THE EFFECT OF NEUROMUSCULAR ELECTRICAL STIMULATION ON HAMSTRING PREHABILITATION

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DECLARATION

I hereby declare that “The effect of neuromuscular electrical stimulation on hamstring prehabilitation” is my own work, that it has not been submitted before for any other degree in any other University, and that the sources I have used have been indicated and acknowledged as complete references.

Jaime André Valadão **October 2018**

Signed__________________

ABSTRACT

Background: Hamstring injuries remain a growing concern within a large variety of sports from the elite athlete to the weekend warrior. A copious amount of research has been performed in an attempt to reduce these injuries. The aim of this study was to understand the changes in lengthened state eccentric strength of the hamstrings following four separate protocols.

Methods: A quantitative research approach, using a true experimental design, was adopted for this study. A convenience sample of non-sedentary, 35 male participants, between the ages of 18 and 35 within the City of Cape Town was used. Participants were randomly allocated to one of four groups namely; Control group (C), resistance training alone (RT), neuromuscular electrical stimulation alone (NMES), or NMES superimposed with RT (NMES&RT). Participant's eccentric hamstring strength was tested in a lengthened state, on the Biodex system 4 Pro™ for the pre- and post-test. The intervention spanned over four weeks. SPSS version 25 was used for data analysis.

Results: All groups demonstrated a mean increase in relative peak torque. However, a repeated-measures analysis of variance (ANOVA) showed no interaction effect ($p = 0.411$) between the four groups. Further analysis using Magnitude-based inferences (MBI), to identify the magnitude of changes, showed a small positive effect for both the NMES and NMES&RT group when compared to the C and RT groups.

Conclusion: Although there are no statistically significant differences between the four groups employed in this study (C, RT, NMES, NMES&RT), NMES and NMES&RT did show small positive effects compared to C and RT with a very low likelihood of negative effects. Thus, using NMES either alone or superimposed with resistance training will be beneficial for trained athletes but it is not a necessity and the use of specific resistance training may be just as effective.

KEY WORDS: Neuromuscular electrical stimulation; Biodex; Lengthened state; Hamstring; Prehabilitation

DEDICATION

I wish to dedicate this thesis to everyone that has ever believed in me. From near or afar. If you are reading this and you have believed in me - Thank you!

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LIST OF ABBREVIATIONS, ACRONYMS, AND SYMBOLS

°/s	Degrees per second
%	Percent
®	Registered Trademark Symbol
ASLR	Active straight leg raise
NFL	American National Football League
ART	Artificial Turf Cohort
CV	Coefficient of Variation
CI	Confidence Interval
CL	Confidence Level
C	Control Group
CMJ	Countermovement Jump
CK	Creatine Kinase
CK-BB	Creatine Kinase-Brain
CK-MM	Creatine Kinase-Muscle
CK-MB	Creatine Kinase-Muscle/Brain
ECC/CON	Eccentric/Concentric
EMG	Electromyography
EMS	Electromyostimulation
HZ	Hertz
LDH	Lactate Dehydrogenase
MBI	Magnitude Based Inferences

MVC	Maximal Voluntary Contraction
NMES	Neuromuscular Electrical Stimulation
NMES&RT	Neuromuscular Stimulation Superimposed with Resistance Training
$Nm{\cdot}kg^{-1}$	Newton-meters per kilogram
PSLR	Passive straight leg raise
RAD/S	Radiant per second
ROM	Range of Motion
RT	Resistance Training
SJ	Squat Jump
SD	Standard deviation
SWE	Swedish First League
UEFA	The Union of European Football Associations
TM	Trademark
UCL	UEFA Champions League
UWC	University of the Western Cape
VS	Versus

Chapter 1

INTRODUCTION

1.1 Background

Neuromuscular electrical stimulation (NMES) is a tool used to induce muscular contractions using electrical impulses via stimulation of the motor nerve. The NMES device delivers electrical impulses through electrodes placed on the skin. The NMES device is widely available and usually portable (Maffiuletti, Minetto, Farina, & Bottinelli, 2011).

NMES has multiple uses and can serve as a strength-training tool for healthy individuals, a rehabilitative and preventative tool for partially immobilized patients to preserve muscle mass, a testing tool of neural and muscular function, and a post-exercise recovery tool (Maffiuletti et al., 2011). NMES has been shown to be more beneficial in improving strength and performance than resistance training alone in trained, untrained, and elite individuals (Filipovic, Kleinöder, Dörmann, & Mester, 2011; Herrero et al., 2010; Paillard, 2008). There is, however, conflicting evidence with regard to NMES such as, when and how it is most beneficial. Some studies have demonstrated NMES to be more beneficial superimposed with exercise and others have shown NMES alone to be more beneficial (Canning & Grenier, 2014; Herrero et al., 2010; Paillard, Noé, Passelergue, & Dupui, 2005; Willoughby & Simpson, 1996; Willoughby & Simpson, 1998). These varying results could lead to the confusion surrounding NMES. Maffiuletti et al. (2011) note this confusion, as they state that there is confusion around its usage in the scientific community with regard to the various methodological approaches used and physiological features of NMES. Not only does this mean there are questions that still need to be answered regarding the effectiveness of NMES, but it also demonstrates the need for further investigation into the most beneficial uses of NMES and strength training in different settings. One such instance where research is needed is the hamstring muscle group. Not only for NMES but hamstring strengthening and injury prevention in general. Although knowledge regarding hamstring injuries has increased over the years the incidences have not decreased (Brukner, 2015). Not only is the occurrence of these injuries high but the re-injury rate has also been reported to be anywhere between 7.7% and 34% in various sports for partial tears of the hamstring (Elliot, Zarins, Powell, & Kenyon, 2011; Malliaropoulos, Isinkaye, Tsitas, & Maffulli, 2011; Orchard & Seward, 2002). This evidence demonstrates the importance of preventing a hamstring injury from occurring initially (prehabilitation).

One question that has been asked is when are the hamstrings active? Peak activity of the hamstrings has been shown to be during the 'terminal swing' phase during gait, when extending the knee (Higashihara, Ono, Kubota, Okuwaki, & Fukubayashi, 2010; Kyröläinen, Komi, & Belli, 1999; Schache, Dorn, Blanch, Brown, & Pandy, 2012; Yu et al., 2008). This is when the hamstrings are in a lengthened state (terminal swing) and have a high eccentric load (Schache et al., 2012; Schmitt, Tyler, & McHugh, 2012; Tyler, Schmitt, Nicholas, & McHugh, 2017). Schmitt et al. (2012) proposed a lengthened state eccentric protocol on an isokinetic dynamometer (Biodex), which was used by Tyler et al. (2017). One of the findings in the study by Tyler et al. (2017) was that there were no re-injuries to any of the participants that completed the rehabilitation including the lengthened state eccentric strengthening of the hamstrings. Although the absence of re-injuries cannot be solely attributed to the lengthened state protocol, this study provides a good premise for lengthened state eccentric training as all re-injuries, in this study, were from participants that did not perform the lengthened state eccentric training. In addition to this study Guex and Millet (2013) advise that eccentric training with hip flexion, leading to a lengthened state of the hamstrings, should be performed for prehabilitation of the hamstrings.

1.2 Purpose of the study

This study aimed to obtain an understanding of various interventions on the relative peak torque of the hamstrings in a lengthened state as well as hamstring flexibility. The groups used within this study were; resistance training alone group (RT), NMES alone group (NMES), NMES superimposed with resistance training group (NMES&RT), and a control group (C). Understanding the differences between these various protocols may assist in recommendations to hamstring prehabilitation and hopefully a reduction in injury rates.

1.3 Aim of the study

The aim of this study was to determine if the lengthened state eccentric strength of the hamstrings changed as a result of RT, NMES, and NMES&RT interventions. The secondary aim was to determine any changes in hamstring flexibility following the four protocols (C, RT, NMES, NMES&RT).

