (3)
Does the intensity vary depending on when the static stretching exerci es are performed?	% of 7
Yes	71% (5)
No	29% (2)
If you promote static stretching to improve performance, do you consider the intensity of the stretching?	% of 7
Yes	71% (5)
No	14% (1)
Blank	14% (1)
If you promote static stretching to improve recovery, do you consider the intensity of the stretching?	% of 7
Yes	86% (6)
No	14% (1)
If you promote static stretching intensity to improve flexibility, do you consider the intensity of the stretching?	% of 7
Yes	86(6)
No	14% (1)

5.4 Discussion

This study aimed to investigate the static stretching practices of athletes and coaches from all levels of sport in the UK, primarily examining if the intensity of static stretching is considered. The results showed that most athletes perform static stretching, and most coaches prescribe static stretching for their athletes which is in accordance with previous research (Babault *et al.* 2021, Judge *et al.* 2013). To the authors' knowledge, this is the first study to investigate if static stretching intensity is considered by athletes and coaches. The results revealed that most athletes do not consider the intensity of static stretching, whereas most coaches do.

5.4.1 General static stretching practices of athletes

Results of this questionnaire show that most athletes who play competitive sports in the UK perform static stretching across gender identities and competition levels. The main reason given for performing static stretching is to improve ROM and flexibility which is in line with previous research (Babault *et al.* 2021). The questionnaire revealed that most athletes performed static stretching in a warm-up which is contradictory of the literature which has shown that static stretching can lead to stretch-induced force loss (Simic *et al.* 2013, Walsh *et al.* 2017), and against advice from the American College of Sports Medicine (ACSM) (Garber *et al.* 2011) and the European College of Sport Science (ECSS) (Magnusson & Renström., 2006). However, the results of this questionnaire showed that most athletes are holding the static stretches for 10-30 seconds which has been shown to not lead to stretch-induced force loss (Behm & Chaouchi, 2011; Behm *et al.* 2016). The most common muscle group stretched was shown to be the hamstrings, which is similar to Babault *et al.* (2021), who did not specify muscles but showed that the lower body was most likely to be stretched. The second most common muscle group to stretch was shown to be different for males and females, males were shown to static stretch the calves whereas females were shown to static stretch the quadriceps.

Babault *et al.* (2021) showed that athletes were unlikely to be supervised when performing static stretching, this questionnaire revealed similar findings with most athletes only sometimes being supervised while performing static stretching. In addition, most athletes stated that their static stretching exercises were self-prescribed, however, higher-level athletes (national and international) were more likely to have been prescribed static stretching by a strength and conditioning coach, this is likely due to athletes competing at a higher level of sport will have more access to strength and conditioning coaches.

A small percentage of athletes (11.5% of females and 6.4% of males) indicated that they do not undertake any static stretching, these respondents were given a chance to expand on their responses. Thematic analysis revealed five key themes as to why they did not perform static stretching. The first theme was a preference for dynamic stretching, *"I prefer to warm up dynamically," "I have read in research that power can be reduced if static stretching has taken place recently before activity. Therefore, I opt for dynamic movements before lifting."* This is in line with previous research which has compared dynamic stretching to static stretching and found that dynamic stretching can sometimes lead to increases in muscular performance (Su *et* *al.* 2017; Zmijewski *et al.* 2020). The next two themes show that respondents do not think performing static stretching as necessary or gain no benefit from it, *"Don't feel benefit of it, no muscle tightness," "Static stretching personally doesn't do anything for me, and I feel like to exercise if something to raise the heart rate which static stretching does not do."* This could be viewed as in line with previous literature, in that static stretching before performance can often lead to stretch-induced force loss. Furthermore, with regard to increasing ROM, resistance training is just as effective in improving ROM as static stretching (Morton *et al.* 2011). In addition, it has been suggested that athletes only need a functional ROM specific to their sport (Ingraham., 2003), therefore, athletes may already possess the required ROM for their sport and thus deem it unnecessary to perform static stretching.

5.4.2 General static stretching practices of coaches

Results from this questionnaire showed that there was only a small percentage difference between coaches who prescribe static stretching (52.6%) and those who do not prescribe it (47.4%). Coaches who prescribe static stretching indicated that static stretching was mostly performed post-training (90%) with 30% indicating using it before training, these results are in accordance with literature regarding the stretch-induced force loss and the ACSM (Garber *et al.* 2011) and the ECSS (Magnusson & Renström., 2006) which recommend not performing static stretching prior to activity or performance, these findings are also similar to previous survey research on the stretching practices of coaches. Judge *et al.* (2013a), Judge *et al.* (2013b) and Judge *et al.* (2020) examined the stretching practices of NCAA cross country, track and field and soccer coaches, respectively. The results revealed that only 11.1% of track and field coaches, 8.5% of cross-country coaches and 0.48% of soccer coaches prescribed solely static stretching pre-activity. The results went on to show that 53.6% of track and field coaches, 52.3% of cross-country coaches and 35% of soccer coaches prescribed static stretching post-activity.

Similarities between the responses from athletes and coaches emerged from this survey. For example, improving ROM was given as the most common reason for static stretching among athletes and coaches, both were followed by improving wellness and reducing muscle pain. Furthermore, the duration of static stretches prescribed by coaches was like what athletes reported with 10-30 second holds having the highest percentage. An interesting difference between athlete and coach responses arose with regards to supervision while static stretching, very few athletes reported being supervised by coaches with some reporting to sometimes being supervised, whereas 50% of coaches indicated that they supervise their athletes during static stretching.

Like the athlete respondents, coaches who indicated that they do not prescribe static stretching were given the opportunity to expand on their answers. The first theme that emerged was a preference for dynamic stretching, describing dynamic stretching as more effective to prepare for training sessions, *"Because I believe dynamic and fluid stretching is more effective and more likely to prevent injury,"* and *"I largely utilise dynamic stretching, activation and potentiation movements to prepare players for our team training sessions."* This theme is the same for athletes and is in accordance with previous literature on the effects of dynamic stretching (Su *et al.* 2017), in addition, one respondent indicated to have read research on the topic; "Because research suggested that dynamic stretches were better for athletes." The second theme was that static stretching prior to activity is against governing body guidelines, specifically the Rugby Football Union (RFU); *"RFU guidelines recommend the use of 'activate' (specific guidance is provided to coaches) warm up movements to minimise injury risk to players."* The last theme was personal and contextual constraints, the coaches were not the type of coach to prescribe static stretching; *"Because I am not the type and level of coach to be allowed to do this."* Or that the stretching was player-led; *"It's normally player led, so it's not really my job."*

5.4.3 Static stretching intensity

To the authors' knowledge, this is the first study to investigate if athletes and coaches consider the intensity of static stretching. The key finding was that athletes were less likely to consider the intensity of static stretching than coaches, 68.1% of the athletes who use static stretching indicated that they do not consider the intensity of static stretching, on the other hand, 70% of coaches indicated that they do consider the intensity of static stretching for their athletes.

Research on the effects of static stretching intensity is limited; this is due to a lack of clear definition and measurement methods (See Chapter 4 of this thesis). Different definitions have been put forward, for example, Jacobs & Sciascia (2011) defined static stretching intensity as:

"The magnitude of force or torque applied to the joint during a stretching exercise," Freitas *et al.* (2015) defined it as:*"The degree of muscle-tendon lengthening induced by a change in joint ROM that is controlled by an individual's subjective tolerance to stretch."* The methods with which static stretching intensity has been measured in previous research have also been varied, some use a subjective scale such as "point of discomfort to point of pain" (Muanjai *et al.* 2017) or a numerical rating scale from zero indicating no pain to ten indicating the worst pain imaginable (Santos *et al.* 2020). Some methods used a more objective scale by including a percentage of the ROM reached at the point of discomfort (Kataura *et al.* 2017; Fukaya *et al.* 2020).

Participants who indicated they consider static stretching intensity were asked to describe how they define and measure the intensity of the stretch. Thematic analysis of athlete definition responses revealed five key themes. The first was perception of intensity, respondents gave definitions such as *"feel the stretch, don't go too far," "push to where you feel discomfort,"* and *"how much it hurts."* The second theme referred to physical parameters, consisting of depth, extent of stretch and force and strain, for example, *"To me the depth of the stretch and the length of time it is held for," "Stretching to a point where I can feel the stretch, holding and then possibly stretching further."* And *"How much strain is exerted on the muscles."* The third definition theme that emerged was the duration and repetitions consisting of definitions such as *"Hold the position for set time until loosing up,"* and *"length of hold."* The next definition theme was individual factors and goals, these definitions considered the goals of the individual and that stretching session, "*"How hard you work," "Slow easy and relaxed."* and the individual's mobility "*Intensity is pushing to the limit but not beyond,"* and *"limit of mobility."* The final athlete definition theme was uncertainty in definition, consisting of ambiguity and curiosity, one response was simply *"Unknown,"* another was in the form a question "*Extent of stretch and hold?"*

Coach definition response thematic analysis revealed four main themes. The first was S*ensory Feedback*, responses included *"The amount of 'stretch' on the muscle and how much this is felt during the stretch,"* and *"How comfortable or uncomfortable it is for an athlete."* The second coach definition was C*oach Support*, indicating that some stretching is supported by coaches. The next definition was *Quantitative Measures*, consisting of *"RPE (Rate of perceived exertion) scale 1-10," "Length held and how far you can stretch the designated muscle,"* and

"The length of time." The final coach definition was *Safe Practice* with the response *"By not pushing past the point of tension."*.

Thematic analysis of responses to how athletes measure static stretching intensity revealed six themes which were all similar to the themes that emerged from the definitions. Measurement themes one and two are similar, one refers to subjective feel and sensation with responses such as "*Purely by feel and experience,"* and *"How much stretch you feel, the burn."* Theme two refers to discomfort and pain level, consisting of responses such as *"How far I can stretch before the discomfort starts,"* and *"By my own feeling of tension/slight discomfort."* These responses coincide with how previous research that employed a subjective method of measuring static stretching intensity (Muanjai *et al.* 2017). The third theme refers to the range of motion and distance, *"Time of stretch and range,"* including physical landmarks to gauge intensity, "*Sometimes distance such as touching toes where there is a visible point/mark to use each time."* The duration of the static stretching emerged as a theme in measuring the intensity, similar to the definition themes. Another theme among athlete responses was a scale or qualitative measurement such as RPE and 1-10 scale, this measurement method is like those commonly used in laboratory research on static stretching intensity (Santos *et al.* 2020), this theme is similar to themes one and two as it involves subjectivity. In addition, the final theme of measurements that emerged from athlete responses was a lack of standard measurement, "*No good measurement. More subjective feel - does it feel I could have stretched further,"* or no answer given; *"No idea," "Don't know"*. Thematic analysis of coach responses to how is static stretching intensity measured revealed four key themes, all similar to those given by athletes. The first referred to flexibility and stretch depth, *"The amount of flexibility of the client and how far into the stretch they can get."* The second theme was on levels of comfort, one respondent gave their method of measuring static stretch intensity: "*Can hold comfortably - low intensity, mildly uncomfortable but not painful – medium, uncomfortable and want to release – high."* The next theme described RPE and suggested between five and seven out of ten. The final theme from coaches was the individuals' ROM which links to the first theme. From these responses, it can be suggested that when static stretching intensity is considered in sporting settings it receives mixed definitions and measurement methods which is in accordance with previous research (See Chapter 4 of this thesis). The most common definitions and measurement methods include some subjectivity of the individual doing the stretching (Santos *et al.* 2020; Muanjai *et al.* 2017). A reoccurring method of measurement was using an RPE scale, the RPE scale of 1-10 (Borg *et al.* 1982) has been utilised in resistance training for decades and has been shown to be a reliable method of subjectively controlling one's intensity when performing resistance training (Larsen *et al.* 2021). In addition, results from Chapter 5 in this thesis showed that stretching to 120% of the ROM at the point of discomfort on an isokinetic dynamometer coincides with a high score on a visual analogue scale from 0-100 which is similar to a 0-10 scale. These combined results may indicate that using an RPE scale could be a reliable method of measuring an individual's stretch intensity when ROM cannot be specifically measured.

Participants who consider the intensity of static stretching were asked to indicate if they consider it when stretching for different outcomes such as flexibility, recovery and performance, i.e. strength and power. Respondents who indicated that they do not consider the intensity of static stretching were asked to expand on why. Thematic analysis of responses revealed several related themes, the first was habitual and routine practice; *"Most of stretching activity is part of a habitual process undertaken prior to & following running sessions,"* and *"I just stretch and hold."* Followed by a lack of awareness and knowledge; *"Don't fully understand it," "Not sure how to measure it,"*

"I don't understand what the intensity means. IE the amount of stretch I should be aiming for or my heart rate whilst stretching? Some clarifications here would help." Responses from these themes suggest that the reason most athletes do not consider the intensity of static stretching is due to having no knowledge of it or not understanding what is meant by intensity in this context. These responses link to the previous research on the intensity of static stretching which has used a mixture of definitions and measurements of stretch intensity (See Chapter 4).

The next related theme was the perception of stretching, participants suggested they did not consider the intensity of static stretching because it is inherently a low-intensity activity; *"Because I believe that static stretches should be completed at a relatively low intensity," "Don't think of it as intense exercise so don't really think about it."*

Thematic analysis of coaches' responses revealed two themes, the first was a lack of consideration and the second was that they let their athletes stretch to where they need.

5.4.4 Limitations

The main limitation of this questionnaire specifically examined athletes and coaches involved in sports in the UK, including international participants would give a broader view of general static stretching practices and considerations of static stretching intensity, this should be considered for future research.

Furthermore, participants were not encouraged to complete the survey if they left it incomplete, nor were they prompted to share the survey with teammates and colleagues; this limited the amount of potential responses to the survey.

5.4.5 Practical applications

Results from this questionnaire show that some athletes and coaches do consider the intensity of static stretch and suggest that utilising different intensities may have different effects on the outcomes of the static stretch.

5.4.6 Future Directions

From the responses within this questionnaire, a future direction for research could be to investigate a reliable method of measuring the intensity of a static stretch. Another could be to investigate the use of static stretching intensity on just athletes from sports that require a high degree of flexibility such as martial artists, gymnasts and dancers.

5.5 Conclusion

In conclusion, static stretching is still utilised by athletes and coaches within sports in the UK despite recommendations from the ECSS and ACSM, however, it is not performed for a long enough duration to lead to stretch-induced force loss. With regards to static stretching intensity, it is considered by some athletes but not most, this is likely due to them having no knowledge of it or the definition of static stretching intensity being too vague. Most coaches considered it for their athletes; however, definitions and measurement methods were varied. Future research should investigate a method of standardised measurement for static stretching intensity.

6 Reliability of high-intensity static stretching on the hamstring group to a standardised intensity over multiple visits.

The results from the previous study (chapter 5) found that the intensity of static stretching is considered by ~31% athletes and ~71% coaches when undertaking or prescribing stretching. The main reasons identified for intensity to "not be considered" is due to a lack of method of measuring the intensity. Therefore, the next study should aim to investigate a reliable method of measuring a high-intensity static stretch and examine the effects of on performance measures such as ROM, strength and power.

Abstract

Static stretching is commonly used in athletic programs, and the intensity of static stretching has recently been examined for its effects on range of motion (ROM), strength and passive stiffness. However, the reliability of high-intensity static stretching across multiple testing sessions has not been investigated. The purpose of this investigation was to examine the reliability of high-intensity static stretching of the hamstrings across five laboratory visits on ROM, strength, power, and passive stiffness. Thirteen physically active males (age: 26±4 years, height: 180±8 cm, body mass: 81±10 Kg) underwent five repeated measures of laboratory static stretching on an isokinetic dynamometer where the point of discomfort (PoD) was measured, followed by a 30-second stretch at 120% PoD. Across the visits, the pooled intraclass correlation coefficient was good for knee extension ROM (0.82), knee flexion strength (0.81) and passive stiffness (0.81). The ROM achieved to determine the PoD before the SS was not different for the five visits (P=0.370). In conclusion, high-intensity static stretching to 120% PoD on an isokinetic dynamometer is reliable across multiple testing sessions.