1.4 Objectives of the study

The objectives of this study were to:

1) Identify the changes in lengthened state eccentric strength of the hamstrings following a four-week training period in four groups (control group, resistance training alone group, NMES alone group, and NMES superimposed with resistance training group),

2) Analyze and compare the relative peak torque differences between these groups,

3) Identify the changes in hamstring flexibility, using an active and passive straight leg raise, following a four-week training period in four groups (control group, resistance training alone group, NMES alone group, and NMES superimposed with resistance training group),

4) Analyze and compare the hamstring flexibility differences between these groups.

1.5 Hypothesis

It was hypothesized that NMES&RT will be the most effective form of increasing the lengthened state eccentric strength of the hamstrings and lead to the largest increase in hamstring flexibility.

1.6 Thesis structure

This thesis has been structured in six chapters.

Chapter one introduces the topic and concepts within this study, identifies the aims and objectives of the study, and states the hypothesis of this study.

Chapter two is the review of the literature relating to this study in an attempt to understand the topic in as much detail as possible including possible factors that could have an impact.

Chapter three details the materials and methods used in this study including the methods for analysis of the data. This chapter details how the study was carried out in as much detail as possible. The data analyses techniques are presented in this chapter.

Chapter four contains the results and findings obtained in this study from the multiple analyses used.

Chapter five is the discussion of the results and findings in this study. Each finding is discussed and elaborated on from the previous chapter, including the potential implications of these findings.

Chapter six provides a brief summary of the findings within this study, particularly this study's limitations, and conclusion of this study as well as recommendations for future work. The references and appendices follow this chapter.

Chapter 2

LITERATURE REVIEW

The purpose of this chapter was to review the literature regarding hamstring injuries, the function of the hamstrings, lengthened state training of the hamstrings, neuromuscular electrical stimulation (NMES), eccentric training and the effects of this training, as well as other factors that need to be considered in this study such as the measurement tools (Biodex) and potential hormonal effects to the training (creatine kinase).

2.1 Hamstring injuries

"*Hamstring injuries have increased by 4% annually in men's professional football, since 2001*" (Ekstrand, Waldén, & Hägglund, 2016, p.731).

Hamstring strains account for 12-16% of all injuries in athletes (Schmitt et al., 2012). Hamstring injuries have been documented to be common in high speed running sports (Elliot et al., 2011; Malliaropoulos et al., 2011; Orchard & Seward, 2002; Tyler et al., 2017). This is due to the hamstrings being active at high levels and undergoing a large amount of strain whilst running, cutting etc., and other factors that are not yet clear (Higashihara et al., 2010; Higashihara, Nagano, Ono, & Fukubayashi, 2018; Kyröläinen, Komi, & Belli, 1999; Schache et al., 2012; Schmitt et al., 2012; Tyler et al., 2017; Yu et al., 2008). Ekstrand, Hägglund, and Waldén (2011) documented injuries in 51 football teams consisting of 2299 players from 2001-2009. This study had three cohorts: The union of European Football

Associations (UEFA) Champions league (UCL) cohort (24 clubs, which were selected as belonging to the best European teams), the Swedish First League (SWE) (15 teams from the Swedish First League), and the artificial turf cohort (ART) (another 15 European teams playing home matches on artificial turf). The researchers discovered that hamstring injuries were the most common muscle injury, accounting for 12% (1084) of all injuries within this study. However, as large as this study was it was only conducted in Europe, only using European team cohorts, and only looking at football players and therefore, may not be a representation of the hamstring injuries globally. High hamstring injury rates have also been reported in other sports such as, American football, Australian football, track and field athletes, and others (Elliot et al., 2011; Malliaropoulos et al., 2011; Orchard & Seward, 2002).

Multiple studies have identified a high re-injury rate for hamstring strains with Orchard and Seward (2002) finding as high as a 34% re-injury rate for Australian Football League players. However, this does of course vary as Malliaropoulos et al. (2011) found anything from a 0-24% re-injury rate, depending on the grade of the tear. In this study by Malliaropoulos et al. (2011) the only group to have a 0% re-injury rate were the individuals that had a grade four tear. This is interesting, as it may not be expected that the group with the ‘worst’ tear would have the lowest re-injury rate. However, there were only six individuals with a grade 4 hamstring tear and every other group had in excess of 25 individuals. There is also a possibility that those with less severe tears may have returned to sport too early. Elliot et al. (2011) found a 16.5% re-injury rate amongst American National

Football League (NFL) players over a ten-year period. Despite a number of studies and efforts aimed at decreasing hamstring injury as well as re-injury, the incidence of these injuries continue to rise (Brukner, 2015). Bahr, Clarsen, and Ekstrand (2018) suggested that the focus should not solely be on separate reports of incidence and severity but to also include injury burden, which can be reported as the total number of days lost per 1000 hours of exposure. In this paper the authors made reference to the UEFA champions league injury data from a paper by McCall, Dupont, and Ekstrand (2016) as an example for their proposed matrix and the researchers found hamstring injuries to be one of the top priorities for reduction.

2.2 Hamstring activation

To begin to understand hamstring injuries, understanding how these muscles function is imperative. When are they active? When do they undergo their highest load? What are their main functions? All of these factors need to be understood in order to attempt to decrease the injury rate. Numerous studies have used electromyography (EMG) analysis of the hamstrings. These studies have identified the hamstrings to be active during mid-swing until terminal stance with peak activity occurring at terminal swing (Higashihara et al., 2010; Kyröläinen et al., 1999; Yu et al., 2008). However, the muscle combinations exerting forces are infinite. Schache et al. (2012) proposed and used a three-dimensional musculoskeletal computer model, which comprised of 12 body segments and 92 musculotendon structures, and identified that all hamstring muscles (semimembranosus, semitendinosus, biceps femoris) reached peak strain, peak musculotendon strain and force, produced peak force, as well as performed a large amount of negative work (energy absorption) during terminal swing. Schache et al. (2012) identified, in the same study, the hamstrings lengthened from early swing phase till terminal swing phase. With the peak length of the musculotendon unit occurring during terminal swing just before foot strike whilst sprinting (Schache, Wrigley, Baker, & Pandy, 2009; Thelen et al., 2004; Yu et al., 2008). The hamstring muscles work at an extremely high load eccentrically during the terminal swing phase (Schache et al., 2012; Schmitt et al., 2012; Tyler et al., 2017). In a more recent study by Higashihara et al. (2017) the researchers assessed the differences in EMG activity during different gait phases of sprinting as well as different sprints (acceleration and maximum-speed phases) and they found the activation of the semitendinosus and biceps femoris long head to differ at different phases of the gait. They also found different activation patterns between the acceleration sprint and maximum speed sprint. Furthermore, in this paper they found the biceps femoris long head to be activated at significantly higher levels during the acceleration sprint at the early stance phase. However there were no differences during the maximum speed sprint at the early stance phase. The knee flexion torque was higher during the maximum speed sprint compared to the acceleration sprint. These results showed the hamstrings work as a strong eccentric knee flexor during a maximum speed sprint. In addition to this, these activation levels seem to change during late stance with the semitendinosus showing greater activation compared to the biceps femoris long head during the maximum speed sprint. There were no differences during this phase during the acceleration sprint. During the swing phase of the maximum speed sprint the semitendinosus elicited higher activation levels. These results show just how complex the hamstring group is with varying activation levels between the group during different phases of the gait as well as during different phases of a sprint (accelerations vs. maximum speed).

2.3 Hamstring flexibility

Hamstring flexibility has been assessed using numerous techniques such as a passive straight leg raise, active straight leg raise, passive knee extension and an active knee extension test (Askling, Nilsson, & Thorstensson, 2010; Guex, Lugrin, Borloz, & Millet, 2016; Heiderscheit, Sherry, Slider, Chumanov, & Thelen, 2010). The clinical commentary by Heiderscheit et al. (2010) noted that the passive straight leg raise followed by an active knee extension test are commonly used in succession to test hamstring flexibility. This does not mean these are the only tests performed for hamstring flexibility nor the best or most effective. Askling et al. (2010) state that there is a hypothesis that active dynamic flexibility tests may be better suited to return to play decisions compared to passive tests. There is no reference for this in their paper so it is unclear if the authors of this paper hypothesize this or if they believe their peers to hold this hypothesis. Multiple studies have used either the passive straight leg raise, active straight leg raise, passive knee extension or the active knee extension test in order to determine hamstring flexibility changes (Abdel-aziem, Soliman, & Abdelraouf, 2018; Askar, Pais, Mohan, Saad, & Shaikhji, 2015; Henderson, Barnes, & Portas, 2010; Leslie, Lanovaz, Andrushko, & Farthing, 2017; Potier, Alexander, & Seynnes, 2009; Witvrouw, Danneels, Asselman, D'Have, & Cambier, 2003). There does seem to be variability in the specific hamstring flexibility tests' used with little consensus among practitioners on which test(s) to use. The active straight leg raise shows high reliability and validity, it also seems to measure a higher range of motion compared to a passive straight leg raise (Askling et al., 2010). It should be noted that the reliability and validity of the active straight leg raise was only assessed and identified in the one study by Askling et al. (2010) with only 22 participants. This is a small sample and further studies would be required to confirm this reliability and validity.

2.4 Lengthened state training

Tyler et al. (2017) had 50 participants with hamstring strains and the researchers developed a protocol for the rehabilitation of their participants on the Biodex. This protocol had the hamstrings in a lengthened state (hip flexed, knee extended), testing the limb eccentrically. This was done in an attempt to simulate the lengthened state of the hamstrings (lengthened at the hip and knee) when it undergoes high eccentric forces (Higashihara et al., 2017; Schache et al., 2012; Schmitt et al., 2012). To achieve this position participants were seated with their trunk flexed to 90° to the horizontal and their hip flexed to 40° above the horizontal plane, thus creating a trunk-to- thigh angle of 50°. The exercise was performed from 90° to 20° of knee flexion. They followed up with the participants 24 ± 12 months after rehabilitation concluded and there were only four re-injuries (8%). It is important to note that the only participants that had a re-injury did not conclude their rehabilitation and thus did not perform lengthened state eccentric training on the Biodex. The long-term follow up had a fairly large window period (24 ± 12 months) and with no details as to which participants were contacted when, we cannot be too sure if some participants may have had a hamstring strain if contacted at a later date or even the same date as the other participants. The other issue with this study is that there was no control group and they also added in trunk strengthening exercises, which has been shown to also be effective in hamstring rehabilitation (Sherry & Best, 2004). Therefore, as noted by the authors, they cannot attribute the low recurrence rate solely to the lengthened state training. Schmitt et al. (2012) found lengthened state eccentric strengthening increased strength of the hamstrings at the end ranges where the hamstring is believed to be most susceptible to injury. In addition to this, Guex and Millet (2013) advised that strengthening of the hamstrings should include eccentric training with a flexed hip, thus, creating a lengthened state.

2.5 Neuromuscular electrical stimulation (NMES)

Neuromuscular electrical stimulation (NMES) or electromyostimulation (EMS) as referred to in some papers and by some practitioners has gained popularity recently within the rehabilitation and strength and conditioning communities with an increasing number of practitioners/coaches using NMES devices for various reasons (for ease, any mention of NMES or EMS will be referred to as NMES) (Filipovic et al., 2011; Herrero et al., 2010; Maffiuletti et al., 2011). This may be due to NMES having numerous effects and benefits, as stated by Maffiuletti et al. (2011). NMES can serve as a strength-training tool, a rehabilitative tool and preventative tool, a testing tool of neural and muscular function, and a post-exercise recovery tool (Maffiuletti et al., 2011). However in the same paper the authors explain that in the scientific community there has been confusion around its usage. Thus, potentially leading to improper use of the machine and possibly unsubstantiated claims about its benefits. Filipovic et al. (2011) systematically reviewed the state of research looking at the effectiveness of strength enhancements and the training regimes and stimulation parameters as well as their influence on the enhancements. These studies answered a large portion of the questions that lead to the confusion.

There are several types of NMES tools/machines, in the studies performed by Filipovic et al. (2011) the Compex® (Medicompex, Ecublens, Switzerland) was used in 37% of the studies. The Compex® delivers a biphasic asymmetrical impulse, which, Kramer et al. (1984); Walmsley et al. (1984); and Snyder-Mackler et al. (1989) all showed asymmetrical to be superior to symmetrical waveforms (as cited in Tim Watson, 2014). Biphasic impulses also are perceived to be more pleasant for an individual and thus higher stimulation can be achieved (Filipovic et al., 2011). The other impulses commonly used are; monophasic and a so-called “Russian current” (Filipovic et al., 2011).

Filipovic et al. (2011) also developed guidelines for the duration of the training period (3-6 weeks), sessions per week (three [3]), impulse frequency (≥60Hz), and duty cycle (3-10 second contraction period and a 20-25% duty cycle) among others. The sessions used in these guidelines were relatively short (10-15 min).

With regard to strengthening and strength training, NMES has been shown to be more beneficial than resistance training alone in the healthy population (trained, untrained, and elite) with isometric and dynamic contractions (Filipovic et al., 2011; Herrero et al., 2010; Paillard, 2008). NMES alone also increases muscle strength (Canning & Grenier, 2014). There are a number of ways an NMES machine can be used namely; isometrically, superimposed, and combined. Isometrically, this is where an individual has the surface electrodes placed on a specific muscle or muscle group with the NMES device connected to the electrodes and the individual does not produce any movement and just allows the NMES machine to produce the contraction. Superimposed, this is where an individual has the NMES device connected in the same way however the individual will produce movement/exercise concurrently with the NMES device. Combined, this is where an individual will undergo an isometric NMES session, as explained above, and then following that they will undergo an exercise session usually training the same muscles involved in the NMES session. Pain and discomfort seems to be reduced when there is a concomitant voluntary contraction (superimposed) (Paillard et al., 2005).

Superimposed NMES has shown to be effective in increasing strength in different muscle groups such as the biceps brachii, elbow flexors, and the quadriceps femoris (Colson, Martin, & Van Hoecke, 2000; Willoughby & Simpson, 1996; Willoughby & Simpson, 1998). Not only does superimposed NMES lead to strength increases in various muscles groups, but it has also been shown to be more beneficial than voluntary exercise alone (Herrero et al., 2010; Willoughby & Simpson, 1996; Willoughby & Simpson, 1998). Due to a number of these factors Herrero et al. (2010) do advise to use a superimposed technique if an individual is looking to increase strength. There is, however conflicting evidence regarding this as Paillard et al. (2005) concluded that superimposed NMES has added benefit over voluntary exercises alone. This could be due to the study by Paillard et al. (2005) being a review article. As can be seen in this review the protocols and methodologies of these studies vary greatly and when looking at earlier research as well as research that does not employ the guidelines as proposed by Filiopvic et al (2011) and others, one would not expect there to be significant adaptations or changes. This highlights the fact that NMES is a specific tool that needs to be used appropriately. We need to be cautious as to how we interpret review articles, as the authors in this review article do not explain as to how they obtained the studies reviewed and the authors reference studies where the superimposed technique is stated to have added benefits but deduce that there are no added benefits with the superimposed technique.