6.1 Introduction

Static stretching is common within sports and the fitness industry and is an established method of increasing an individual's joint range of motion (ROM) and flexibility (Medeiros *et al.* 2016). This increase in ROM is theorised to be due to two main mechanisms, the first theory is an increase in the musculotendinous unit (MTU) compliance which describes the ability of the MTU to lengthen (Morse *et al.* 2008). The second theory is neurological, theorising that when an individual stretches a certain muscle, they improve their stretch tolerance which is an individual's ability to cope with the discomfort or pain experienced during a stretch (Weppler & Magnusson, 2010). Achieving and maintaining good ROM at different joints can be beneficial for sports performance and activities of daily life as it can allow use of a full functional ROM, however, static stretching has been shown to acutely decrease strength and power, termed the stretch-induced force loss (Simic *et al.* 2013, Walsh *et al.* 2017, Gesel *et al.* 2022).

Many underpinning mechanisms for this decrease in strength and power following static stretching have been suggested, the most accepted theory is that it is due to a decrease in MTU stiffness which can slow down force transmission from muscle to bone (Behm *et al.* 2020). Yet, recent research has found that some variables may change the outcome of static stretching on strength and power. For example, studies have demonstrated that static stretches for less than 30 seconds had little to no effect on force output, whereas longer than 30 seconds lead to reduced force output (Behm *et al.* 2011, Behm *et al.* 2016). A variable that has been examined less is the intensity of static stretching. Static stretching intensity is defined as: "*The degree of muscle-tendon lengthening induced by a change in joint ROM that is controlled by an individual's subjective tolerance to stretch*" (Freitas *et al.* 2015). Research on the acute effects of different static stretching intensities has shown that a high-intensity of stretching may lead to a greater increase in ROM (Kataura *et al.* 2017, Takeuchi *et al.* 2020), yet some studies have shown no difference in ROM increases following either low or high-intensity static stretching (Muanjai *et al.* 2017, Santos *et al.* 2020). The acute effects of different intensities of static stretching on strength are also inconclusive with only four studies having been conducted so far. Three of these studies observed a greater force loss after a high-intensity stretch than a low-intensity stretch (Kataura *et al.* 2017, Rodriques *et al.* 2017, Apostolopoulos *et al.* 2018), the remaining study did not observe a decrease in strength following high or low-intensity stretching (Takeuchi *et al.* 2020).

Due to the current lack of research on the acute effects of different intensities of static stretching on ROM and strength, no conclusions can be drawn (Chapter 4). The lack of research and varied results may be due to methodological inconsistencies in which a high or low-intensity stretch is achieved. Some studies use a subjective rating scale such as a one to ten scale or visual analogue scale from 'no pain' to 'worse pain imaginable' (Santos *et al.* 2017, Nakamura *et al.* 2022) or simply the 'point of discomfort (PoD) for a low-intensity stretch and 'point of pain (PoP) for a high-intensity stretch (Muanjai *et al.* 2017). Whereas most of the studies use a percentage of the ROM measure at the PoD, usually 120% of the ROM from the PoD is used for a high-intensity stretch (Takeuchi *et al.* 2020, Takeuchi *et al.* 2021). Currently, no research has been conducted on the reliability of techniques used to achieve a certain intensity of stretch. Therefore, the primary aim of this study is to test the reliability of using 120%PoD as generating a high-intensity static stretch across multiple stretching visits. The secondary aim will be to examine the acute effects of a high-intensity static stretch on ROM, strength and power.

6.2 Methods

6.2.1 Ethical approval

Ethical approval was granted for the study by University of Worcester's College of Business, Psychology and Sport Ethics Panel (CBPS22230006-R).

6.2.2 Participants

The study recruited 13 male participants (18-35 years old) with characteristics presented in Table 5.1. All were briefed on the study aims and protocol and gave informed consent. Participants were excluded if they had lower limb injuries in the six months prior to taking part in the study. Using a power of 80%, an alpha error of 0.05 and effect size of 0.8 using G*Power version 3..1.9.7 software (Heinrich Heine University Düsseldorf, Düsseldorf, Germany) demonstrated that 15 participants would be required for this study, with an expected dropout rate of two.

Table 6.1 Participant Characteristics

Age (years)	26±4
Height (cm)	180±8
Body Mass (Kg)	81±10
BMI	25±3

6.2.3 Study design

A repeated-measures design was used to assess the reliability of using 120%PoD angle as a high-intensity stretch and to examine the effects on strength and power (Figure 5.1). This study was conducted in the biomechanics laboratory at the University of Worcester.

Participants visited the laboratory five times with a minimum of 72 hours separating each visit. Five visits were chosen because within the literature there are different methods of measuring stretching intensity. However, a key, often overlooked consideration of these methods is that there is individual day-to-day variability in flexibility. Therefore, studies comparing outcomes from stretching at diffferent intensities do not control for this variability in daily flexibility. Therefore, the aim of the study is to determine the reliability of a static stretching intensity (120% of the point of discomfort –POD). The first visit was a familiarisation to allow for possible learning effects of the protocol and was also included in the analysis. Participants first performed a warm-up on a stationary bike (Monark Ergomedic 874E, Monark Sports and Medical, Vansbro, Sweden) at approximately 60 RPM for five minutes. Performance measures of ROM, passive stiffness, maximal isometric strength on the isokinetic dynamometer (Humac Norm Isokinetic dynamometer CSMi) and power tests on a force plate were then taken, this was followed by a 10-minute break before a 30-second-high-intensity static stretching intervention. Immediately following the stretching intervention, participants were asked to mark on a visual analogue scale how the stretch felt from 'no pain at all' to 'worst pain imaginable.' The performance measures were then repeated in the same order as before the stretch intervention.

6.2.4 Static stretching protocol

Participants were seated in an isokinetic dynamometer in a hip flexed position which has been shown to allow a sufficient stretch of the hamstrings (Matsuo *et al.* 2013). To achieve this position the angle between the backrest and seat of the isokinetic dynamometer was set to 60°. The participant's dominant leg was then extended by the primary researcher to an angle 120% greater than the angle they scored in the pre-intervention ROM test, this position was then held for 30 seconds, with participants instructed to relax.

6.2.5 Range of motion

Participants were seated in the isokinetic dynamometer in the same position as the stretch protocol. The investigator moved the participant's dominant leg into knee extension and the participant was then instructed to indicate the first moment they felt the stretch. This angle was used as their point of discomfort ROM angle.

6.2.6 Passive stiffness

In the same seated position as the ROM test, the participants' dominant leg was passively extended by the dynamometer up to the PoD angle and back down. Participants were instructed to relax.

6.2.7 Isometric strength

In the same hip flexion position on the isokinetic dynamometer as the ROM test, the arm of the dynamometer took the participant's dominant leg up to 50% of the angle achieved in the ROM test, participants were then instructed to flex their knee hard as they could, this was held for six seconds.

6.2.8 Power

Power was measured using two single-leg jump techniques on a force plate. The first was a single-leg drop jump off a 20-centimetre box, participants were instructed to jump as high as they could. The second jump test was a single-leg pogo jump which involved three small hops and a fourth maximal single-leg jump, participants were instructed to jump as high as they could on the fourth jump.

6.2.9 Stretch sensation

To measure stretch sensation, immediately following the stretch participants were asked to mark on a 10-centimeter visual analogue scale how they perceived the stretch from 'No pain at all' to 'worst pain imaginable.' This was based on similar numerical rating scales used in previous research (Apostolopoulos et al., 2018, Nakamura et al., 2022).

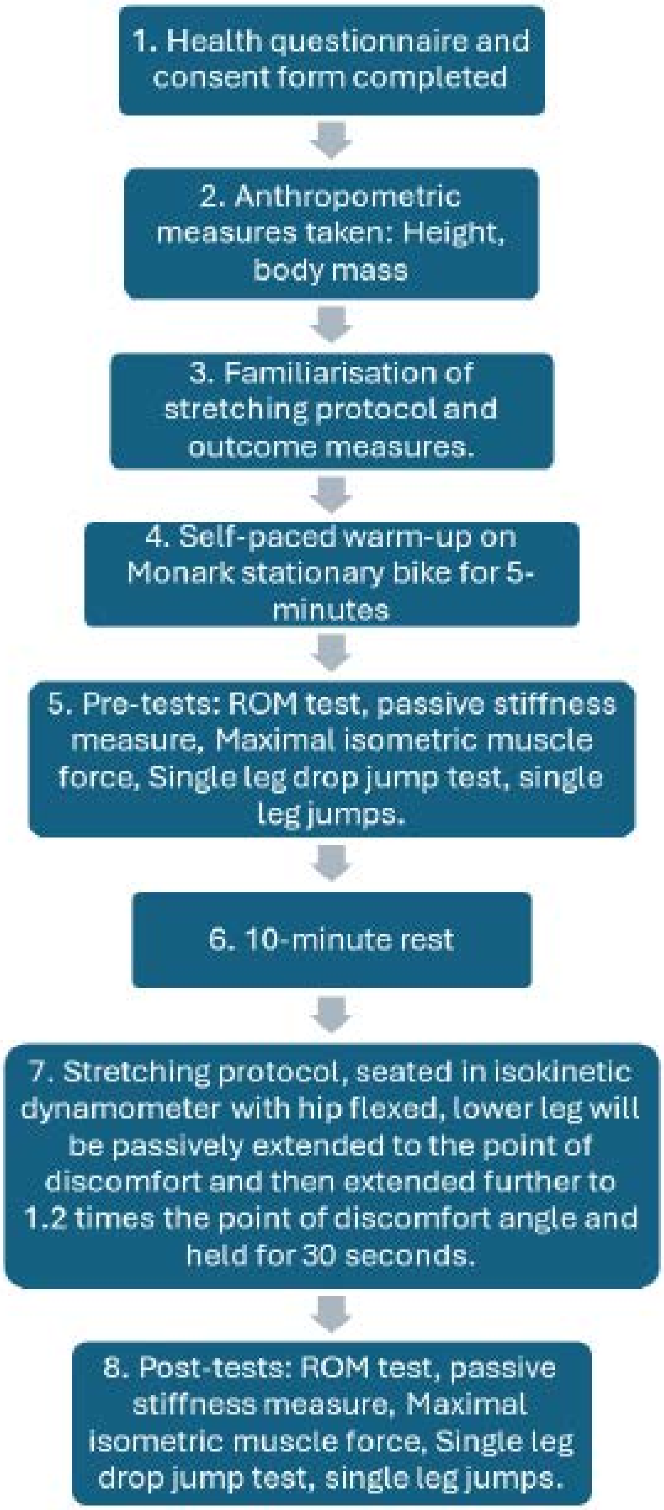

Figure 6.1 Flow chart of study procedure

6.2.10 Statistical analysis

Statistical analysis was conducted using SPSS 29.01.0 (IBM SPSS Statistics, Armonk, NY: IBM Corp). Data normality was assessed using Shapiro-wilks test, and no data violated the assumption of normality. Variables were analysed for time (i.e., Visit 1-5), with a one-way repeated measures ANOVA. Repeated measurements were checked for sphericity violations using Mauchly's test and if violated, Greenhouse-Geisser correction was applied. An alpha level of $p<0.05$ was set for statistical significance. Where differences occurred partial-eta2 ($\eta p2$) is reported and followed by pairwise post hoc comparisons. Intraclass correlation coefficients (ICC) were calculated for the visits of each visit compared to the previous visit (i.e., 2-1, 3-2, 4-3, 5-4). The pooled ICC was also calculated. ICC was interpreted with the following criteria: <0.5 poor reliability, 0.5-0.75 moderate reliability, 0.75-0.9 good reliability and >0.9 excellent reliability (Koo et al., 2016). An alpha level of 5% was set for statistical significance, however, if P was <0.10 this was interpreted as a trend towards significance and confidence intervals were reported. (Greenland et al., 2016, Greenland et al., 2019).

6.3 Results

6.3.1 Range of Motion

The ROM achieved to determine the point of discomfort before the static stretching was not different for the five visits ($F_{(2.260, 27.115)}=1.095$, $p=0.370$) (Figure 5.2A). As a result, there was also no difference in degrees of the high-intensity stretching across the five visits ($F_{(2.151, 25.817)}=1.2387$, $p=0.295$) (Figure 5.2B). However, the ROM achieved following the static stretching across the visits was different ($F_{(2.464, 29.564)}=3.685$, $p=0.029$, $\eta p2 = 0.235$.) The ROM achieved following the high-intensity static stretching on visit one was different to visit four ($p=0.008$, $d=0.873$, 95%CI [-14.452, -2.625]), and five ($p=0.024$, $d=0.717$, 95%CI [-18.575, -1.57]). Visit three was also different to visit four ($p=0.019$, $d=0.755$, 95%CI [-11.634, -1.289]) and five ($p=0.018$, $d=0.755$, 95%CI [-7.498, 4.421]). The ΔROM showed a significant change from pre to post in all visits ($p=0.043$).

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6.3.2 Passive Stiffness

The peak torque achieved during the stretch was different across time ($F_{(4,48)}$=3.675, p=0.011, ηp2 = 0.234), with the torque achieved in visit two, lower than visit three (p=0.017, d=0.690, 95% CI [-18.981, -2.238]), four (p=0.022, d=0.649, 95%CI [-14.454, -1.360]) and five (p=0.006, d=0.852, 95% CI [-21.317, -4.543]) (Figure 5.3 A). Following the stretching, the gravity corrected passive stiffness achieved was not different across the visits ($F_{(4, 48)}$=0.492, p=0.742) (Figure 5.3B).

6.3.3 Maximal Isometric Voluntary Contraction

There was no difference in the MVIC produced before the high-intensity static stretch across the visits ($F_{(2.352, 28.331)}$=1.494, p=0.241, ηp2=0.111). Similarly, the MVIC produced following the 30-second high-intensity stretch was also not different across the visits ($F_{(2.342, 28.099)}$=0.761, p=0.556, ηp2= 0.060) (Figure 5.4).

The Δ change in strength for pre to post from each visit was different ($F_{(4,48)}$=3.227, p=0.02, ηp2=0.212) (V1: Δ5.2±17.8, V2: Δ-1.2±11.8, V3: Δ-2.6±9.1, V4: Δ-12.0±12.1, V5-3.5±9.9 Kg), with the change following visit one and four (p=0.003, 95% CI [-13.149, 20.826]), two and four (p=0.025, 95% CI [-12.543, 13.655]), three and four (p=0.049, 95% CI [-7.191, 17.024]), and four and five (p=0.026, 95% CI [-20.504, 0.609]).

6.3.4 Vertical Jumps

There was no difference in drop jump force measured before the high-intensity static stretch ($F_{(3.30,39.679)}$=0.206, p=0.934, ηp2=0.017) or following the high-intensity static stretch across visits ($F_{(2.502, 30.021)}$=1.389, p=0.252, ηp2=0.104) (Figure 5.5A). Nor was there any difference in the single leg hops taken before ($F_{(2.674, 32.081)}$=1.536, p=0.207, ηp2=0.113) or after the stretch intervention across visits ($F_{(2.894, 34.723)}$=0.869, p=0.489, ηp2=0.068) (Figure 5.5B).

6.3.4. Perception of Stretch

Participants' perception of the stretching intensity was also not different across the visits ($F_{(4, 44)}$=0.616, p=0.474). (V1: 55±22, V2: 49±25, V3: 57±21, V4 52±21, V5: 56±23 mm).