As we know strength is not the sole determinant in sport performance or injury prevention, there have been studies that have used more sport specific measures following NMES training. Herrero, Izquierdo, Maffiuletti, and Garcia-López (2006) assessed, sprint time, jumping ability, isometric strength, and muscle cross-sectional area. The researchers found that NMES combined with plyometric training lead to a decrease in 20m-sprint time but not with NMES alone or plyometric training alone. The combined group also showed significant relative increases in both the squat jump and countermovement jump compared to an NMES alone, plyometric alone, and control group. The NMES alone as well as the combined group lead to an increase in isometric strength. The final analysis by Herrero et al., looking at muscle cross- sectional area, showed that only the NMES alone and combined groups lead to a significant increase in thigh cross-sectional area. A possible reasoning for the plyometric exercise not showing effects could be due to the protocol that was used. The plyometric protocol only consisted of various jumps, namely 90-105 jumps a session with no resistance and with this one would not necessarily expect an increase in cross-sectional area. The participants in the study were also physically active prior to the study and the plyometric alone sessions may have led to a decrease in their load but both NMES would have provided some training stimulus and this potentially could lead to slight bias towards these groups as participants stopped all strength and endurance training. Another possible reason for the results obtained could be that the NMES provided a different stimulus to their usual training regimes leading to other adaptions (neural etc.). Although in addition to this study, Maffiuletti, Dugnani, Folz, Di Pierno, and Mauro (2002) published a study with very similar methodology assessing strength and two different jumps (squat jump [SJ] and countermovement jump [CMJ]). This study identified a significant increase in strength as well as both jumps compared to a control. Both studies had a four-week intervention period.

Parker, Bennett, Hieb, Hollar, and Roe (2003) demonstrated that NMES applied thrice a week had a significant increase in strength gains as opposed to NMES applied twice a week. Although in this study the researchers admit that they may have had a low statistical power due to the small number of subjects. It is also important to note that the researchers were only able to identify significant differences in a control and a thrice a week group but no differences between a twice a week group and either the thrice a week or control group. When one looks at the pairwise comparison between the twice and thrice a week group it is noticeable that the thrice a week group trained at a significantly higher intensity in the final week of the program and with a relatively short period (four weeks) this may have made a difference in the outcomes assessed. Notably too, only isometric contractions were performed and there were no dynamic exercises involved. There are numerous metabolic and other physiological effects of NMES training that differ from traditional strength training. The reviews performed by Paillard (2008) and Nosaka, Aldayel, Jubeau, and Chen (2011) detailed these differences, which include: motor unit recruitment: NMES seem to activate larger motor units, which seem to be more superficially located, ahead of smaller ones (McComas, Fawcett, Campbell, & Sica, 1971; Lexell, Henriksson-Larsen, and Sjostrom, 1983) whereas traditional voluntary contractions activate smaller motor units then larger ones according to the intensity of the stimulation (Paillard, 2008). Metabolic activation: at low exercise intensity NMES can enhance carbohydrate oxidation, energy consumption, and whole-body glucose uptake compared to voluntary contraction (Hamada, Hayashi, Kimura, Nakao, & Moritani, 2004). Muscle fatigue: NMES leads to earlier muscular fatigue compared to voluntary contractions (Paillard, 2008). Muscle damage: NMES tend to have greater effects on indirect markers of muscle damage such as, creatine kinase (CK) levels. There are also acute decreases in maximal voluntary contraction (MVC) following exercise sessions, compared to voluntary contractions (Nosaka et al., 2011). This could lead to a longer recovery period needed for individuals not familiar with NMES training. Other studies have also noted that NMES can create profound muscle damage (Maffiuletti et al., 2011; Nosaka et al., 2011). It is important to note that the hamstring muscles seem to be slightly more sensitive to the damaging effects of NMES than the quadriceps with individuals noting increased perceived muscle soreness (Vanderthommen, Triffaux, Demoulin, Crielaard, & Croisier, 2012). One explanation for this could be that the quadriceps are more involved with activities of daily living, potentially leading to an increased threshold for improvements and physiological effects (Veldman, Gondin, Place, & Maffiuletti, 2016).

NMES has been shown to be effective in increasing strength with an isokinetic dynamometer being used as the assessment tool (via torque production) by numerous studies (Avila, Brasileiro, & Salvini, 2008; Bircan et al., 2002; Cavlak, Baskan, & Yildiz, 2011; Hortobãgyi, Scott, Lambert, Hamilton, & Tracy, 1999). The systematic review and analysis performed by Filipovic, Kleinöder, Dörmann, and Mester (2012) also showed that both concentric and eccentric strength/torque production on an isokinetic dynamometer increases after NMES interventions. These results lead to the belief that if there is an effect using an NMES intervention, an isokinetic concentric or eccentric test will be appropriate to identify it. The majority of these studies, however, used the quadriceps femoris as the tested muscle group (concentric knee extension, eccentric knee flexion) and it cannot simply be assumed that every other muscle/muscle group will demonstrate the same effect.

Training level (trained vs untrained) does seem to be a factor in results from NMES protocols with untrained individuals seemingly having greater increases in strength when compared to trained individuals (Filipovic et al., 2012; Herrero et al., 2010). Although in the same systematic review elite athletes seem to have the greatest increases in strength compared to trained as well as untrained individuals. However, a more in-depth look into the study shows that the elite athletes protocols were the closest to the final guidelines proposed by Filipovic et al. (2011). This potentially means that the relatively superior protocols used on the elite athletes is the reason for their larger improvements in comparison to trained and untrained individuals. With this understanding it can be expected for trained individuals to demonstrate slightly smaller effects from an NMES intervention.

It has been shown that three to four days post NMES sessions is insufficient time for the muscles to adapt to the training stimulus from NMES training for testing (Herrero et al., 2010). Thus, there may be a “rebound effect” when training stimulus stops with NMES, leading to enhanced muscle voluntary contraction (Herrero et al., 2006). This is important as for a reliable and valid test the training effects would need to have taken place. Testing individuals within three days of an NMES session may compromise the reliability and validity of those results. Numerous studies have demonstrated that the improvements from NMES training remain comfortably above baseline/pre-training values for more than two-four weeks (Herrero et al., 2006; Gondin, Guette, Ballay, & Martin, 2006). Malatesta, Cattaneo, Dugnani, and Maffiuletti (2003) assessed the SJ and CMJ following a four-week NMES training program and found there to be much larger improvements 10 days after the participants final session compared to directly after the four-week program for both jumps (SJ and CMJ). This demonstrates the need for a detraining period following NMES for not just strength measures but also measures of jumps/ 'functional movements'.

It is also essential to identify the motor point of the muscles prior to use of NMES as to increase the stimulation effect (lower levels, higher stimulation) and decrease discomfort (Gobbo, Maffiuletti, Orizio, & Minetto, 2014). The motor point can be described as the skin area above the muscle where a muscle twitch can be evoked with the lowest electrical current (Gobbo et al., 2014). This allows for participants to have higher impulse intensities and therefore a higher contraction and hopefully increased effects from the NMES. Higher intensities with NMES is important for increased strength adaptions as although there are still increases in strength with lower intensities (<60% MVC) NMES at higher intensities (maximal tolerable intensity) is significantly superior to lower intensities

(Natsume, Ozaki, Kakigi, Kobayashi, & Naito, 2018).

There are limited studies detailing the lack of efficacy of NMES, potentially partly due to publication bias. Publication bias occurs when journals are more inclined to publish papers with positive outcomes or statistically significant findings (Kumar & Yale, 2016; Smith & Noble, 2014). However there are a few studies in which NMES, using various methodologies, were found to have little to no effect. These studies are important to examine, as there are numerous studies, which have found NMES to be beneficial for various outcomes (Avila et al., 2008; Bircan et al., 2002; Canning & Grenier, 2014; Colson et al., 2000; Currier & Mann, 1983; Filipovic et al., 2011; Filipovic et al., 2012; Gondin et al., 2006; Herrero et al., 2006; Herrero et al., 2006; Herrero et al., 2010; Hortobãgyi et al., 1999; Maffiuletti et al., 2002; Maffiuletti et al., 2011; Malatesta et al., 2003; Natsume et al., 2018; Paillard, 2008; Parker et al., 2003; Willoughby & Simpson, 1996; Willoughby & Simpson, 1998).

Mathes et al. (2017) found NMES superimposed with cycling to have no benefits over just cycling for endurance performance and anaerobic capacity. This study used participants that were not performing specified endurance training, which is quite vague but it gives the impression they were trained (as they were also sport students) but not trained in endurance cycling. If that were the case it would be expected to have both groups increase in the measures assessed due to a new stimulus. There were also numerous issues with their NMES protocol used, especially according to the guidelines proposed by Filipovic et al. (2011). Their protocol used a contraction time of 10 seconds and a rest of only 2 seconds leading to a duty cycle of over 80% (with guidelines of 20-25%). The authors were not clear on the time of NMES during each session but participants were allowed to increase the stimulation intensity every 10 minutes. Most other studies' protocol only lasted 10-15 minutes or less (Herrero et al., 2010; Malatesta et al., 2003; Parker et al., 2003; Paillard et al., 2010; Benito-Martinez, Lara- Sánchez, Berdejo-del-Fresno, & Martinez-López, 2011). Added to this higher load participants also underwent 14 sessions in 4 weeks, which is over 3 times a week. As expected the researchers did find the participants in the NMES superimposed with cycling group to have higher levels of markers of muscle damage namely; creatine kinase (CK) and lactate dehydrogenase (LDH). Recovery and reducing fatigue are vital to allow for supercompensation (Turner, 2011). However, the protocol implemented by Mathes et al. (2017) may have led to insufficient time for recovery, leaving the body in fatigue and potentially hindered supercompensation.

Cavlak et al. (2011) found both isometric training and NMES to increase multiple factors (isokinetic tests, decline squat, single leg hop, step up, fixed weight repetition test, and quadriceps circumference). The researchers did however find no significant differences between the two groups for all these factors, apart from the quadriceps circumference, where the NMES group had a significant increase in size compared to the isometric training group. In this study the participants that were in the NMES group performed no other exercise and they purely used the NMES isometrically. A Russian current was used which could have potentially lead to increased discomfort during the sessions and a lower training intensity/stimulation in response (Filipovic et al., 2011). The authors were also not clear on the time from the intervention to the post-test, thus not specifying if there was a detraining period or not.

2.6 Eccentric training

Eccentric training has been shown to lead to a rightward shift in the length-tension relationship (Aquino et al., 2010). The length-tension relationship is the amount of force exerted by a muscle at specific ranges of the muscle. This is believed to be because of the longitudinal addition of sarcomeres (Brockett, Morgan, & Proske, 2001; Kilgallon, Donnelly, & Shafat, 2007), which is greater when eccentric contractions are performed at longer muscle lengths (Butterfield & Herzog, 2006). However, in the Aquino et al. (2010) paper the rightward shift in the length-tension relationship found may not have been due to the addition of sarcomeres as concluded by the authors. In their study the researchers had three groups and only one of the groups performed strengthening exercises the other two were, a control group, and a stretching group. The strengthening group performed exercises in a lengthened state and thus making it more specific to longer muscle lengths in the hamstring. Therefore, it may be reasoned that the specificity of the exercises lead to the rightward shift of the length-tension relationship. It may be naïve to conclude the eccentric training leads to a rightward shift of the length-tension relationship from this study alone. Brockett et al. (2001) however also found that eccentric training performed on the hamstrings in healthy humans resulted in a rightward shift in the length-tension relationship. Caution needs to be taken when making deductions from this study alone as they had no control group but their strengthening protocol was eccentric training but not necessarily at long muscle lengths. Therefore these two studies together provide slightly stronger evidence for eccentric training leading to a shift in the length-tension relationship as Aquino et al (2010) focused their intervention at long muscle lengths while Brocket et al. (2001) focused on eccentric training and both lead to a rightward shift of the length-tension relationship in the hamstrings. Looking at other muscle groups McHugh and Tetro (2003) demonstrated a rightward shift in the length-tension relationship of the quadriceps femoris muscle group following eccentric exercise. Both Brocket et al. (2001) and the McHugh and Tetro (2003) studies demonstrated these changes within two weeks. In contrast to these findings Orishimo and McHugh (2015) found that lengthened state eccentric training for four weeks increased hamstring strength but did not lead to a change in the length-tension relationship this could be due to this study predominately using bodyweight exercises and possibly not providing a large enough stimulus to provide the proposed adaptions (longitudinal addition of sarcomeres) for a rightward shift in the length-tension relationship. Eccentric training has also been shown to increase hamstring flexibility using multiple hamstring flexibility tests (Abdel-aziem et al., 2018; Askar et al., 2015; Guex et al., 2016; Leslie et al., 2017; Potier et al., 2009).

Eccentric training has been used for over 70 years and is currently being used to manage numerous conditions and injuries such as; lower limb tendinopathies, anterior cruciate ligament (ACL) reconstruction, and hamstring strains (Lorenz & Reiman, 2011). The paper by Lorenz and Reiman (2011) summarized the research on eccentric training for these conditions in a clinical commentary, although a clinical commentary is not the gold standard of studies they do provide numerous eccentric exercises for the hamstrings for prevention and rehabilitation of hamstring strains. Another clinical commentary by Heiderscheit et al. (2010) also provided multiple exercises for the prevention and rehabilitation of hamstring strains. The exercises presented in this paper focused slightly more on exercises with the hamstring in a lengthened state compared to the paper by Lorenz and Reiman (2011). Orishimo and McHugh (2015) also provided numerous exercises for eccentric training of the hamstrings in a lengthened state. Orishimo and McHugh (2015) used EMG analysis to identify activity of the gluteus maximus, bicep femoris, and semitendinosus between four exercises, three of which were lengthened- state eccentric exercises for the hamstring namely: the diver, the glider, and the slider.

- The Diver: With the participant standing they simulate a dive (lifting the uninvolved leg) flex the hip of the involved leg and stretching the arms forward attempting maximal hip extension of the lifted leg with the pelvis horizontal. The knee should be at approximately 10-20° on the standing leg and 90° in the lifted leg, then returning to the starting position and repeating.
- The Glider: With the participant standing and holding on to a support with their legs slightly split. The participants weight should be on the heel of the involved leg (front) with approximately 10-20° flexion in the knee. The participant then glides backwards on the uninvolved leg (on a friction mat/towel/paper) and then slowly returns to the starting

position (gliding the foot back to the front using the arms if necessary).

- The Slider: The participant performs a supine double-leg bridge and then lowers their torso to the floor by extending their knees and sliding their foot till full extension then slowly returning to the starting position.

The glider and the slider activated the hamstring muscles at a significantly greater level compared to the gluteus maximus with the diver activating all three muscles at a similar level. The authors also identified a small but significant increase in isometric hamstring strength, which provides evidence that body weight exercises in lengthened state eccentric training of the hamstrings, provides enough stimulus for strength improvements. The authors did not provide the training level of their participants, they only stated they were uninjured.

2.7 Isokinetic dynamometry

The isokinetic dynamometer used in this study was the Biodex System 4 Pro™. The Biodex (Biodex medical systems, Shirley, New York, USA) has been shown to have an acceptable mechanical reliability and validity (Drouin, Valovich-McLeod, Shultz, Gansneder, & Perrin, 2004). Mechanical reliability of an isokinetic dynamometer testing human muscle function refers to the dynamometer being both consistent and free from error whilst its validity refers to it measuring the variable it is intending to measure (Portney & Watkins, 2000 as cited in Drouin et al., 2004). Feiring, Ellenbecker and Derscheid (1990) demonstrated that it was reliable for test-retest measures. The Biodex system 4 Pro™ has also specifically been shown to be reliable for test-retest measures (Tankevicius, Lankaite, Krisciunas, 2013). It should be noted that the study by Tankevicius et al., 2013 was performed on ankle inversion and eversion. No other research could be found with regard to test- retest measures, reliability, and validity, for other limbs with the Biodex system 4 Pro™ specifically.