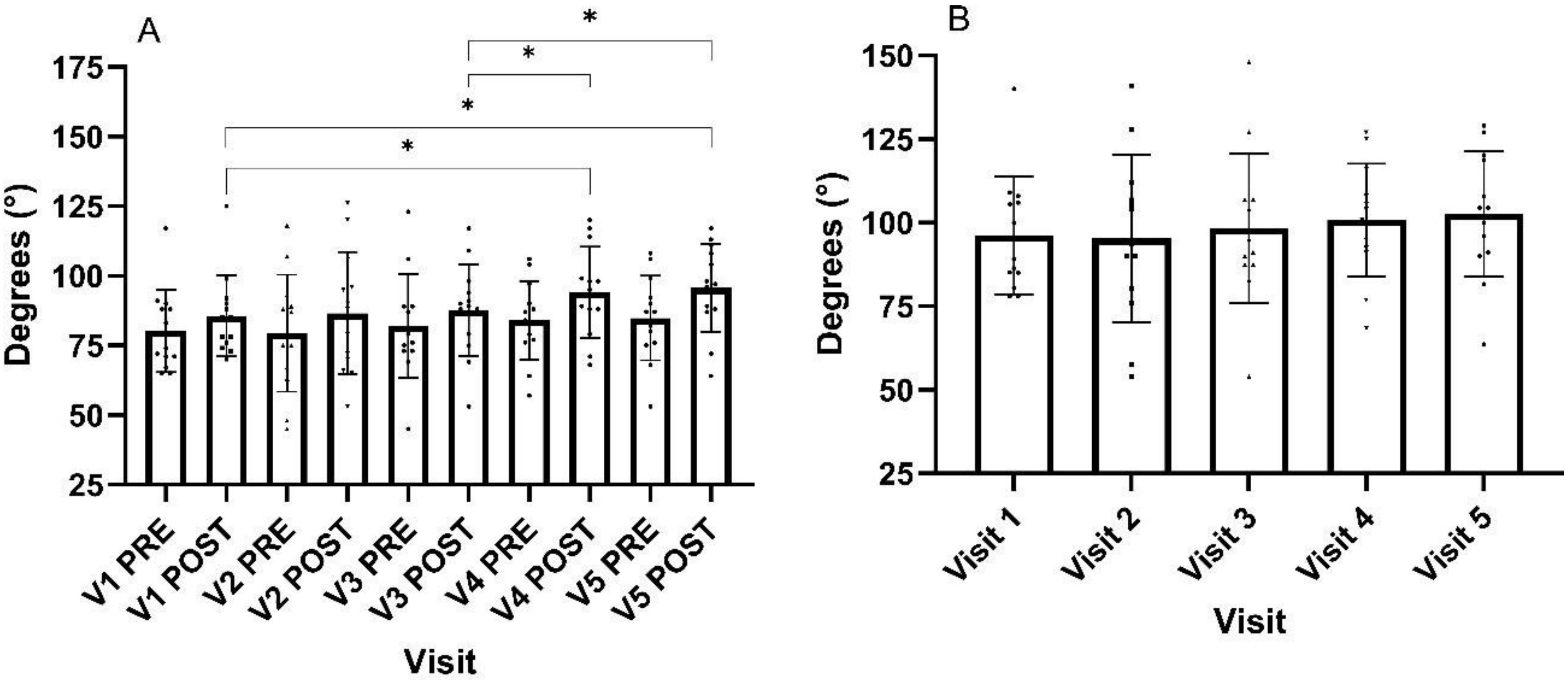

Figure 6.2 A ROM achieved to the point of discomfort, pre and post static stretching at 120% of the point of discomfort. 2B static stretching degrees for the 120% point of discomfort for the five visits. * different (p<0.05).

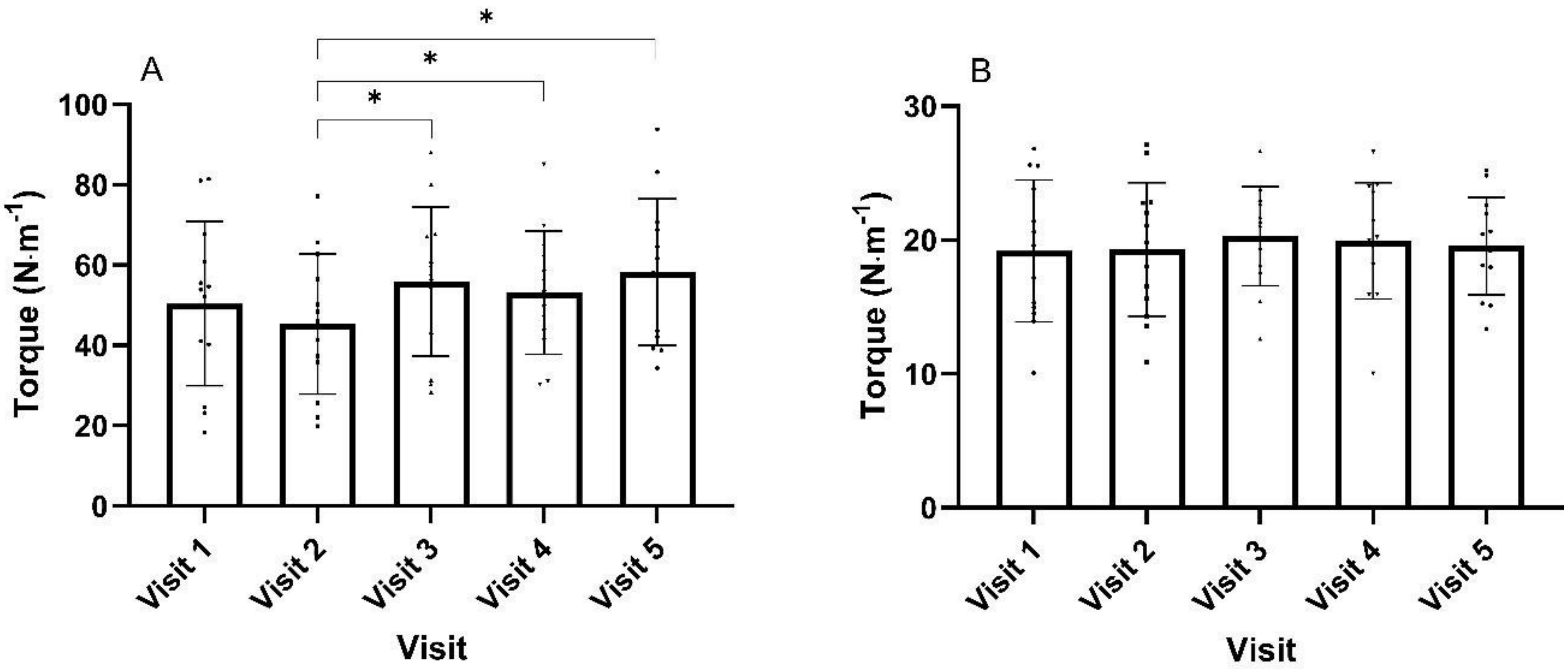

Figure 6.3 A Peak Torque achieved during the stretches to 120% of the point of discomfort, 2B gravity corrected passive stiffness following the static stretching. * different ($p<0.05$).

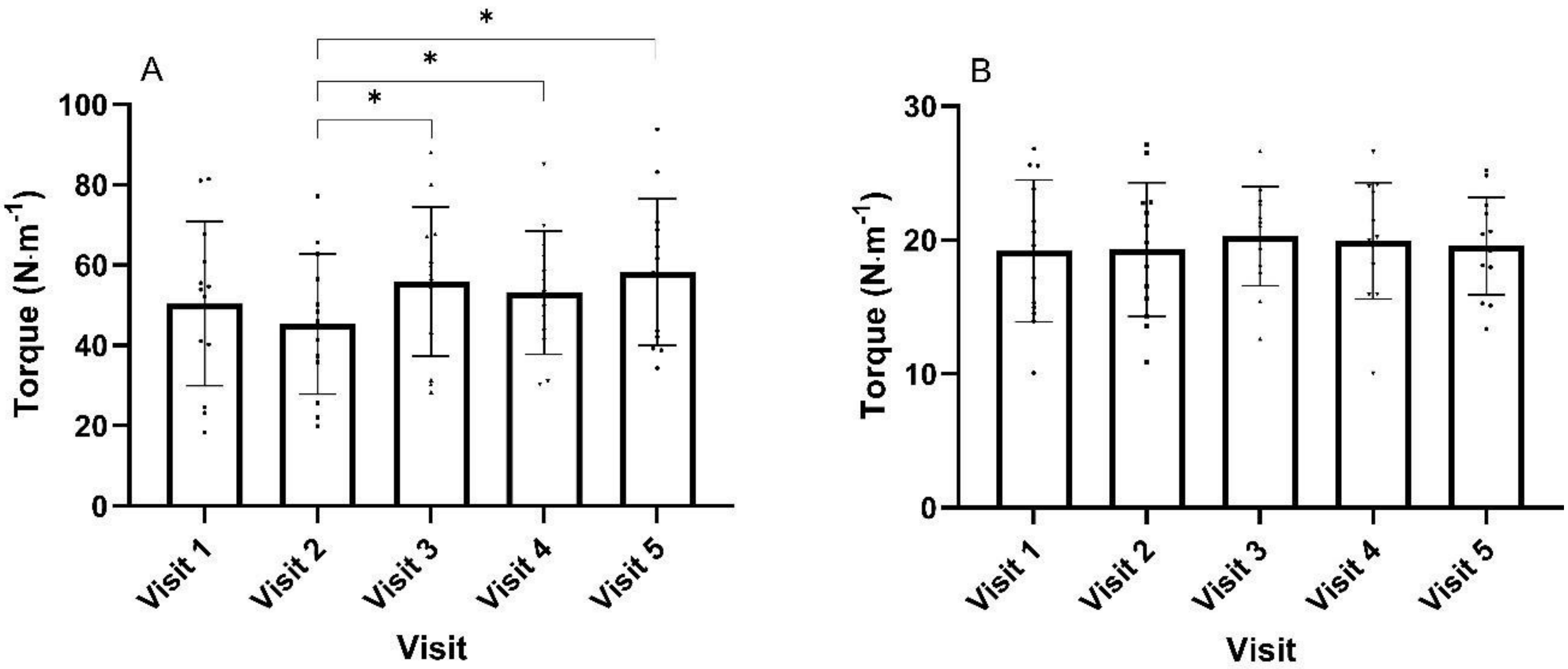

Figure 6.4 Maximal voluntary isometric contraction of the knee flexors at 50% range of motion pre and post 30-seconds static stretching at 120% point of discomfort. * different ($p<0.05$).

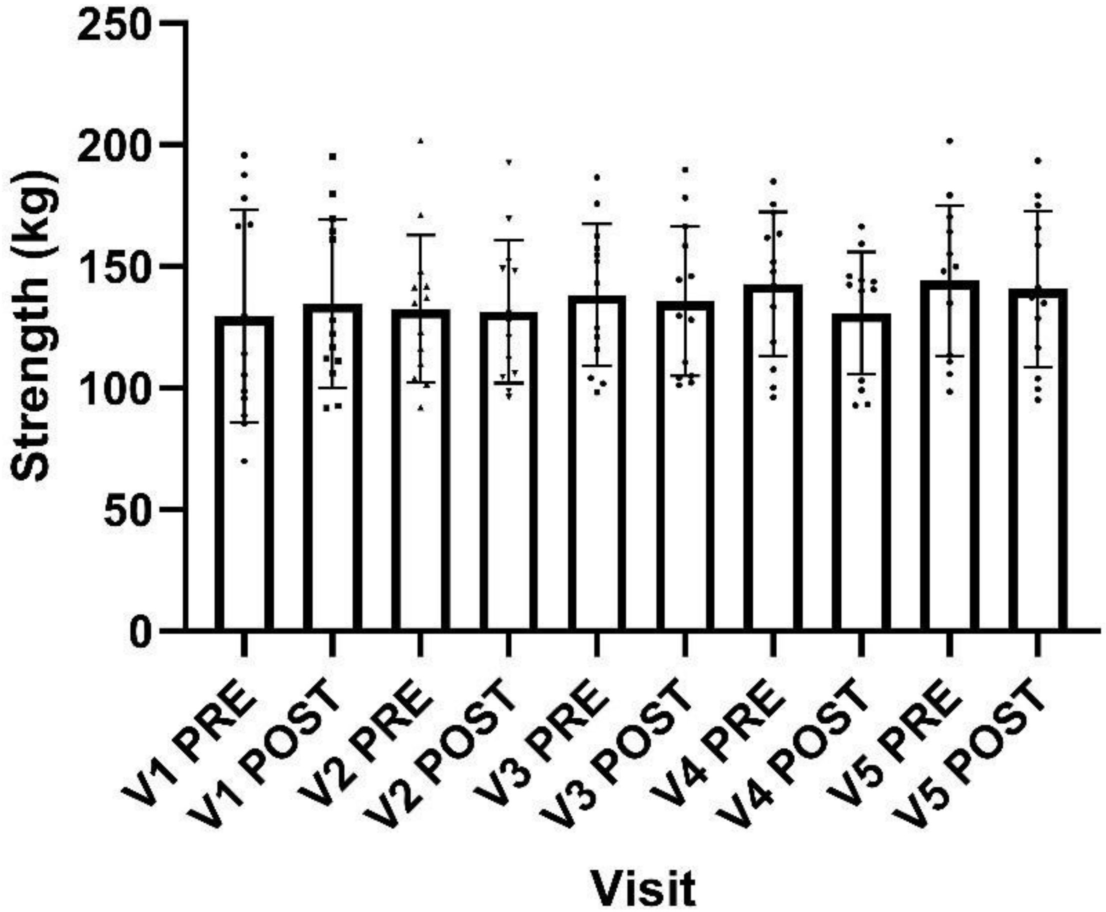

Figure 6.5 Maximal voluntary isometric contraction of the knee flexors at 50% range of motion pre and post 30-seconds static stretching at 120% point of discomfort.

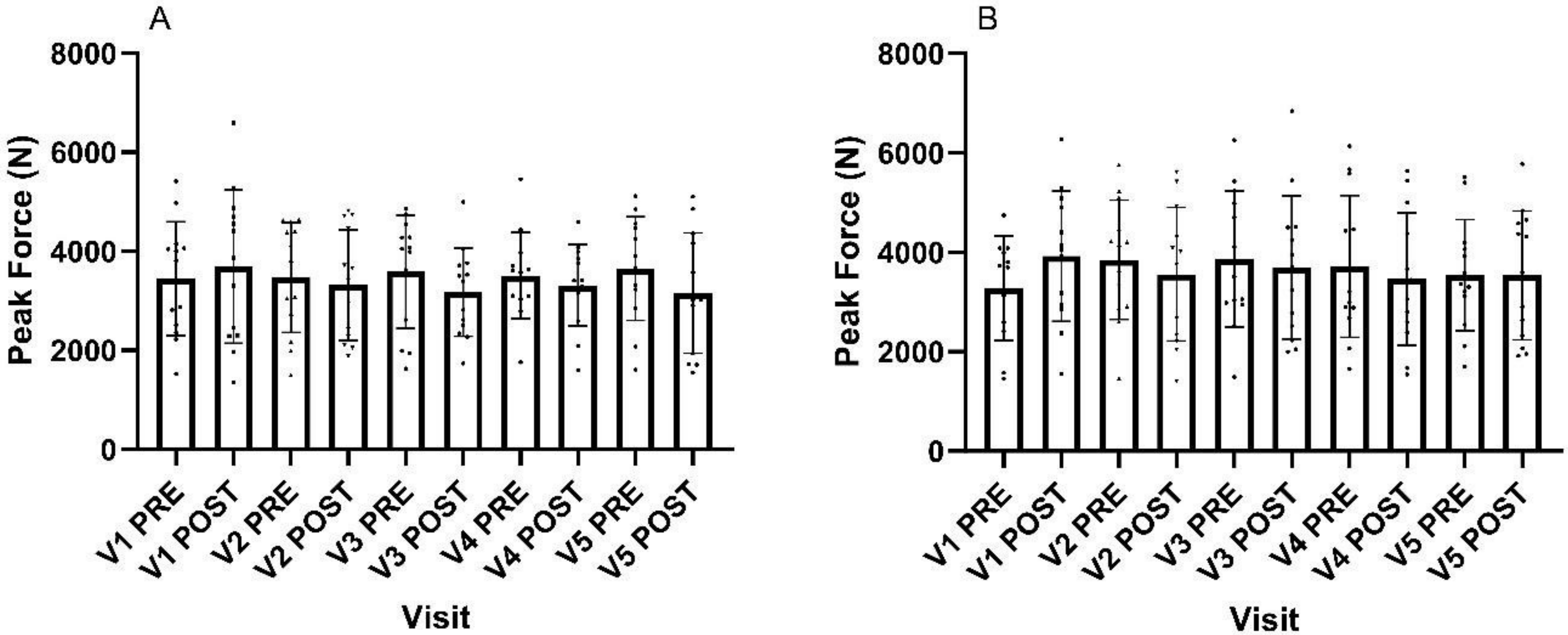

Figure 6.6 A Peak force from a single leg vertical jump off a 20-centimetre box, pre and post static stretching at 120% of the point of discomfort. 5.4B Peak force from a single leg, fourth maximal jump immediately following 3 hops, pre and post static stretching at 120% of the point of discomfort

6.3.5 Reliability of static stretching

The reliability and confidence intervals for knee extension ROM, knee flexion peak MVC force and passive stiffness are illustrated in Table 5.2.