The hamstring "lengthened state" isokinetic protocol, where an individual's hip is flexed and knee is extended, has been described and performed by numerous studies (McHugh & Nesse, 2008; Schmitt et al. 2012; Tyler et al. 2017). Biodex medical systems have accepted these lengthened state protocols and included them in their pre-set protocols as well as the ability to report on them on the Biodex System 4 Pro™. Tyler et al. (2017) performed the isometric protocol for testing and the eccentric protocol for training. In this study they noted that the effectiveness of the discharge criteria could be the reason for the low re-injury rate in their study and not necessarily the rehabilitation protocol. Their one-discharge criterion was "lengthened state eccentric training pain free at 0.35 rad/s (20°/s) throughout available ROM while resisting with maximal effort" (Tyler et al., 2017, p.140.).

2.8 Creatine Kinase

Creatine Kinase (CK) is an enzyme that has had copious amounts of research over the years, dating as far back as 1980's. CK is a compact enzyme found in the cytosol and mitochondria of tissues. CK has two subunits namely: muscle type (M) and brain type (B) and these subunits allow for specific isoenzymes namely: cardiac muscle (CK-MB), skeletal muscle (CK- MM), and brain (CK-BB) (Baird, Graham, Baker, & Bickerstaff, 2012). This allows for specific information regarding the location of tissue injury (Koch, Pereira, & Machado, 2014). Before understanding the potential markers CK provides to exercise it needs to be stressed that there are large individual differences in baseline CK values (Koch et al., 2014; Baird et al., 2012) with individuals who train in intense exercise with high-volumes have significantly raised base levels of CK (Chevion et al., 2003 as cited in Baird et al., 2012). CK is believed to be a marker of muscle damage/functional status of muscle tissue along with lactate dehydrogenase, myoglobin, troponin and others (Brancaccio, Maffulli, & Limongelli, 2007; Baird et al., 2012). This has led to high CK levels being relating to impaired muscle function or condition. One of the reasons why CK has been used as an indirect marker for muscle damage, an indicator for training intensity, and diagnostic marker for overtraining, is its ease of identification and relatively low cost of assays to be quantified (Koch et al., 2014).

Not only has it been demonstrated that there are large individual differences in CK levels at baseline but individuals have been classified as either “high responders” or “low responders” in light of some individuals expressing a much higher rise in CK levels following resistance training (Brancaccio et al., 2007; Koch et al., 2014).

Increases in CK levels can possibly be attributed to sarcolemma and Z- disk damage and eccentric exercise tend to lead to damage to the sarcomere and perforations in the sarcolemma (Clarkson & Sayers, 1999) and thus increased CK levels (Smith et al., 1994). Not only eccentric exercise leads to damage of the muscle and these structures but concentric and isometric exercise can also lead to this damage (Koch et al., 2014). The relationship between CK levels and load is very complicated and there are numerous factors tat can cause a rise in CK levels with shorter rest intervals seeming to lead to an increase in CK levels (Koch et al., 2014). Untrained individuals tend to have higher increases in CK levels following exercise compared to trained individuals (Vincent & Vincent, 1997; Fehrenbach et al., 2000 as cited in Brancaccio et al., 2010). One reason for this may be that familiarization of the exercise with adaptions seemingly happen quickly (Koch et al., 2014). One single exposure to resistance or eccentric training seems to lead to some protection against muscle damage in subsequent bouts and is known as the "the repeated bout effect", seemingly to be quite prominent in CK levels (Koch et al., 2014; Chen, 2006; Nosaka & Saldanha Aoki, 2011). As stated in the review articles by Koch et al. (2014) and Baird et al. (2012), such variability in studies regarding CK has led to making interpretations, guidelines, and procedures with regard to CK quite difficult. This should be kept in mind when discussing and making conclusions concerning exercise and CK levels.

CK levels may be of particular interest in studies where NMES is used as multiple studies have found the use of NMES used in various protocols to lead to an increase in CK levels (Nosaka et al., 2011; Jubeau et al., 2008; Jubeau, Muthalib, Millet, Maffiuletti, & Nosaka, 2012; Nosaka, Newton & Sacco, 2002). The study by Nosaka et al. (2012) demonstrated that performing eccentric exercises ‘against’ the NMES contraction potentially leads to decreased MVC, increased muscle soreness, and CK levels compared to isometric contractions with NMES. This provides the premise that not only does NMES increase CK levels and muscle damage but NMES with eccentric exercise could accentuate that.

To summarize, it is clear that hamstring injuries place a big burden on sportsmen/women and the methods that have been employed to reduce and prevent these injuries have not yet been sufficient. Including lengthened state training of the hamstrings has shown merit although further research is needed. NMES is another tool used in strength and condition, and rehabilitation settings that have shown promise and potential, although very little research has been done specifically on the hamstrings with NMES. Thus adding NMES to lengthened state hamstring training could prove to be a novel and effective method for strengthening of the hamstrings.

Chapter 3

MATERIALS AND METHODS

This study, ‘The effect of neuromuscular electrical stimulation on hamstring prehabilitation’ was an experimental study investigating the most effective method for increasing lengthened state eccentric strength of the hamstrings with four different protocols/methods. An additional aim was to assess the changes in hamstring flexibility using an active straight leg raise (ASLR) and passive straight leg raise (PSLR).

3.1 Design and sampling

3.1.1 Design

This research study aimed to assess, measure and evaluate the lengthened state eccentric strength of the hamstring following four separate protocols namely; resistance training alone (RT), neuromuscular electrical stimulation alone (NMES), NMES superimposed with RT (NMES&RT), and a control group (C). For this reason, a true experimental design was selected for inquiry. Experimental research seeks to determine if a specific treatment influences an outcome. The impact of these treatments is assessed by providing specific treatments to one or more groups and withholding it from another and then determining how all groups scored on an outcome. Experiments include true experiments, with the random assignment of subjects to treatment conditions (Keppel, 1991; Creswell, 2009). This study thus adopts a quantitative research approach with a true experimental design, which will provide the framework for data collection

3.1.2 Sampling

Non-sedentary males that partake in high-speed running and/or cutting sports within the City of Cape Town between the ages of 18 and 35 years old were eligible for the study. Participants were classified as non-sedentary if they participated in at least 30 minutes of moderate activity for a minimum of three days a week (American College of Sports Medicine [ACSM], 2010). According to the Western Cape Government, census data reports that the size of this specific population (non-sedentary males between the ages of 18 and 35 that partake in high-speed running sport in the City of Cape Town) is approximately 352 100 people (Moss, n.d.; Western Cape Government Provincial Treasury, 2015). A non-probability sampling method was employed for this study, and more specifically, a convenience sampling technique was adopted for the recruitment of participants before random assignment to experimental and control groups for the intervention (Creswell, 2009). Non-probability sampling is when not all individuals of a population have a chance of participating in the study. Convenience sampling is when participants are chosen based on their convenience or availability (Creswell, 2009). Due to the size of the population and a limited research team a true random sample is not viable.

Participants for the study were recruited from multiple sports teams and clubs around the City of Cape Town who were contacted with information of the study. Table 3.1 summarizes the exercise and sport facilities that were contacted in this research study. In order to decrease selection bias, clubs and facilities were selected at random. Selection bias can occur when proper randomization of individuals or groups selected is not achieved and thus the study sample is not representative of the population due to the sampling methods used (Kumar & Yale, 2016; Smith & Noble, 2014). A database of clubs was accessed via the City of Cape Town's website (City of Cape Town, n.d.). Additionally athletes were also recruited from other sport clubs/facilities not on the City of Cape Towns' list if they met the eligibility criteria for this study. This was done in another attempt to decrease selection bias. Forty-two male participants between the ages of 18 and 35 agreed to take part in the study from 22 various clubs/facilities.

Table. 3.1. Clubs and facilities contacted for the study

	Clubs/facilities (n= 22)
Club/facility	-
Cricket clubs	6
Rugby clubs	5
Hockey clubs	3
Football clubs	2
CrossFit® gyms	2
Other	2
Indoor football facilities	1
Tennis clubs	1

3.1.1 Inclusion and exclusion criteria

3.1.1.1 Inclusion criteria

- Only non-sedentary individuals were eligible
- Only male participants were eligible
- The coefficient of variation (CV) of the isokinetic testing had to be less than 15% to be valid for inclusion to the study

3.1.1.2 Exclusion criteria

- Any clinically diagnosed hamstring injury that was not rehabilitated. This was based on participants self-reporting
- Any current hamstring injuries at the time of the study
- A self-report of any joint, ligament, tendon, or muscular pain that may produce hamstring pain were excluded
- Any co-existing lower-limb and/or pelvic fractures

3.2 Research setting

Pre and post-testing took place at the University of the Western Cape (UWC) Biokinetics clinic, as this is where the equipment needed for testing was located. The intervention sessions took place at various venues that were suitable for the participants as to make it more possible for the participants to attend intervention sessions.

3.2 Data collection

3.3.1 Instrumentation

The isokinetic dynamometer used was the Biodex System 4 Pro™ (Biodex medical systems, Shirley, New York, USA). The same dynamometer was used for all participants included in the study at the pre- and post-test phases. The Biodex is an isokinetic dynamometer that has the ability to report on eccentric strength as well as the ability to put the hamstring in a lengthened state. The Biodex system 4 Pro™ was chosen as the testing tool as it has shown to be reliable for test-retest measures (Tankevicius et al., 2013). Previous models of the Biodex have also been shown to have high mechanical reliability and validity (Drouin et al., 2004).

The neuromuscular electrical stimulation (NMES) device used to test the effects of NMES on lengthened state eccentric strength of the hamstrings was the Compex® SP4 (Medicompex, Ecublens, Switzerland). The Compex® SP4 was used as it has the ability to perform NMES stimulation following the guidelines described by Filipovic et al. (2011). The "strength" programme was used as it has a contraction setting at 75Hz for an 18-minute program with four-second contractions and a 21.05% duty cycle (Filipovic et al., 2011).

3.3.2 Recruitment

The aforementioned clubs/facilities were approached where a brief overview of the study was given. An information session was hosted by the researcher to inform potential participants of the research study underway.

Those individuals who showed interest were then given a detailed information sheet (Appendix B) for consideration including the requirements and potential benefits of the study. Additionally, a questions and answer session was held for all concerns and queries from athletes and coaches. All participants who agreed to take part in the study completed a consent form (Appendix C) and then proceeded to complete a questionnaire to assess their eligibility. Computer randomization was used to ensure randomization of participants using Microsoft Excel 2011 (Microsoft Corporation, Redmond. WA). Participants were only assigned to groups after entering the study thus decreasing selection bias. Unfortunately due to the physical nature of the study participants were not able to be blinded as to which group they were allocated to. In addition to the information sheet a detailed verbal explanation of the study was given to each participant prior to the pre-test as to understand the requirements of the study. As participants were recruited at various times there had to be a minimum amount of four participants prior to this randomization as to ensure all participants had an equal chance of being allocated to any group and thus maintaining the 'randomness'. This was decided prior to the commencement of the study. The pre-test protocol was standard across all groups. This research was approved by the University of the Western Cape's research ethics committee (BM16/4/3).

3.3.3 Pre-test

The pre-test was performed on the isokinetic dynamometer at the Biokinetics clinic at the University of the Western Cape. As part of the pre-test assessment, an active and passive straight-leg raise (ASLR, PSLR) and modified Thomas test with a 5-minute standardized warm up on a stationary bike was performed by each participant prior to testing, in this order. The pre-test was conducted by the researcher, who is a qualified Biokineticist and registered with the Health Professionals Council of South Africa. This testing protocol is within the scope of practice for Biokineticists, to test patient and athlete active and passive hamstring strength for rehabilitation and exercise prescription (Health professions council of South Africa [HPCSA], n.d.).

The isokinetic test comprised of knee extension/flexion on eccentric/concentric (ECC/CON) with the trunk at 90° and the hip flexed at 40° degrees thus leading to a trunk-to-thigh angle of 50°. This was confirmed with a goniometer prior to isokinetic testing. This was done to assist with positioning the hamstrings in a lengthened state. The knee angle/ROM was set between 90° and 20°, so as to put the hamstrings in a lengthened state, as described by by Tyler et al. (2017) and accepted by Biodex medical systems as one of their standard protocols with the equipment.

For each participant, a coefficient of variation (CV) was employed to ensure validity and reliability of test results. A coefficient of variation is the ratio of the standard deviation to the mean (Everitt, 2002). This assists in determining the reproducibility of the test.

Each participant then performed three repetitions on their dominant leg as part of the pre-test process. It was ensured that the CV was <15%, if the CV was >15% the test was performed again to ensure the validity and reliability of their test results. The isokinetic torque value that was used was Newton-meters per kilogram (Nm·kg^{-1}). This was obtained by dividing participant's raw peak torque value by their bodyweight.

3.3.4 Intervention

The duration of the intervention took place over a period of 4 weeks (Filipovic et al., 2011). Participants were allocated to one of four groups, in the manner explained above. The groups were namely; control group (C), resistance training/exercise alone group (RT), neuromuscular electrical stimulation alone group (NMES), or NMES superimposed with resistance training (NMES&RT). Figure 3.1 details the assignment of participants to their respective groups and the procedure of the study.

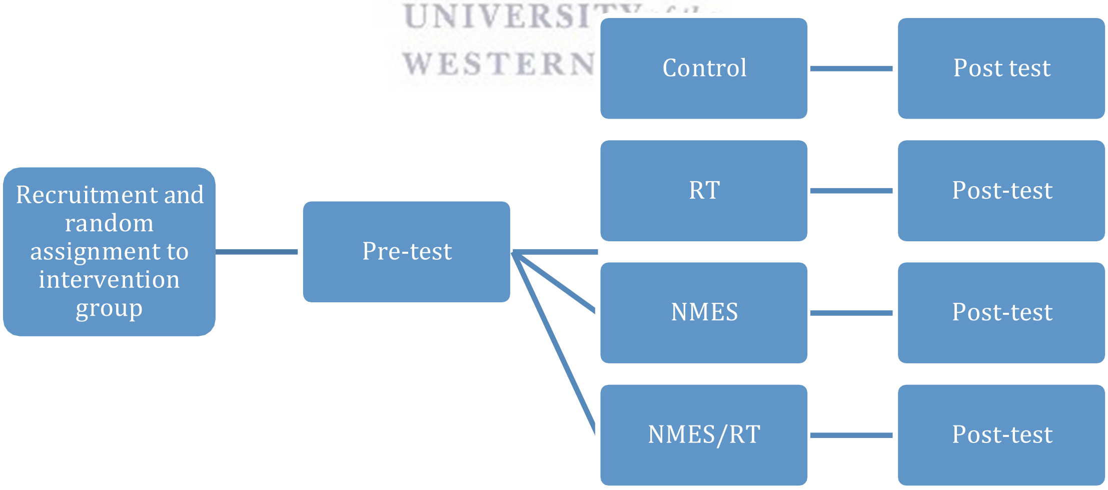

Figure. 3.1. Study procedure and flow

3.3.4.1 RT group

The RT group performed four exercises (Heiderscheit et al., 2010; Orishimo & McHugh, 2015);

1. The diver
2. The glider
3. The slider
4. Single-leg hamstring bridge

These exercise were performed three times a week. Details of the exercises can be found in the appendices. The participants in the RT group were allowed to continue with sporting activity but were not permitted to perform any resistance training on the hamstrings for the four weeks.