Table 6.2 Reliability as assessed by intraclass correlation and 95% confidence interval (CI) for knee extension ROM, peak MVIC and passive stiffness.

	Visit 2 - 1	Visit 3 - 2	Visit 4 -3	Visit 5 - 4	Pooled ICC
Knee extension ROM	0.71 (0.37-0.88)	0.90 (0.75-0.96)	0.89 0.72-0.96	0.84 (0.62-0.94)	0.82 (0.68-0.92)
Knee flexion MVIC	0.87 (0.68-0.85)	0.69 (0.34-0.87)	0.78 (0.50-0.91)	0.85 (0.63-0.94)	0.81 (0.66-0.91)
Passive stiffness	0.86 (0.67-0.95)	0.85 (0.65-0.94)	0.86 (0.66-0.95)	0.74 (0.43-0.89)	0.81 (0.71-0.93)

6.4 Discussion

There are several key findings from this study. The primary aim of this study was to test the reliability of a 120%POD hamstring static stretch as a high-intensity static stretch. This method of high-intensity static stretching has been used in several studies (Kataura *et al.* 2017, Takeuchi *et al.* 2021), however, the reliability has not been examined, the main finding from the current study shows that this is a reliable method of generating a high-intensity static stretch as participants' perception of stretch remained high each visit. To the author's knowledge, this is the first study to investigate the reliability of a high-intensity static stretching method. The stretching sensation achieved within the present study is comparable to previous studies. For example, the pain reported by participants on the visual analogue scale was ~50 mm for all the visits. Previous studies have reported when stretching the quadriceps at 120% ROM to be 59.5 mm (Nakamura *et al.* 2021) and ~60 mm (Takeuchi *et al.* 2021). Therefore, the stretching in the present study indicates that pain during the static stretching was very high. Furthermore, as the pain reported on the VAS was unchanged across the visits, it confirms that participants reliably identify the POD and a high-intensity stretch. From an applied perspective however, it should be recognised that due to subjective nature of pain, requiring participants with a high pain threshold to stretch to their PoD could be placing greater stress on the tissues than for an individual with a lower threshold (Behm, 2018).

The secondary aim of this study was to investigate the acute effects of 120%PoD static stretch on ROM, passive stiffness, MVIC strength and single-leg jump power. The results showed that ROM was increased following the static stretch which is in line with previous research (Medeiros *et al.*, 2016, Marchetti *et al.* 2019). Increases in ROM following static stretching are often attributed to decreases in passive stiffness (Morse *et al.* 2008), however, results from this study show that passive stiffness remained unchanged following the static stretch, this suggests that the increases in ROM following a high-intensity static stretch are due to an increase in stretch tolerance (Weppler & Magnusson, 2010, Killen *et al.* 2019). The duration of static stretch in this study was 30 seconds, it is theorised that shorter duration stretches (<60 seconds) may be insufficient to reduce passive stiffness (Matsuo *et al.* 2013; Stafilidis & Tilp, 2015).

Knee flexion MVIC was reduced following the high-intensity static stretch in each visit which is in accordance with previous literature (Kataura *et al.* 2017, Rodriques *et al.* 2017). Decreases in strength following static stretching are multifactorial and often attributed to decreases in passive stiffness, however, the high-intensity static stretch used in this study did not decrease passive stiffness, therefore, the decrease in MVIC may likely be due to other underlying mechanisms such as reduced neural activity such as a decrease in EMG activity (Trajano *et al.* 2017) or reduced tendon stiffness resulting in the MTU performing at a shorter and weaker part of the length-tension relationship (Cramer *et al.* 2005).

Static stretches of similar duration (~30 seconds) have been shown to have trivial to no effect on strength output (Behm *et al.* 2016), therefore, it could be suggested that the high-intensity nature of the stretching plays a greater role in the stretch-induced force loss at shorter durations.

Furthermore, power output measured using a drop jump and a single leg hop test were unchanged pre to post, previous research suggests that power is decreased following a static stretch intervention (Simic *et al.* 2013), this may be due to passive stiffness remaining unchanged. In addition, this difference in findings may be due to the muscles used within these specific movements.

6.4.1 Limitations

There are several limitations within this study, the first of which is that this study only examined healthy males aged 18 to 35, which was chosen as a homogenous and convenience sample. Therefore, it is not known if reliability is affected in females, as it is unclear if menstrual cycle hormone fluctuations alter joint laxity (Park *et al.*. 2009; Shagawa *et al.* 2021). In addition, while the participants in the current study were moderately active, none of them were elite athletes, studies have shown that elite athletes may respond differently to acute static stretching (Egan *et al.* 2006; Molacek *et al.* 2010).

Another limitation is that this study only examined the effects on the hamstrings, future research should be conducted on other muscle groups, however, for other muscles such as the quadriceps, it may not be biomechanically possible to stretch to 120% of the PoD ROM. A further limitation of the current study is that it did not compare the effects of different intensities such as 100% or 110% PoD or different durations of stretch on performance measures. Lastly, this experiment measured reliability in a laboratory and is limited to this setting. Therefore, application in the applied environment needs to be determined.

6.5 Conclusion

Across five laboratory visits, the range of motion achieved of the hamstrings during a 30-second static stretch on an isokinetic dynamometer to the point of discomfort is not different across multiple sessions, in addition, there was no change in participants perception of the stretching intensity suggesting that a static stretch of the hamstrings at 120% of the point of discomfort is a reliable method of producing a high-intensity static stretch. Furthermore, there were also no changes in gravity-corrected passive stiffness, strength and power following the static stretching. There is also good, pooled reliability in range of motion, knee flexion strength and passive stiffness across multiple testing visits.

7 Effects of different duration of low and high-intensity static stretching on range of motion, muscle activation, architecture, strength and power.

Results from the previous study showed that a 30 second hamstring stretch at 120%POD was a reliable method of generating a high-intensity static stretch, based on this, the next study should compare the effects of different intensities and durations of static stretch on ROM, strength and power. In addition, the next study could investigate some potential underlying mechanisms for changes to strength and power following the static stretch.

Abstract

The effects of static stretching on ROM, strength and power have been extensively researched, however, the effects remain unclear, especially with regards to the intensity of static stretching. This investigation aimed to compare the effects of three different static stretching conditions of different intensities and durations on ROM, strength and power. In addition, this investigation examined the effects of the static stretch conditions on potential underlying mechanisms of passive stiffness, EMG and muscle architecture. Fourteen healthy males (Age: 26.5±5.8 years, Height: 177.9±6.6 cm, Body mass: 78.6±10.5 kg) underwent four laboratory visits consisting of an ultrasound of Bicep femoris, a ROM test to the PoD with EMG measurements, hamstring flexion strength test with EMG measurements and single leg jump tests. Participants then performed a static stretch intervention of the hamstring, in visits 2 and 3, participants static stretched to either 100% or 120%PoD for 30 seconds in a randomised order and in visit 4, stretched to 120% for 60 seconds. Results showed ROM increased following all three conditions with 120%*60s leading to a greater increase (P=0.024) and passive stiffness decreased over time (p=0.007). No changes were observed for strength, power, EMG or muscle architecture. In conclusion, long duration and high-intensity SS leads

to greater increases in ROM, these static stretch conditions showed no changes to strength and power.

7.1 Introduction

The effects of static stretching on performance have been extensively researched yet findings continue to be conflicting and inconclusive. Research once showed that static stretching prior to exercise can have a negative impact on strength and power output which could then negatively affect sports performance. It is theorised that static stretching reduces muscle-tendon unit (MTU) stiffness, which in turn decreases the speed at which muscle can produce force to the bone known as the stretch-induced force loss (Walsh *et al.* 2017; Gesel *et al.* 2022). This has been disputed by studies examining different durations of static stretching which have observed that shorter durations of static stretching (<30 seconds) may not lead to negative effects (Kay & Blazevich, 2012; Behm *et al.* 2016). This is thought to be due to shorter duration stretches not being long enough to reduce MTU stiffness to the point that it negatively impacts force production (Chaabene, 2019).

A variable that is gaining more attention within the literature is the intensity of static stretching, this is defined as: *"The degree of muscle-tendon lengthening induced by a change in joint range of motion (ROM) that is controlled by an individual's subjective tolerance to stretch"* (Freitas *et al.* 2015). The intensity of a static stretch is important for increasing joint ROM as too little force may not elicit any changes to ROM and too much intensity may lead to tissue strain or an inflammatory response (Jacobs & Sciascia, 2011; McClure *et al.* 1994). Recent research has shown that higher-intensity static stretches are likely to lead to a greater acute increase in ROM compared to lower intensities (Kataura *et al.* 2017; Takeuchi *et al.* 2020). Research examining different intensities of static stretching on strength is conflicting as some studies have shown that higher intensity will lead to a greater stretch-induced force loss than lower intensities (Kataura *et al.* 2017; Rodriques *et al.* 2017). However, other studies have found no difference between high and low-intensity static stretching on subsequent strength output (Apostolopoulos *et al.* 2018, Takeuchi *et al.* 2020). The systematic review presented in chapter 4 further highlighted the inconsistency in studies reporting that high-intensity stretching causes a force decrement.

Another theory for stretch-induced force loss is due to a decrease in muscle signalling activity, as measured by electromyography (EMG). This theory is disputed due to some studies finding a decrease in EMG activity following static stretching (Fowles *et al.* 2000; Behm *et al.* 2001) and some finding static stretching to not affect EMG activity (Kay & Blazevich, 2009; Palmer *et al.* 2019). Contradictory findings may be due to the duration of static stretches used, for example, Behm *et al.* (2001) used 45 seconds and Palmer *et al.* (2019) used 30, 60 and 120-second stretches. Furthermore, these conflicting findings may also be due to differences in the intensity of stretch used or lack of accounting for intensity as neither Behm *et al.* (2001) nor Palmer *et al.* (2019) described the intensity that their participants stretched to. As a result, different static stretching intensities may lead to different effects on EMG activity.

Changes to properties of muscle architecture following static stretching have also been suggested to be partly responsible for the stretch-induced force loss, for example, increases in pennation angle may reduce muscle force (Eng *et al.* 2018). Alterations to muscle architecture can also be beneficial for muscle force, for example, a longer fascicle length may contribute to faster sprint times (Wakahara *et al.* 2013). However, studies that have investigated an acute bout of static stretching on muscle architecture have not observed any changes (Ce *et al.* 2015; Opplert *et al.* 2016). It has been suggested that static stretching to the point of discomfort used in these studies was not of sufficient enough intensity to elicit architectural changes.

The primary aim of this study is to examine the acute effect of low-intensity and high-intensity static stretching on joint ROM, strength, power, EMG activity and muscle architecture. The secondary aims are to investigate the effects of a high-intensity static stretch for different durations (30 seconds and 60 seconds) on ROM, strength, EMG activity and muscle architecture.

7.2 Methods

7.2.1 6.2.1 Ethical approval

Ethical approval was granted for the study by the University of Worcester’s Health and Sciences Ethics Panel (HS22230037).

7.2.2 Participant characteristics

The study recruited 14 male participants (18-35 years old) with characteristics presented in table 7.1. The power calculation in chapter 3, General Methods, indicated that 15 participants were required, however, 14 were recruited within the recruitment period for this experiment. All were briefed on the study aims and protocol and gave informed consent. Participants were excluded if they had lower limb injuries in the six months prior to taking part in the study.

Table 7.1 Participant characteristics

Age (years)	26.5±5.8
Height (cm)	177.9±6.6
Body mass (Kg)	78.6±10.5
BMI	24.8±2.9

7.2.3 Study Design

Participants visited the laboratory four times with a minimum of seven days separating each visit. The first visit was a familiarisation to allow for possible learning effects of the protocol. Participants first performed a warm-up on a stationary bike (Monark Ergomedic 874E, Monark Sports and Medical, Vansbro, Sweden) at approximately 60RPM for five minutes. Ultrasound of the dominant leg Bicep Femoris was then recorded. Performance measures of ROM, passive stiffness, maximal isometric strength on the isokinetic dynamometer (Humac Norm Isokinetic dynamometer CSMi), and power tests on a force plate were then taken, this was followed by a 10-minute break before the static stretching intervention. Immediately following the stretching intervention, participants were asked to mark on a visual analogue scale how the stretch felt from 'no pain at all' to 'worst pain imaginable.' The performance and ultrasound measures were then repeated in the same order as before the stretch intervention. Surface EMG of the Bicep Femoris was measured during the ROM and MVIC tests both pre and post-stretch and during the stretch intervention (Figure 6.4).

7.2.4 Static stretching protocol

Participants were seated in an isokinetic dynamometer in a hip flexed position which has been shown to allow a sufficient stretch of the hamstrings (Matsuo *et al.* 2013). To achieve this position the angle between the backrest and seat of the isokinetic dynamometer was set to 60°. The participant's dominant leg was then extended by the primary researcher to 100% or 120% of the angle they scored in the pre-intervention ROM test, this position was then held for 30 seconds during visits one, two and three and for 60 seconds in visit 4. Participants were instructed to relax.

7.2.5 Range of motion

Participants were seated in the isokinetic dynamometer in the same position as the stretch protocol. The primary investigator moved the participant's dominant leg into knee extension, and the participant was then instructed to indicate the first moment they felt the stretch. This angle was used as their point of discomfort ROM angle.

7.2.6 Passive stiffness

In the same seated position as the ROM test, the participants' dominant leg was passively extended by the dynamometer up to the PoD angle and back down. Participants were instructed to relax.

7.2.7 Isometric strength

In the same hip flexion position on the isokinetic dynamometer as the ROM test, the arm of the dynamometer took the participant's dominant leg up to 50% of the angle achieved in the ROM test. Participants were then instructed to flex their knee as hard as they could, this was held for six seconds.

7.2.8 Power

Power was measured using two single-leg jump techniques on a force plate. The first was a single-leg drop jump off a 20-centimetre box; participants were instructed to jump as high as they could. The second jump test was a single-leg pogo jump which involved three small hops and a fourth maximal single-leg jump; participants were instructed to jump as high as they could on the fourth jump.

7.2.9 Stretch sensation

To measure stretch sensation immediately following the stretch, participants were asked to mark on a 10-centimeter visual analogue scale how they perceived the stretch from ‘No pain at all’ to ‘worst pain imaginable.’ The mark was then measured by ruler.

7.2.10 Electromyography

Electromyography of the biceps femoris was taken during the ROM, MVIC and static stretch. Signals were recorded using SX230 EMG surface electrodes, DLK900 DataLINK acquisition unit and DataLOG v10.27 software (Biometrics Ltd, Newport UK). Electrodes were placed according to SENIAM guidelines (http://seniam.org/bicepsfemoris.html.) The site for electrode placement was identified by palpating for the ischial tuberosity and the insertion at the lateral epicondyle of the femur and then measuring the midpoint between the two landmarks (Figure 6.1). The skin was prepared, shaving if necessary, cleansing and abrading to minimise skin-to-electrode impedance.

In the DataLOG software time markers were used to identify and isolate which part of the signal was produced during the measures. This section of the raw EMG signals was demeaned, rectified and filtered using a rolling 50 ms root mean square (RMS). The maximum EMG signal for each measure was recorded.

Figure 7.1 Surface EMG amplifiers placement.

7.2.11 Ultrasound

The fascicle angle and length of the Bicep Femoris were assessed pre- and post-static stretch intervention using a Sonoscape E2 EXP (digital colour doppler ultrasound system) with an L471 Linear array (16-4 MHz) probe. All participants were in a supine position with their knees extended and ankles in a neutral position.

Images for the pennation angle were taken at the midpoint between the proximal and distal musculotendinous junction (MTJ) landmarks, pennation angle was calculated from the insertion of the fascicles to the aponeurosis. To measure fascicle length the panoramic setting was used which involved the primary investigator (JB) slowly moving the probe from the distal MTJ towards the proximal MTJ. The fascicle length was determined by measuring the distance between the upper aponeurosis and deeper aponeurosis along the fascicular path. The use of panoramic imaging has been shown to be a reliable method of measuring hamstring muscle architecture (Palmer et al., 2015).

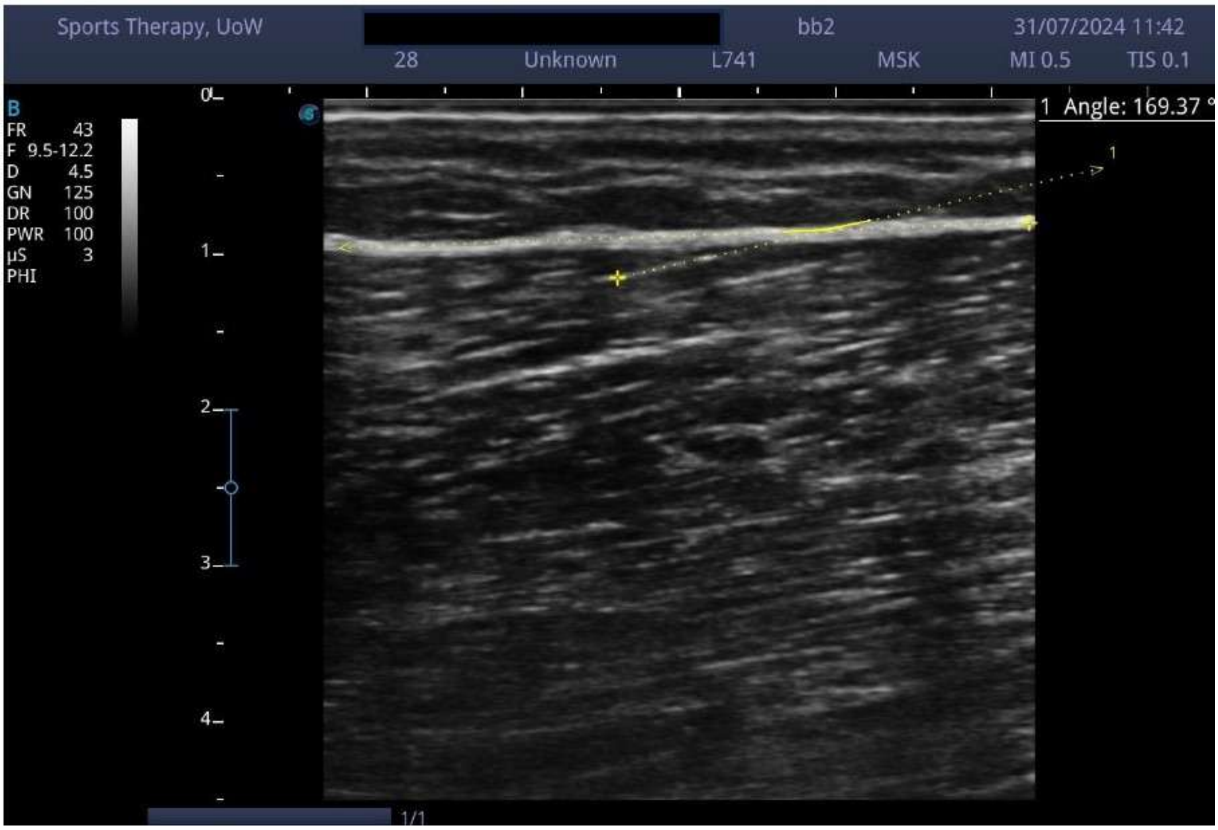

Figure 7.2 Pennation angle of the biceps femoris from the ultrnsound field.

Figure 7.3 Fascicle length from of the biceps femoris from the ultrasound field.

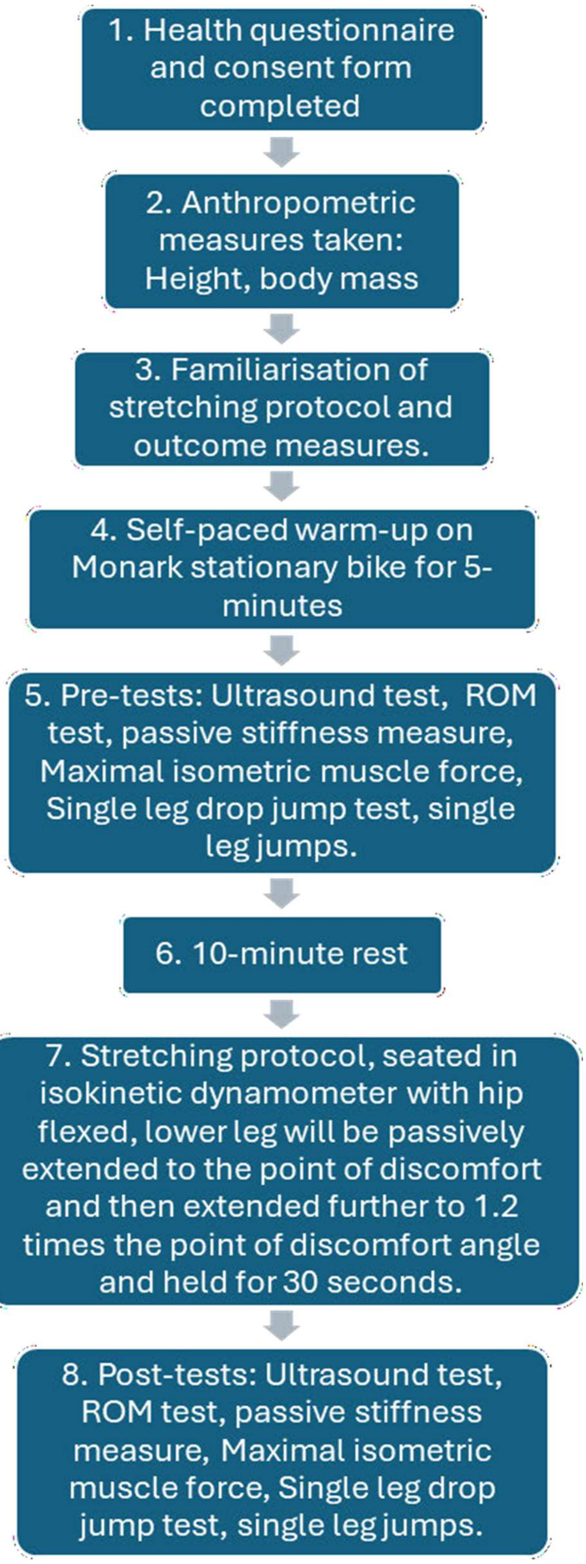

Figure 7.4 Flowchart of study procedure

7.2.12 Statistical analysis

Statistical analysis was conducted using SPSS 29.01.0 (IBM SPSS Statistics, Armonk, NY: IBM Corp). Data normality was assessed using the Shapiro-Wilks test, with no violations in normality found. Variables were analysed between conditions (100%*30s vs 120%*30s vs 120%*60s) and time (Pre vs Post) with a two-by-three-way repeated measures ANOVA. Repeated measurements were checked for sphericity violations using Mauchly's test and if violated, Greenhouse-Geisser correction was applied. Where differences occurred partial-eta2 ($\eta p2$) is reported and followed by pairwise post hoc comparisons. An alpha level of $p<0.05$ was set for statistical significance, however, 95% Confidence interval was calculated when $p<0.07$ (Greenland et al., 2016, Greenland et al., 2019). Delta (Δ) change was calculated by finding the difference between participant's pre- and post-scores for each visit, these values were then compared with a one-way repeated measures ANOVA.

7.3 Results

7.3.1 Range of Motion

For ROM, there was an effect over time ($F_{(1,13)}=41.663$, $p<0.001$, $\eta p2=0.762$), however, there was no effect between the conditions (p=0.501) (Figure 6.5A). There was also a strong trend for an interaction between the conditions and over time (p=0.067). For the three conditions, there was a large effect of d=0.89, d=1.53 and d=1.55 for 100%*30s, 120%*30s and 120%*60s, respectively to increase over time. The ΔROM between the conditions also had a strong trend (p=0.064) with the 120%*60s stretch different to the 100%*30s stretch (p=0.024, d=0.680, 95% CI [0.584, 7.130]) (Figure 6.5 B).

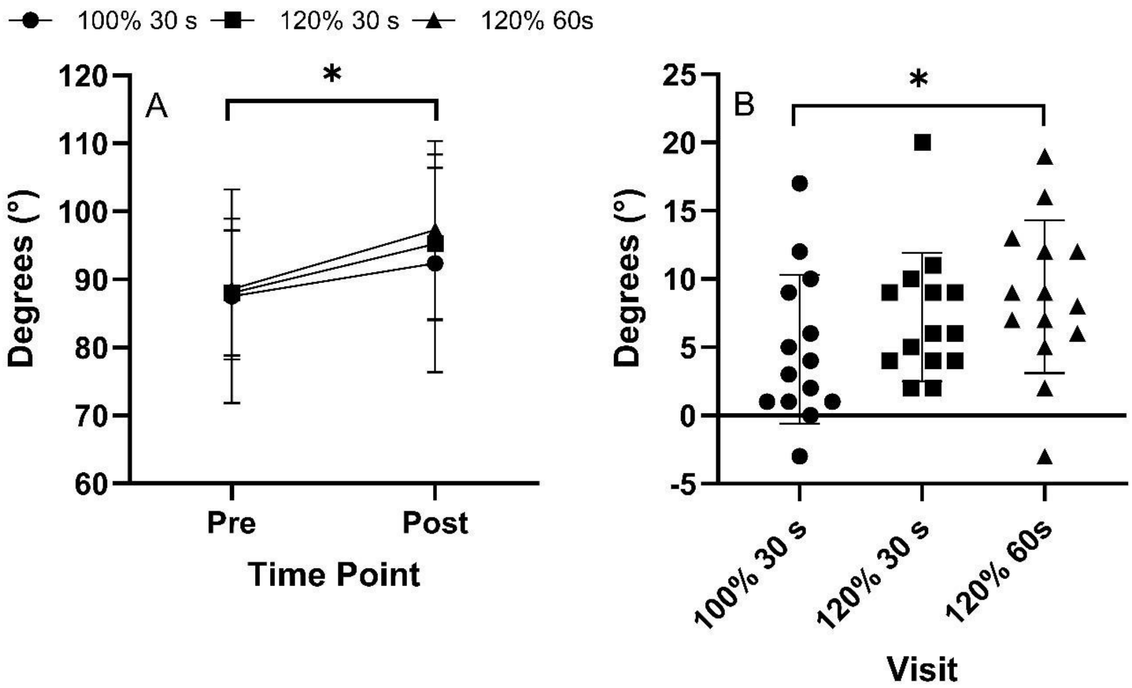

Figure 7.5 A Range of motion of the knee flexors pre and post stretching at different durations and intensities. B change of motion of the knee flexors pre and post stretching at different durations and intensities * different (p<0.05).

7.3.2 Maximal Voluntary Isometric Contraction

For knee flexion MVIC, there was no effect between the conditions (p=0.619), over time (p=0.684) or an interaction (p=0.118). The ΔMVIC between the conditions also showed no change (p=0.118) and there was a strong trend for an effect between 120%*30s and 120%*60s (p=0.069, 95% CI [-1.076, 25.022]).

7.3.3 Passive Stiffness

For passive stiffness, there was no effect between the conditions (p=0.639), or an interaction (p=0.143), however there was a change over time between the pre and post time points (p=0.003, 95% CI [1.187, 4.594]) (Figure 6.6). The Δ passive stiffness between the conditions showed no change (p=0.143).

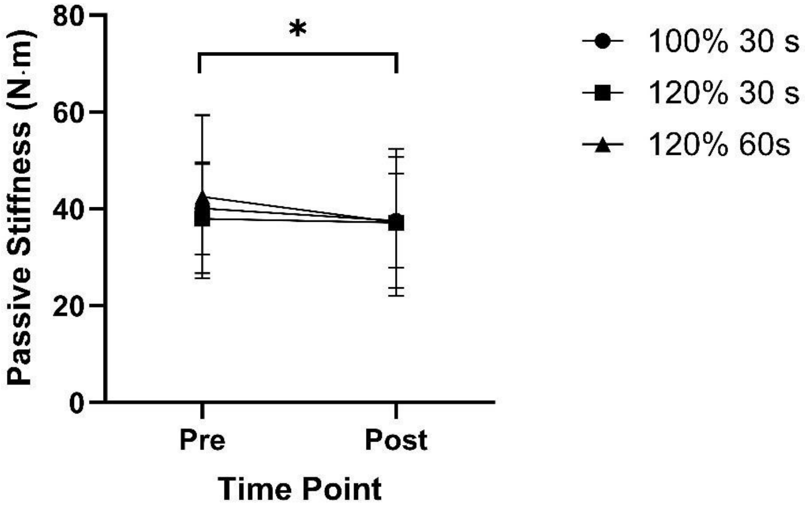

Figure 7.6 Change in passive stiffness of the knee flexors pre and post stretching at different durations and intensities. * different (p<0.05) across time.

7.3.4 Vertical jumps

For the drop jump, there was no effect between conditions (p=0.422), or an interaction (p=0.744). There was a strong trend for an effect over time (p=0.078, 95% CI [-22.329, 372.557]). For the single leg hop, there was no effect between conditions (p=0.179), or an interaction (p=0.927). However, there was a strong trend for an effect over time (p=0.057, 95% CI [-558.023, 9.542]).

There was no Δ change for either the drop jump (p=0.774) or the single leg hops (p=0.927).

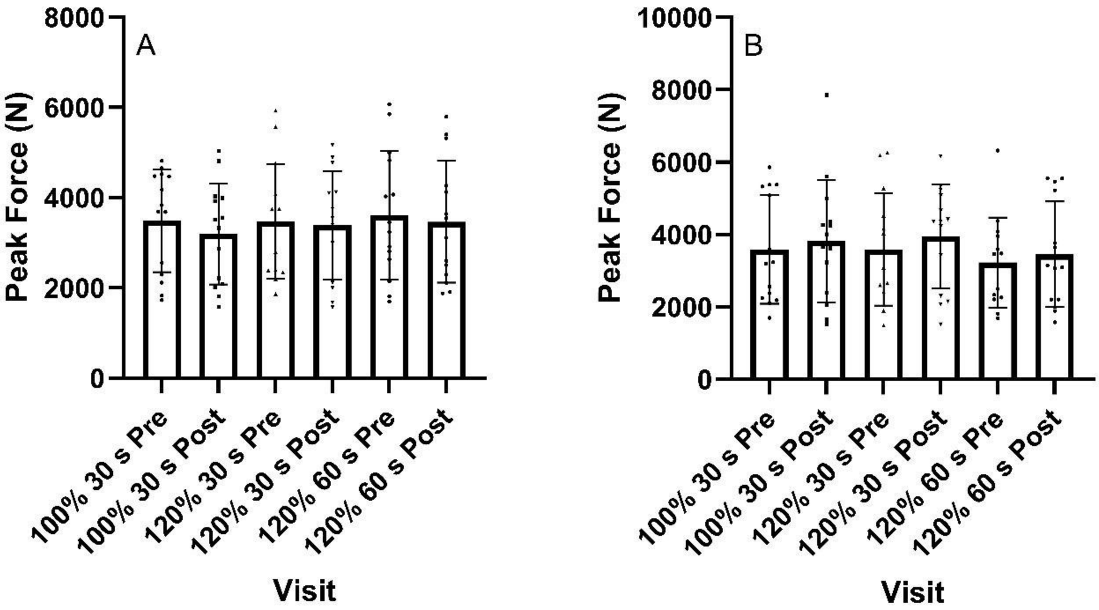

Figure 7.7 Peak force produced during a vertical jump before and after different duration and intensities of static stretching, B Peak force produced during a vertical jump following three prior hop jumps.

7.3.5 Muscle architecture

For fascicle angle, there was no effect between the conditions (p=0.869), over time (p=0.576) or an interaction (p=0.238) (Figure 7.2). For fascicle length, there was no effect between conditions (p=0.622), over time (p=0.522) or an interaction (p=0.296) (Figure 7.3).

There was no Δ change to either fascicle angle (p=0.238) or fascicle length (p=0.296).

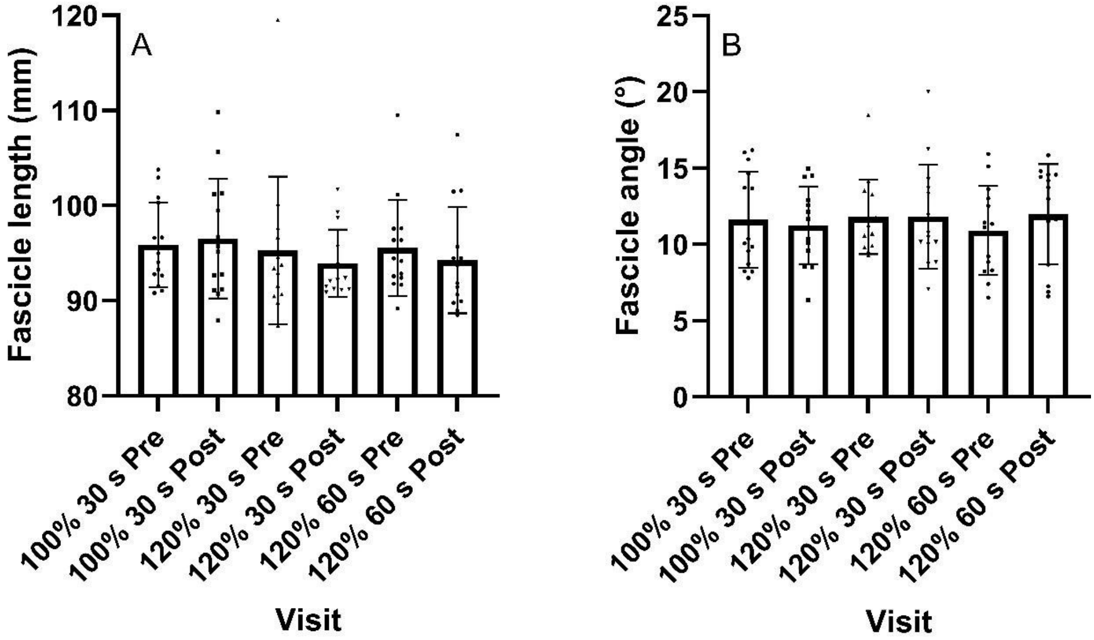

Figure 7.8 A Fascicle length of the biceps femoris, before and after static stretching of different intensities and durations. B fascicle angle of the biceps femoris, before and after static stretching of different intensities and durations.

7.3.6 EMG

For the EMG signal during the ROM test, there was no effect between the conditions (p=0.417), over time (p=0.524), or an interaction (p=0.324). For the EMG during the MVIC test, there was also no effect between conditions (p=0.554), over time (p=0.176), or an interaction (p=0.937).

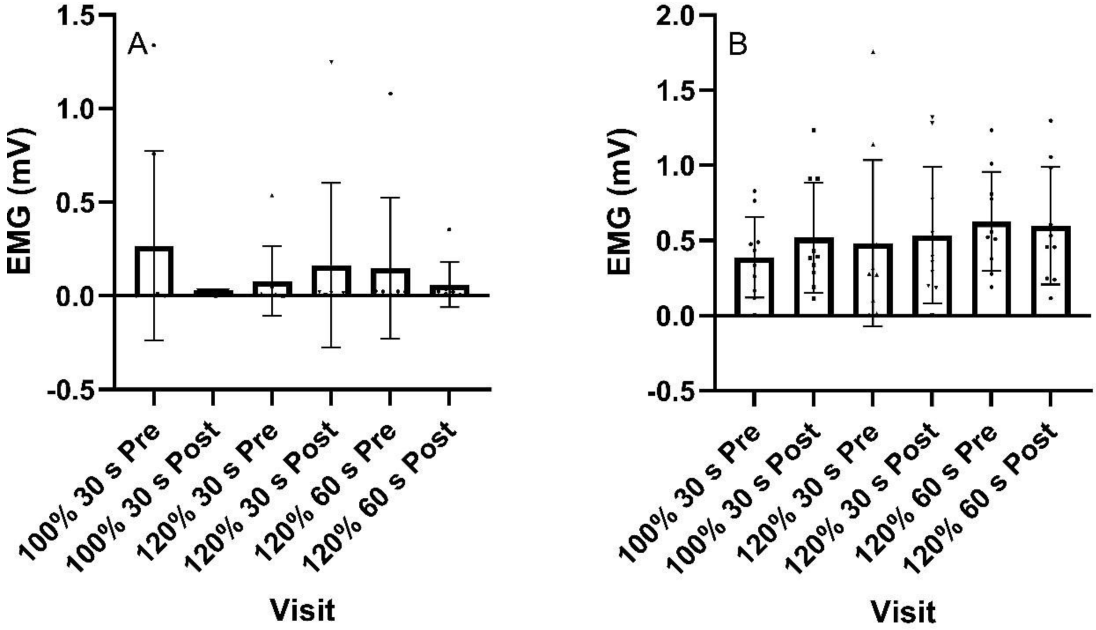

Figure 7.9 A Electromyography (EMG) signal during the range of motion procedure before and after different duration and intensities of static stretching, B Electromyography (EMG) signal during the maximal voluntary contraction before and after different duration and intensities of static stretching.

7.4 Discussion

This study aimed to examine the acute effects of three static stretching conditions of different intensity and duration (100%*30s, 120%*30s and 120%*60s) on ROM, strength, power, muscle activation and architecture. All three conditions led to an increase in ROM, with the 120%*60s condition leading to a greater increase than the 100%*30s condition. There was a decrease in passive stiffness following all stretch conditions but no differences between the conditions. There was no change to knee flexion MVIC, drop jump and single leg hop performances following any of the stretch conditions. There was also no change to muscle architecture measures, specifically fascicle angle and fascicle length, furthermore, there was no change to EMG output during the ROM and MVIC tests.

ROM increased following each static stretching condition, with the high-intensity and high duration condition (120%*60s) leading to a greater increase than the low-intensity and low duration condition (100%*30s). This is in accordance with previous research on the effects of static stretching intensity, Kataura *et al.* (2017) showed that ROM increases following 80%, 100% and 120% intensities, with the greatest increase occurring following the 120% intensity stretch. However, within the current study, there was no difference between the 100%*30s and the 120%*30s, this may indicate that increases in ROM are more due to the duration of the stretch rather than the intensity. Increases in ROM are attributed to decreases in passive stiffness (Morse *et al.* 2008) or an increase in stretch tolerance (Killen *et al.* 2019). Results from this study observed a decrease in passive stiffness following all static stretching conditions, however, no difference between conditions was observed. This may suggest that the greater increase in ROM following the 120%*60s condition was due to an increase in stretch tolerance.

The results of this study showed no change to MVIC strength performance following all static stretch conditions and no differences between conditions. These results are not in agreement with the majority of research on the effects of static stretching on strength (Power *et al.* 2004; Simic *et al.* 2013; Walsh *et al.* 2017) which show that static stretching leads to a decrease in strength. In addition, research on different intensities of static stretching on strength has shown that higher intensities lead to a greater reduction in strength (Kataura *et al.* 2017, Rodrigues *et al.* 2017, Chapter 5 of this thesis), however, this was not observed within the current study. A common mechanism theorised for stretch-induced force loss is a reduction in passive stiffness (Behm *et al.* 2016). However, within the current study, a reduction in passive stiffness was observed following the static stretching conditions, yet there was no decrease in strength. This finding is in accordance with a previous study which also observed a decrease in hamstring passive stiffness and no decrease in peak torque (Takeuchi *et al.* 2020). Short-duration static stretches (<60 seconds) have been shown to not affect passive stiffness which then does not lead to stretch-induced force loss (Matsuo *et al.* 2013; Stafilidis & Tilp, 2015). It could be speculated that the reduction in passive stiffness observed in the current study was not a sufficient reduction to then reduce strength. It has been shown that static stretches held for longer than 30 seconds are more likely to lead to stretch-induced force loss (Behm & Chaouchi, 2011; Behm *et al.* 2016), Ogura *et al.* (2007) compared 30-second and 60-second hamstring static stretching on hamstring MVC and observed a greater decrease in strength following the longer duration condition; the results from the current study contradict these findings. In addition, the total volume of static stretching may affect the stretch-induced force loss, for example, Rodrigues *et al.* (2017) examined two sets of 30-seconds of high-intensity static stretching on quadricep peak concentric force, it could be proposed that one repetition of static stretching is not sufficient to lead to the stretch-induced force loss.

Another factor that may explain not observing the stretch-induced force loss is the time between the static stretching intervention and the strength test. Due to the order of procedures and the ultrasound measurements in the current study, there was a greater time between the stretch intervention and the strength test compared to the study in Chapter 5 of this thesis. Previous research has found that the time between the stretch and the strength test may impact results, for example, Ryan *et al.* (2008) and Mizuno *et al.* (2014) both found that plantar flexion strength decreases immediately following static stretching but recovers within ten minutes. Nakamura *et al.* (2022) demonstrated similar findings for the hamstrings, observing that knee flexion MVIC decreases immediately following static stretching and trends towards recovering after ten minutes and fully recovering after 20 minutes. However, contradictory findings have been found, for example, Power *et al.* (2004) observed strength decreases for up to 120 minutes following a static stretching intervention and Haddad *et al.* (2014) showed that strength and explosiveness could be diminished for up to 24 hours following static stretching.

A neurological mechanism that may also explain why the stretch-induced force loss was not observed following the static stretching intervention within the current study is EMG. Reductions in EMG following static stretching have been suggested as a theory for the stretch-induced force loss (Behm *et al.* 2019). Results from the current study observed no change to Bicep Femoris EMG during the ROM test or strength test following static stretching which may indicate why there was no decrease in strength. This agrees with previous research, for example, Palmer *et al.* (2019) observed no reductions in hamstring peak torque or EMG after 30, 60 and 120 seconds of static stretching.

This study examined power output using two different single leg jump techniques, specifically, a drop jump test from a 20-cm box, and a single leg hop test. Results showed no change following the static stretching intervention from pre- to post-test under any stretch condition. Static stretching has been shown to reduce power in vertical jump tests (Hough *et al.* 2009; Gesel *et al.* 2022). Under different intensities, Behm & Kibele (2007) showed a decrease in vertical jump height but no difference between intensities and Melo *et al.* (2021) did not observe any changes to a 20-metre sprint test following different intensities of static stretches. Reductions in power following static stretching are also often attributed to decreases in passive stiffness (Behm *et al.* 2019), however, the current study contradicts this as there was a reduction in passive stiffness but no change to power output. In addition, the duration of static stretching may not have been sufficient to affect power output, for example, Palmer *et al.* (2019) compared 30 seconds, 60-second and 120-second on hamstring rates of force development (RFD) and showed that the 30- and 60-second conditions did not lead to a decrease in RFD while the 120-second condition did. Systematic reviews have shown that static stretching for less than 60 seconds is unlikely to lead to stretch-induced force loss (Kay & Blazevich., 2012; Behm *et al.* 2016).

The finding that performing a single static stretch to a high-intensity and a long duration increases ROM but does not lead to the stretch-induced force loss could be viewed as a positive effect as it could mean individuals could perform this static stretch condition without experiencing negative effects.

Another aim of this study was to examine the effects of different intensities and durations on muscle architecture, specifically, fascicle length and fascicle angle of the Bicep Femoris. Alterations to muscle force following static stretching have been attributed to changes in fascicle length and angle (Eng *et al.* 2018). Research on the effects of static stretching on muscle architecture has not observed any changes (Ce *et al.* 2015; Opplert *et al.* 2016). However, it has been theorised that the static stretch needs to be of a sufficient intensity to lead to changes in muscle architecture (Sato *et al.* 2020). Results from the current study showed no changes to fascicle length or angle following any of the static stretch conditions. Alterations to muscle architecture have been shown to occur following an 8-week training programme of repeated bouts of static stretching at a high-intensity and a high volume (Freitas *et al.* 2015), however, there are currently no studies which show muscle architecture changing following just a single bout of static stretching.

7.4.1 Practical applications

Results from this study showed an increase in ROM and no decreases in strength or power following all three static stretch conditions. This suggests that athletes can perform a single 30 to 60 second hamstring stretch at a high-intensity and gain the benefits of increased knee extension ROM without experiencing the stretch induced force loss.

7.4.2 Limitations

A limitation to the current study was the sample size of 14 participants, which was due to the time frame of the PhD, in addition, the participants were all males between the ages of 18 and 35 years old and either sedentary or recreationally active according to standards set by McKay *et al.* (2021). This demographic was a homogenous sample with the previous study in this thesis (Chapter 6) and a convenience sample. Future research should examine the effects of the static stretching conditions on different populations such as females, high-level athletes and individuals who participate in sports and activities which require extreme ROM such as dancers and gymnasts.

Another limitation arises with the recording conditions of the EMG measurements. The skin was cleaned with alcohol swabs before electrodes were placed on the skin, however, this may not have been sufficient to acquire an accurate reading. Furthermore, the angle of the seat of the isokinetic dynamometer may have affected outcomes by slightly dislodging the electrode from its placement, to limit this, more tape was used to secure the electrode to its placement. In addition, if a reading was taken but the EMG signal was not recorded then this was repeated after a short rest for the participant. A further limitation is that this study only examined the effects on the hamstrings, and it is unknown if the same effects would occur for other commonly stretched muscle groups such as the quadriceps, the gastrocnemius or the upper body. However, it is not clear if it is biomechanically possible to stretch the gastrocnemius or the quadriceps to 120%POD.

7.4.3 Future directions

There are several directions that future research on this topic could go. One could be to examine the effects of 120%POD static stretching on different outcome measures which could be more ecologically valid such as squat strength or vertical jump height and power with a run up. Another could be to compare the effects of an even shorter duration such as 10 to 20 second stretch.

7.5 Conclusion

In conclusion, performing a single static stretch at different intensities and durations leads to an increase in ROM, with a greater increase following the high-intensity and longer duration condition. In addition, these static stretching conditions did not lead to changes in strength and power due to several potential factors such as duration and volume of static stretch, or the time in between the stretch and performance measures. Furthermore, no changes were observed to EMG output or muscle architecture. Findings suggest that a single repetition of a 30 to 60-second static stretch between 100% and 120% intensity is not sufficient to induce force loss.

8 General Discussion

The acute effects of static stretching have been extensively researched, and it has been shown to be a reliable method of increasing ROM (Medeiros *et al.* 2016), however, the effects on strength and power have been contradictory. According to systematic reviews, static stretching before strength and power performances is likely to reduce force (Simic *et al.* 2013; Behm *et al.* 2016), however, outcomes of static stretching differ due to several variables such as duration and intensity. Research on different durations of static stretching has shown that stretches held for less than 30 seconds are unlikely to lead to stretch-induced force loss and stretching for more than 30 seconds is more likely to reduce force (Behm & Chaouchi, 2011; Behm *et al.* 2016), however, research on the effects of static stretching intensity on ROM, strength and power is limited. Therefore, the main aims of the studies within this thesis were to investigate the reliability of a method of generating a high-intensity static stretch and to examine the effects of different intensities of static stretching on strength and power. Chapters 4 and 5 of this thesis presented a systematic review and questionnaire which both showed that knowledge of the effects of different intensities of static stretching is varied due to methodological inconsistencies with regards to how a high-intensity static stretch is measured and generated. Chapter 6 of this thesis tested the reliability of using 120% point of discomfort static stretch as a high-intensity static stretch and showed that it is consistently a high-intensity static stretch. Chapter 7 examined the effects of 120%POD with different durations on strength, power and investigated potential underlying mechanisms of stretch induced force loss. Results showed that ROM was increased but no changes were observed to strength, power or the underlying mechanisms specifically fascicle angle, fascicle length and EMG.

The first study presented within this thesis (Chapter 4) was a systematic review of the current research on the effects of different intensities of static stretching on ROM, strength and power. This study reviewed a total of 18 studies, 14 of which examined ROM, six examined the effects on strength and three on power. This study showed that ROM increases no matter the level of intensity of static stretch, with several studies showing that a higher intensity leads to a greater increase in ROM. With regards to strength and power, the findings were contradictory, some studies showed that the higher intensity of static stretch led to a greater decrease in force whereas others did not find a difference between the intensities. Furthermore, this study observed that the contradictory results from the studies within the review are potentially due to the use of different methods of measuring the intensity of the static stretches. Common methods used to measure static stretching intensity include subjective measures such as a 0-10 scale or visual analogue scale (VAS) from 'No pain' to 'Worst pain imaginable,' others used the 'Point of discomfort' to the 'Point of pain.' Other methods included more objective measures for example a percentage of the ROM reached at the 'Point of discomfort.' None of these methods had been examined for reliability.

Due to the findings within the first study, the second study within this thesis (Chapter 5) was to investigate the static stretching practices of athletes and coaches who participate in competitive sports within the UK and specifically investigated the views on the intensity of static stretching. This study distributed the questionnaire using JISC online software. This study included responses from several gender identities and athletes and coaches from different levels of sport within the UK: recreational, regional, national and international. A total of one-hundred and sixty-six responses were obtained, 147 athletes and 19 coaches. Results showed that most athletes across different sports, competition levels and genders perform static stretching (92%) mainly for improving ROM (94%) with the most common muscle to stretch being the hamstrings (74%) which is in accordance with previous research (Babault *et al.* 2021). Furthermore, results showed that most coaches programmed the use of static stretching for their athletes (53%) and was also mainly to improve ROM (70%). To the author's knowledge, this is the first study to investigate if athletes and coaches consider the intensity of static stretching. Results showed that athletes were more likely to not consider the intensity of static stretching (68%) and that coaches were more likely to consider the intensity of static stretching (70%). Respondents who indicated that they do consider the intensity of static stretching were required to describe how they define and measure it, thematic analysis revealed a variety of definitions such as subjective perception of intensity including feelings of comfort or discomfort, *"push to where you feel discomfort,"* and physical parameters consisting of depth, extent of stretch and force and strain; *"How much strain is exerted on the muscles."* Responses to how static stretching is measured revealed similar themes to the definition responses. For example, subjective feel, discomfort and pain, *"How much stretch you feel, the burn."* and *"How far I can stretch before the discomfort starts."* Another measurement theme was the use of physical landmarks; "*Sometimes distance such as touching toes where there is a visible point/mark to use each time.*".

Furthermore, respondents who indicated that they do not consider the intensity of static stretching were required to give a brief explanation, thematic analysis revealed that a key theme as to not considering static stretching intensity was due to a lack of awareness or knowledge on how it is defined or measured; *"I don't understand what the intensity means. IE the amount of stretch I should be aiming for or my heart rate whilst stretching? Some clarifications here would help,"* and *"Not sure how to measure it."*

Results from the thematic analysis show that definitions and methods of measuring static stretching intensity are varied but show that subjective methods are commonly used. This is supported by the findings from the study presented in Chapter 4 of this thesis. In addition, a key reason why athletes and coaches do not consider the intensity of a static stretch is due to the lack of clear definitions and measurements.

Due to findings from chapters 4 and 5, the following study, Chapter 6, was designed to examine the reliability of one of the methods of measuring static stretching intensity in generating a high-intensity static stretch. The secondary aim was to examine the effects of high-intensity static stretching on ROM, strength and power. The method of measuring a high-intensity static stretch which was assessed in this study was using a percentage of the ROM achieved at the 'Point of discomfort' of a knee extension static stretch. Specifically, stretching to 120% of the 'Point of discomfort.'

The key finding from this study showed that this method was reliable in generating a high-intensity static stretch of the hamstrings. In addition, this study showed that a 120%PoD static stretch of the hamstrings held for 30 seconds increased ROM, led to a decrease in strength, specifically a 6-second knee flexion isometric strength test, and no change to power examined using two single leg jump tests. Increases in ROM are commonly attributed to two underlying mechanisms; a reduction in passive stiffness (Morse *et al.* 2008) and/or an increase in stretch tolerance (Weppler & Magnusson, 2010, Killen *et al.* 2019). Results from this study did not observe a reduction in passive stiffness therefore suggesting that the increase in ROM following a high-intensity static stretch is due to an increase in stretch tolerance. The reduction in strength following the static stretch protocol is in accordance with previous research of the effects of high-intensity static stretching (Kataura *et al.* 2017; Rodrigues *et al.* 2017). The underlying mechanisms of the reduction in force following static stretching are strongly debated (Behm *et al.* 2020), a mechanism which is often given as the cause of the stretch-induced force loss is a reduction in passive stiffness (Behm *et al.* 2016). However, the passive stiffness of the hamstring remained unaffected by the static stretching within this study. This suggests that the mechanism which reduces force following a high-intensity static stretch is not a reduction in passive stiffness but another mechanism such as a reduction in EMG (Trajano *et al.* 2017). Power remained unchanged in this study which is not in accordance with previous research (Simic *et al.* 2013). The fact that power remained unchanged could be due to passive stiffness also remaining unchanged following the static stretching protocol. Changes in passive stiffness have been shown to vary depending on the duration of the static stretch as shorter duration static stretches (<60 seconds) have been shown to not affect passive stiffness (Matsuo *et al.* 2013; Stafilidis & Tilp, 2015).

The following study within this thesis (Chapter 7) aimed to examine the effects of different durations and intensities of static stretching on ROM, strength and power utilising the method that the previous study showed to be a reliable method of generating a high-intensity static stretch. In addition, this study aimed to examine the effects of static stretching on EMG output and muscle architecture changes, specifically fascicle angle and fascicle length. Changes to EMG output and muscle architecture have both been suggested as mechanisms for the stretch-induced force loss (Behm *et al.* 2020; Eng *et al.* 2018). The static stretch conditions were 100%*30s, 120%*30s and 120%*60sec. Results showed that all three conditions led to an increase in ROM with a greater increase occurring following the 120%*60s condition, this is in accordance with previous research which shows that the higher intensity static stretch leads to greater acute increases in ROM (Kataura *et al.* 2017; Freitas *et al.* 2015). However, within the current study, results showed no difference between 100%*30s and 120%*30s conditions which may indicate that increases in ROM may be more due to duration rather than intensity. The results of this study found that none of the static stretching conditions led to changes to knee flexion MVIC performance which contradicts the majority of previous research which shows that static stretching leads to a decrease in strength (Power *et al.* 2004; Simic *et al.* 2013; Walsh *et al.* 2017). In addition, the results contradict research on different intensities of static stretching on strength (Kataura *et al.* 2017, Rodrigues *et al.* 2017, Chapter 5 of this thesis).

There are several potential reasons as to why no decrease in strength was observed. The first is the duration of static stretching, it has been shown that static stretches for less than 60 seconds are less likely to lead to stretch-induced force loss (Matsuo *et al.* 2013; Stafilidis & Tilp, 2015). Furthermore, the static stretch condition utilised in this study only used one repetition of the static stretches, Rodrigues *et al.* (2017) suggested that just one repetition may not be sufficient to lead to the stretch-induced force loss. Differences in procedure between the present study and the study presented in Chapter 5 suggest that no strength decrease was observed, potentially due to the time between the static stretch and performing the MVC. For example, it has been shown that knee flexion MVIC strength performance has been shown to be trending towards recovery within 10 minutes and then fully recovered within 20 minutes following a static stretching intervention (Nakamura *et al.*, 2022). The laboratory procedure in chapter 5 meant that the strength test was performed within two minutes of performing the static stretch, whereas in the current study there was more time due to performing the ultrasound tests immediately following the static stretch. Results of the study presented in Chapter 7 suggest that individuals can perform a single static stretch for 30 to 60 seconds at a high-intensity and not experience a decrease in force while gaining benefits from an increase in ROM. There are several underlying mechanisms often used to attribute the stretch-induced force loss, common mechanisms are a reduction in passive stiffness (Behm *et al.* 2016), reductions in EMG output (Behm *et al.* 2019) or alterations to muscle architecture (Eng *et al.* 2018).

Results from the studies in Chapters 5 and 6 found contradictory results for passive stiffness. Chapter 5 showed no change to passive stiffness following 120%*30s static stretching condition yet oobserved a decrease in knee flexion MVIC, whereas Chapter 6 showed a decrease in passive stiffness following all three static stretch conditions, however, there was no decrease in strength. This suggests that changes in passive stiffness do not play a role in reductions in force. The stretch-induced force loss is also often attributed to reductions in EMG output (Behm *et al.* 2019), however, the results of the study in Chapter 6 showed no reductions in EMG which could explain why there were no decreases in strength and power performances.

This is in accordance with previous research which has shown no change to hamstring EMG or peak torque following 30, 60 and 120-second static stretching interventions (Palmer *et al.* 2019). Furthermore, changes to muscle architecture have been suggested to lead to stretch-induced force loss, specifically, increases in fascicle angle (Eng *et al.* 2018), results from the study in Chapter 6 showed no change to fascicle angle or fascicle length following the static stretching conditions. It has been shown that changes to muscle architecture from static stretching do not occur following an acute bout of static stretching (Ce *et al.* 2015; Opplert *et al.* 2016) and are more likely to occur following a chronic 8-week static stretching program (Freitas *et al.* 2015).

8.1 Practical Application

There are several practical applications that arise from the results of studies within this thesis. For research practitioners, when conducting investigations into the effects of high-intensity static stretching, chapter 6 showed that a 30 second static stretch to 120%POD of the hamstrings is a reliable method of generating a high-intensity static stretch and should be used for future research. The stretching protocol used within these studies was performed on an isokinetic dynamometer, however, for coaches and athletes who are unlikely to have access to an isokinetic dynamometer to be able to stretch to specific angles, results from chapter 6 have shown that a 120%PoD static stretch is subjectively a high-intensity static stretch as it correlates with athletes VAS scores taken following a high-intensity static stretch, this suggests that athletes could self-assess their static stretch intensity.

The studies presented within chapters 6 and 7 in this thesis showed that athletes and coaches who utilise static stretching should consider the intensity, studies within this thesis have shown that a single hamstring static stretch for 30 to 60 seconds at a 120% PoD increases ROM without reducing power output. With regards to strength, findings within this thesis were contradictory, however, chapter 7 showed that strength may not be reduced following a high-intensity static stretch if there is five to ten minutes between the static stretch and strength performance. These findings suggest that athletes could undertake some static stretching to a high-intensity prior to training or a game.

8.2 Limitations

The research presented in this thesis is not without its limitations. Firstly, due to the relatively low amount of literature on the effects of static stretching intensity the first study presented within this thesis (Chapter 4), a systematic review, only included 18 studies. This reflects that this is a relatively new topic of investigation as the oldest study included in the review dates to 2015. In addition, several of those studies scored low on the PEDro scale which limits the conclusions that can be drawn.

The main limitation that arises in Chapter 5 is the number of respondents to the questionnaire with 147 athletes and 19 coaches. A greater sample size would give a broader, more reliable view of the general static stretching practices and views on static stretching intensity within sports in the UK. Furthermore, females are included in this questionnaire but are underrepresented when compared to males and are less included in laboratory-based research such as in Chapters 6 and 7 in this thesis. This study also only investigated the static stretching practices of athletes and coaches in sports within the UK, future research should examine the practices of athletes and coaches from other countries.

There are several limitations in the studies presented in Chapters 6 and 7. The first is that the participants utilised were of a homogenous group; healthy males, 18 to 35 years old. The effects of the static stretching may be different for females as it is not known if the reliability is affected in females, as it is unclear if menstrual cycle hormone fluctuations alter joint laxity (Park *et al.*. 2009; Shagawa *et al.* 2021). Furthermore, Elliot-Sale (2021) identified that including females in research is essential to informing sex-specific guidelines and understanding. In addition, none of the participants were elite athletes or participated in sports and activities which require extreme ranges of motion, studies have shown that elite athletes may respond differently to acute static stretching (Egan *et al.* 2006; Molacek *et al.* 2010). Future research should examine the reliability and effects of 120% static stretching on females, high-level athletes and individuals who undertake static stretching training regularly. A further limitation that arises is that the stretch method used only examined the hamstring muscles. Future research should examine the reliability and effects of 120% static stretching of other commonly stretched muscle groups such as the quadriceps and gastrocnemius; however, it is unknown if it is biomechanically possible to stretch to 120% point of discomfort for these specific muscle groups. Further limitations arise with regard to the recording conditions of the EMG measurements. The skin was cleaned with alcohol swabs before electrodes were placed on the skin, however, this may not have been sufficient to acquire an accurate reading. Furthermore, the angle of the seat of the isokinetic dynamometer may have affected outcomes by slight movement of the electrode from its placement.

Results from the studies in Chapters 6 and 7 used similar static stretching protocols yet showed contradictory findings on the effects of static stretching on knee flexion MVIC. Chapter 6 found that static stretching to 120% for 30 seconds reduced knee flexion MVIC whereas none of the static stretching conditions in Chapter 7 (100%*30s, 120%*30s and 120%*60s) led to a decrease in knee flexion MVIC performance. This is potentially due to the time between the stretching condition and the strength performance test (Nakamura *et al.* 2022) as the study in Chapter 7 had a longer period between stretch intervention and post-stretch performance tests due to conducting ultrasound measurements. This suggests that future research should investigate how long reductions in strength can last following a high-intensity static stretching protocol. Furthermore, the static stretching protocols in Chapters 6 and 7 investigated the effects of just one repetition of static stretching. Future research should examine the effects of multiple repetitions on strength and power.

The strength test used in Chapters 6 and 7 was a knee flexion isometric contraction for six seconds, another potential direction of future research is the effects of high-intensity static stretching on different contraction types such as concentric or eccentric, current research has shown that static stretching leads to a greater decrease in isometric contraction than concentric or eccentric (Behm *et al.* 2016). Current research has shown both isometric and concentric contractions to be decreased following high-intensity static stretching (Kataura *et al.* 2017; Rodrigues et el., 2017), however, research has yet to compare the effects of different stretch intensities on different contraction types.

8.3 Future Directions

There are several directions that future research could go. The first would be to test the reliability of 120%PoD as a high-intensity static stretch on different populations such as females and individuals considered as elite athletes and the effects on ROM, strength and power. In addition, this method of generating a high-intensity static stretch should be examined on different muscle groups.

Next, the protocols used in the studies in this thesis only used one repetition of static stretch, future research should examine the effects of multiple repetitions of 120%PoD static stretching on strength and power. Furthermore, future research should examine the effects of 120%PoD static stretching on different measures of strength and power such as squats, deadlifts and sprint speed which would be more ecologically valid.

8.4 Conclusions

In conclusion, chapter 6 showed that a 30 second hamstring static stretch at 120%POD is a reliable method of generating a high-intensity static stretch when compared to a subjective method. Furthermore, chapters 6 and 7 showed that a high-intensity static stretch for 30 to 60 seconds increases knee flexion ROM without reducing power output and is unlikely to reduce strength performance.

9 References

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Appendix 1 Informed Consent Form

University of Worcester

INFORMED CONSENT FORM

Title of Project: Effects of short duration low and high-intensity static stretching on range of motion, muscle activation, muscle architecture, strength and power.

Participant identification number for this study………………………………
Name of Researcher: Joseph Bryant

I, the undersigned, confirm that (**please initial boxes as appropriate**):

1.	I have read and understood the information about the project, as provided in the Information Sheet dated 13th June 2023 or it has been read to me.	
2.	I have been able to ask questions about the project and my participation and my questions have been answered to my satisfaction.	
3.	I have been explained the details of the familiarisation process and I understand that taking part in this study involves maximal stretching of the hamstrings during which discomfort will be experienced.	
4.	No audio or videos will be taken, some photos of the joint angles on the isokinetic dynamometer maybe used.	
5.	I understand that a small area of hair on my leg will need to be shaved for electrode connectivity.	
6.	I understand that taking part in the study has as a potential risk of minor injury from the stretching protocol and potentially some muscle soreness.	
7.	I understand I can withdraw at any time without giving reasons and that I will not be penalised for withdrawing nor will I be questioned on why I have withdrawn.	
8.	I understand that the information I provide will be used for: a PhD thesis, conference presentations and published study within an academic journal.	
9.	The procedures regarding confidentiality have been clearly explained (e.g. use of names, pseudonyms, anonymisation of data, etc.) to me.	
10.	I understand that personal information collected about me that can identify me, such as my name, or where I live, will not be shared beyond the study team.	
11.	I understand that other researchers will have access to this data only if they agree to preserve the confidentiality of the data and if they agree to the terms I have specified in this form.	
12.	I am aware there is a 2-week post-data collection data withdrawal period.	
13.	I voluntarily agree to participate in the study.	
14.	I know who to contact if I have any concerns about this research	

Name of Participant	Signature	Date
Name of Researcher	Signature	Date

Appendix 2 Health History Questionnaire

University of Worcester
School of Sport and Exercise Science

SECTION A: PRE-TEST QUESTIONNAIRE

As you are to be a participant in this laboratory, please complete the following questionnaire truthfully and completely. The purpose of this questionnaire is to ensure that you are in a fit and healthy state to complete an exercise test and/or blood analysis. If any issues are identified in the questionnaire, we will recommend that you consult with your GP to verify your suitability for the laboratory test. Data will be treated in accordance with the UW Data Protection Policy. The questionnaire has four sections (A, B, C and D), of which section B only needs to be completed if blood sampling will be part of the procedures completed in the testing and section D only if repeated testing (i.e., multiple laboratory visits) is being completed.

Purpose (tick and insert details)

☐ Teaching — Module and teacher: ______________________

☐ Independent Study — Student: ______________________

☐ MPC external client — Staff member: ______________________

☐ School Visit — School or college: ______________________

Today's Date: ____________________

Participant Name: ___________________________Date of Birth & age: __________________

Sex: _________Email: ___________________________Mobile number: __________________

Please provide details of someone that we could contact in an emergency.

Name: ____________________Contact Number: ____________________

1. **How would you describe your current level of physical activity?**

sedentary ☐ moderately active ☐ highly active ☐

---

2. **How would you describe your current level of fitness?**

very unfit ☐ moderately fit ☐ trained ☐ highly trained ☐

---

3. **How would you consider your current weight?**

underweight ☐ ideal weight ☐ slightly overweight ☐ very overweight ☐

---

4. **Smoking habits**	**Yes**	**No**
Are you a current smoker?	☐	☐
If *yes* a regular smoker of.........per day		
an occasional smoker of.........per day		
Are you a previous smoker?	☐	☐

If *yes* of.........per day

how long since stopping? .... months/years *

---

5. Consumption of alcohol **Yes** **No**

Do you drink alcoholic drinks? ☐ ☐

On average, how many units of alcohol per week do you drink? ....

1 unit = a single shot of spirits 25 ml. 2 units = a pint of low strength lager/beer (3% ABV), a can of moderate strength lager/beer/cider (5% ABV), or a standard glass of wine (12% ABV).
Current UK guidelines advise limiting alcohol intake to 14 units a week for women and men. This is equivalent to drinking no more than 6 pints of average-strength beer (4% ABV) or 7 medium-sized glasses of wine (175ml, 12% ABV) a week.

Have you consumed alcohol in the last 24 hours? **Yes** ☐ **No** ☐

If yes, how much did you drink (in units) ....

---

6. Have you had to consult your Doctor within the last 6 months? **Yes** ☐ **No** ☐

If *yes* please give brief details:

---

7. Are you taking any form of medication? **Yes** ☐ **No** ☐

If *yes* please give brief details:

---

8. Have you suffered from a bacterial or viral infection in the last 2 weeks? **Yes** ☐ **No** ☐

If *yes* please give brief details:

9. Do you suffer, have a history of, or currently receive medical treatment for any conditions related to: *(Please tick as appropriate)*	**Yes**	**No**
Asthma	☐	☐
Cancer	☐	☐
Cardiovascular (e.g. prior recognition of a heart murmur)	☐	☐
Chronic Kidney Disease	☐	☐
Chronic Obstructive Pulmonary Disease (COPD)	☐	☐
Diabetes (type 1 or 2)	☐	☐
Dizziness or Fainting	☐	☐
Unexplained breathlessness or fatigue following exercise	☐	☐
Exertional chest pain/ discomfort	☐	☐
Epilepsy	☐	☐
Gastrointestinal (e.g. piles, haemorrhoids)	☐	☐
High Cholesterol	☐	☐
Liver Disease	☐	☐
Musculoskeletal (e.g. arthritis, tendinitis)	☐	☐
Neurological	☐	☐
Respiratory (e.g. Asthma, Bronchitis)	☐	☐
Skin (e.g. Eczema, Psoriasis)	☐	☐
Stroke or Transient Ischaemic Attack (TIA)	☐	☐
Thyroid Disease (e.g. hyper, hypo)	☐	☐
Other	☐	☐

If *yes* to any of the above conditions, please give brief details:

10.	**Are you aware of any close family members with heart disease?**	**Yes**	**No**
If *yes* please give brief details:		☐	☐

11.	**Are you aware of any of the following cardiac conditions in any close family members?**	**Yes**	**No**
(Please tick as appropriate)			
Hypertrophic or dilated cardiomyopathy		☐	☐
Long-QT syndrome or other ion channelopathies		☐	☐
Marfan syndrome		☐	☐
Clinically important arrhythmias		☐	☐

If *yes* to any of the above conditions, please give brief details:

12.	**Do you consume any dietary supplements?**	**Yes**	**No**
If *yes* please give brief details (including quantities):		☐	☐

	Yes	**No**

13. **Do you currently have any form of muscle or joint injury?** ☐ ☐

If *yes* please give brief details:

		Yes	No
14.	**Do you have any allergies**	☐	☐

If *yes* please give brief details:

		Yes	No
15.	**Have you had to suspend training in the last two weeks for a physical reason?**	☐	☐

If *yes* please give brief details:

		Yes	No
16.	**Is there anything to your knowledge that may prevent you from successfully completing the tests that have been outlined to you?**	☐	☐

If *yes* please give brief details:

---

17. Have you had a Covid-19 vaccination?

No ☐ Single ☐ Double ☐

Yes No

18.	**Have you ever had a positive test for Covid-19?**	☐	☐
19.	**Have you had any Covid-19 symptoms in the last 14 days?** New cough, elevated temperature, loss of smell or taste	☐	☐
20.	**Have you been exposed to anyone with confirmed Covid-19 within the last 14 days?**	☐	☐

If *yes* to any of Questions 18 – 20 please give brief details:

21.	**Have you had a negative lateral flow or PCR test within the last 48 hours?**	☐	☐

SECTION B (COMPLETE ONLY IF BLOOD SAMPLING WILL BE COMPLETED AS PART OF THE TESTING PROCEDURES)

		Yes	No
22.	**Are you receiving any medicines, dental treatment, have had recent illness or attending hospital outpatients?**	☐	☐

If *yes* please give brief details:

		Yes	No
23.	**Have you ever been advised by a doctor not to give blood**?	☐	☐

If *yes* please give brief details:

24.	**Do you suffer, have a history of, or currently receive medical treatment for any conditions related to:**	**Yes**	**No**
Allergy to latex		☐	☐
Blood borne illness		☐	☐
Hepatitis (jaundice) or been in contact with a case in the last 6 months		☐	☐
Tropical disease (for example malaria)		☐	☐

If yes to any of the above conditions, please give brief details:

25.	**Do you have a phobia of blood or needles?**	**Yes**	**No**
		☐	☐

If *yes* please give brief details:

Staff Reviewer

Notes on review of HHQ answers:

Staff Reviewer Signed: ____________________ Date:____________________

A survey on the static stretching practices of coaches and athletes from a variety of sports and competition levels within the UK.

Participant Information Sheet

Title of Project: A survey into the static stretching practices of recreational and professional athletes

and coaches within different levels of UK sport. The University of Worcester engages in a wide range

of research which seeks to provide greater understanding of the world around us, to contribute to

improved human health and well-being and to provide answers to social, economic and

environmental problems. Joseph Bryant is a PhD student in the School of Sports & Exercise science

at the University of Worcester. Dr Matthew Cook is a Senior Lecturer in the School of Sports &

Exercise Science at the University of Worcester. We would like to invite you to take part in a research

project which involves completing an anonymous online survey. Before you decide to take part, it is

important for you to understand why the research is being carried out and what it will involve. What is

the purpose of the research? This study aims to investigate the current application of static stretching

during warm up routines used among sports coaches, strength and conditioning coaches and those

you participate in exercise or sport at any level. Furthermore, we are interested if they take intensity

of the stretching into consideration. Participants and coaches will be from different levels of

competition ranging from recreational, amateur to semi- and full professional athletes. Who is funding

the research? No funding is required for this study as it is part of a PhD studentship. Why have I been invited to take part? You have received this invitation because you are either a coach, you play in

sport or exercise recreationally. We are hoping to recruit as many participants as possible for this

study from different levels of sport. This includes recreational exercisers, athletes at all levels and

sports coaches at all levels. What will happen if I agree to take part? If you agree to take part, you will

read the participant information sheet. You will then complete the consent form before then

completing the online anonymous survey. The survey should take approximately 15-minutes to

complete. The types of questions will be closed ended and some will simply be yes or no. All

questions will be optional or have a prefer not to say option. Do I have to take part? No. It is up to you

to decide whether or not you want to take part in this study. Deciding to take part or not will not

impact you in any way. If you do decide to take part, you will be asked at the start of the survey to

agree to a number of statements to indicate that you are over 18 years old, have read and understood

this information and agree to take part in the survey. By submitting the survey, you are providing

consent for the data you have given to be used in the study. You can withdraw from the study by

closing the browser page down without submitting your responses and your data will not be saved.

You will be able to withdraw your responses after submitting as you will generate an ID code, this will maintain anonymity. What are the benefits for me in taking part? The main benefit from taking part

will be contributing to knowledge regarding the use of static stretching within warm up routines of

people who exercise, play sport or coach sport across different sports or levels. Then in turn, may

help shape recommendations for those different groups to support best practice within warmups. Are

there any risks for me if I take part? Participating in this research presents no risks or disadvantages

to participants. What will you do with my data? The data you submit will be treated confidentially at all

times. No personal identifiable information will be obtained during or as part of the study. Your

answers will be completely anonymous. The research is being carried out as part of a PhD project at

the University of Worcester and the results will be presented in the form of a PhD thesis dissertation

which should be completed by no later than 31st January 2025. We may submit all or part of this

research for publication to academic and/or professional journals and present this research at

conferences. During the project, all data will be kept securely in a password-protected university

server in line with the University's Policy for the Effective Management of Research Data and its

Information Security Policy. The data will only be accessible to the researcher and the researcher's supervisors (see contact details below). How long will you keep my data for? At the completion of the

project, we will retain your data in the anonymised form that it was collected for 10 years. This

anonymised data will be archived and shared in line with our Policy for the Effective Management of

Research Data Thank you for taking the time to read this information If you have any questions or

would like further information, please contact us. Joseph Bryant, bryj1_21@uni.worc.ac.uk Dr

Matthew Cook matthew.cook@worc.ac.uk Who has oversight of the research? The research has

been approved by the Research Ethics Panel for the College of Business, Psychology and Sport in

line with the University's Research Ethics Policy. The University is registered with the Information

Commissioner's Office and the University Data Protection Officer is Helen Johnstone. For more on the

University approach to Information Assurance and Security visit:

https://www.worcester.ac.uk/informationassurance/index.html. If you would like to speak to an

independent person who is not a member of the research team, please contact the University of

Worcester, using the following details: Secretary to Research Ethics Panel for College of Business,

Psychology and Sport, University of Worcester, Henwick Grove, Worcester, WR2 6AJ

contactable at: ethics@worc.ac.uk

Informed consent

1. I have read and understood the information about the project, as provided in the Information Sheet

dated 30th March 2023 or it has been read to me. 2. I have been given the opportunity and the

contact details of the researcher to ask questions about the project and my participation.

3. I understand that taking part in this study involves completing a questionnaire about static

stretching practices in sport. 4. I understand that taking part in the study carries no risk.

5. I understand I can withdraw at any time until I submit my responses at the end of the

survey and that I will not be penalised for withdrawing nor will I be questioned on why I have

withdrawn. 6. I understand that the information I provide will be used for: a PhD thesis,

conference presentations and published study within an academic journal. 7. The procedures

regarding confidentiality have been clearly explained (e.g. use of names, pseudonyms,

anonymisation of data, etc.) to me within the participant information sheet. 8. I understand

that other researchers will have access to this data only if they agree to preserve the confidentiality

of the data and if they agree to the terms I have specified in this form. And I am aware there is a 2-

week post-data collection data withdrawal period. 9. I voluntarily agree to participate in the

project. 10. I know who to contact if I have any concerns about this research.
11. I am

over 18 years old. 12. I understand the answers to the questions I give are
anonymous.

Please confirm the following: *

I agree to participate in this questionnaire

ID code

In order to be able to withdraw your response after completion of this survey,
Please

take this time to generate your unique ID code. The code is made up of the
first and

second letter of your place of birth, day of the month you were born (e.g. the
1st would

be written as 01) And finally your middle initial. Please remember this or write
it down.

For example, someone born in Worcester on the 3rd day of the month with the
middle

initial of G, their code would be WO03G.

Coach or Athlete

Are you a coach or an athlete? *

I am a coach (head coach, Skills coach, S&C coach or similar)

I am an athlete

Coach questions

What sport do you coach?

What level of competition do you coach?

International

National

Regional

Recreational

What is your coaching role?

Strength & conditioning

Skills coach

head coach

sports therapist

sports scientist

What is your coaching educational background?

How many years of coaching experience do you have?

<1 year

1-3 years

3-5 years

> 5 years

Is your coaching role paid or voluntary?

Paid

Voluntary

Do you prescibe static stretching for your athletes?

Yes

No

Static stretching - Yes

Why do you prescibe static stretching for your athletes?

To reduce joint pain

To reduce muscle pain

To reduce muscle stiffness

To improve flexibility/ range of motion

To improve strength

To improve power

To improve wellness

Other

If you selected 'other' please expand

Do you prescibe when your athletes perform static stretching exercises?

Before training

During training

After training

On a separate, dedicated session

Are your athletes supervised during static stretching?

Yes

No

Sometimes

I don't know

Are the static stretching exercises held for a specific duration?

Less than 10 seconds

10-30 seconds

30-60 seconds

Longer than 60 seconds

I don't know

Static stretching intensity

Do you consider the intensity of static stretching?

Yes

No

Consider Intensity - Yes

How is static stretching intensity defined?

How is static stretching intensity measured?

Does the intensity vary depending on when the static stretching exercises are performed?

Yes

No

If you promote static stretching to improve performance, do you consider the intensity of

the stretching?

Yes

No

If you promote static stretching to improve recovery, do you consider the intensity of the

stretching?

Yes

No

If you promote static stretching intensity to improve flexibility, do you consider the

intensity of the stretching?

Yes

No

Static stretching - No

Please expand on why you do not prescibe static stretching for your athletes.

Consider intensity- No

Why do you not consider the intensity of static stretching?

Athlete questions

What is your main sport?

What is your age?

18-20 years

20-29 years

30-39 years

40-49 years

50-59 years

>60 years

What gender do you identify as?

What level of competition do you currently participate in?

International

National

Regional

Recreational

How many years have you taken part in your sport?

<1 year

1-4 years

4-8 years

>8 years

Do you consider static stretching exercises?

Yes

No

Static stretching - Yes

Why do you undertake static stretching exercises?

To reduce joint pain

To reduce muscle pain

To improve range of motion/flexibility

To improve strength

To improve power

To improve wellness

Other

If you selected other, please expand here

Do you undertake static stretching exercises within a warm-up?

Yes

No

Do you undertake static stretching exercises as part of a cool down?

Yes

No

Do you perform other stretching techniques?

Active

Passive

Dynamic

Ballistic

Oscillations

PNF, contract-relax

PNF, hold-relax

Are static stretching exercises prescribed by a coach, trainer or strength & conditioning

coach?

Coach

Trainer

S&C coach

Myself

Are you supervised during static stretching exercises?

Yes

No

Sometimes

Are static stretches held for a specific duration?

Less than 10 seconds

10-30 seconds

30-60 seconds

Longer than 60 seconds

When are static stretching exercises performed?

Before training

During training

After training

Separate, dedicated session

How often are static stretching exercises performed?

Everyday

Every training session

1-5 times per week

1-2 times per month

1-6 times per year

Which areas or muscle groups are targeted by the static stretching exercises?

Upper body

Lower body

Both

Quadriceps

Hamstrings

Gluteal muscles

Calves

Biceps, Triceps, Pectorals

shoulder

Neck

Back

Abdominals

Static stretching intensity

Do you consider the intensity of static stretching?

Yes

No

Consider Intensity - Yes

How is static stretching intensity defined?

How is static stretching intensity measured?

If you undertake static stretching exercises to improve performance, do you consider the

intensity of the stretching?

Yes

No

If you undertake static stretching exercises to improve recovery, do you consider the

intensity of the stretching?

Yes

No

If you undertake static stretching exercises to improve flexibility, do you consider the

intensity of the stretching?

Yes

No

Do you feel that intensity of static stretching is important to elicit changes in flexibility?

Yes

No

Static stretching - No

Why do you not undertake static stretching exercises?

Consider Intensity - no

Why do you not consider the intensity of static stretching?