3.3.4.2 NMES group

The NMES group had NMES administered on the hamstrings three times a week with no exercises. The participants in the NMES group were allowed to continue with sporting activity but were not permitted to perform any resistance training on the hamstrings for the four weeks.

3.3.4.3 NMES&RT group

The NMES&RT group performed the same four exercises as the RT group but with NMES superimposed. This was performed three times a week- as per the guidelines by Filipovic et al. (2011). The participants in the NMES&RT group were allowed to continue with sporting activity but were not permitted to perform any resistance training on the hamstrings for the four weeks.

3.3.4.4 Control group

The control group had no intervention administered for the four weeks. The participants in the control group were allowed to continue with sporting activity but were not permitted to perform any resistance training on the hamstrings for the four weeks.

In an attempt to ensure the effectiveness of the NMES groups all NMES groups had their motor point identified (Gobbo et al., 2014) prior to the start of their first session by the researcher. The motor point of the medial (semimembranosus and semitendinosus) and lateral (biceps femoris) hamstring was identified using a motor point pen. The motor point pen was used to scan the skin over the hamstring muscles. The motor point was identified as the area of skin that required the lowest current intensity to produce a mechanical response such as a muscle twitch (Gobbo et al., 2014). The motor points were noted, in an attempt to ensure electrode placement over the motor points every session, as it was not viable to identify the motor point at the start of every session for every participant. The electrodes used were self-adhesive. One large electrode (10 cm x 5 cm) was placed just below the gluteal fold on the posterior surface of the thigh. Two small electrodes (5 cm x 5 cm) were placed over the motor point of the medial hamstring and lateral hamstring respectively. No shaving was required for placement of the electrodes.

3.3.5 Post-test

Then between four days and prior to two weeks after their final intervention session the participants performed the post-test, which follows the same procedure/protocol as the pre-test, as to allow their hamstring muscles adequate time to adapt to the training stimulus (Herrero et al., 2010) and to avoid detraining. As Herrero et al (2010) showed that three days after cessation of NMES was not enough time for muscles that have undergone NMES training to adapt to the training stimulus, numerous studies and systematic reviews have shown that increases in strength following NMES have remained the same or even increased in periods longer than two weeks of cessation from NMES (Filipovic et al., 2011, Filipovic et al., 2011, Herrero, 2010). The post-test was not performed after two weeks following the intervention as after two weeks after resistance training there is a notable decrease in strength (McArdle, Katch, & Katch, 2010). Another clinician, with similar experience on the Biodex, conducted the post-test as to provide blinding and decrease the risk of ascertainment bias. Ascertainment bias can occur when there is knowledge of which intervention each participant received (Kumar & Yale, 2016).

3.4 Analysis of data

The data were analyzed using SPSS software version 25. All data were initially tested for normality using a Shapiro-Wilks test to ensure the assumption of normal distribution, which statistical tests are based, are not violated and thus parametric testing may be performed (Ghasemi & Zahediasl, 2012). A paired t-test was used for within group changes and then a repeated-measures analysis of variance (ANOVA) test was run. Following that a post-hoc analysis using a bonferroni correction was run if there was an interaction effect between intervention and time for any analysis where a repeated-measures ANOVA was run. The responses of each intervention were compared. Adjustment for multiple testing was done as the statistical significance for the t-test was set at $p<0.0125$, as this is *a* = 0.05 divided by the number of groups (four) to reduce risk of a Type I error and $p<0.05$ was used for all other cases (Bender & Lange, 2001). Multiple testing was performed in an attempt to decrease the risk of a Type II error (Rothman, 1990). A Type I error is when a null hypothesis is rejected when it is in fact true or concluding there are differences between groups when there is not, also known as a false positive. Whereas a Type II error is when a null hypothesis is accepted when it is in fact false or concluding there are no differences between groups when there is, also known as a false negative (Bender & Lange, 2001; Lochner, Bhandari, & Tornetta, 2001; Rothman, 1990).

Following this, Magnitude based inferences (MBI) were used to identify the magnitude of the effect of each group. Uncertainty of the estimates, shown as 90% confidence intervals for the change scores (Batterham & Hopkins, 2006), the between group differences (mean percentage [%]), the standardized effect size (cohen's *d*) for each between group analysis, was calculated using Hopkins' pre-post parallel group spreadsheet (Hopkins, 2017). The smallest worthwhile effect was defined as 0.2 times the between subject standard deviation of the baseline value (Hopkins, Marshall, Batterham, & Hanin, 2009). Qualitative inferences were based on the disposition of the confidence interval for the mean difference in relation to the smallest worthwhile effect. The probability that the true population difference between the groups was substantial (beneficial/harmful) or negligible were qualified via probabilistic terms as described by Batterham and Hopkins (2006) and effect sizes were categorized as follows: 0.00–0.19 = negligible; 0.20–0.59 = small; 0.60–1.19 = moderate; 1.20–1.99 = large; 2.00–3.99 = very large; 4.0 = extremely large (Batterham & Hopkins, 2006).

Following the testing periods, all participants' data were analyzed using the aforementioned methods to identify the most effective intervention within this study and gather further insight in order to test the initial hypothesis of this study's inquiry.

Chapter 4

RESULTS

To test the hypothesis that NMES&RT combined is the most effective intervention to increase the lengthened state eccentric strength of the hamstrings Forty-two male participants were originally recruited from various sports clubs and facilities within the City of Cape Town (rugby, football, hockey, cricket, tennis, indoor football, CrossFit®). They were all recruited at various times during the intervention, which took place over a seven-month period from March 2017 to September 2017. Computer randomization was used for the random assignment of participants to the different research groups namely; resistance training alone (RT), neuromuscular electrical stimulation alone (NMES), neuromuscular electrical stimulation superimposed with resistance training (NMES&RT), and a control group (C). Seven of the participants dropped out due to various reasons (e.g. injury, not being able to attend all sessions etc.). Thus a total of 35 participants completed the intervention. All data were analyzed using SPSS version 25.

4.1 Peak torque

All data were initially tested for normality using a Shapiro-Wilk test to ensure the assumption of a normal distribution, which the other statistical tests are based on, was not violated (Ghasemi & Zahediasl, 2012). Both the pre-test (p = 0.995) and post-test (p = 0.954) were not statistically significant, indicating that there was no evidence against the assumption of normality and thus we could assume the data was normally distributed and parametric testing was performed.

To understand within-group changes for each group, a paired t-test was performed for each intervention with statistical significance being set at *p*<0.0125, which is the statistical significance of 0.05 divided by four (number of groups) in order to decrease the risk of a Type I error, as multiple hypothesis testing can compound the Type I error (Bender & Lange, 2001).

Table. 4.1. Paired t-tests including means and standard deviations for the pre- test and post-test isokinetic peak torque ($Nm \cdot kg^{-1}$) results as well as differences within each intervention from the two testing phases

Group	Pre-test mean (± SD)	Post-test mean (± SD)	Mean difference (± SD)	t value	*p* value
Control (n=9)	2.26 (± 0.52)	2.36 (± 0.49)	0.10 (± 0.25)	-1.22	0.257
RT alone (n=10)	2.49 (± 0.43)	2.54 (± 0.44)	0.05 (± 0.32)	-0.44	0.672
NMES alone (n=8)	2.42 (± 0.39)	2.65 (± 0.32)	0.23 (± 0.36)	-1.81	0.114
NMES&RT (n=8)	2.64 (± 0.55)	2.88 (± 0.54)	0.24 (± 0.16)	-4.33	0.003*

**Statistical significance at p <0.0125*

The greatest mean difference was in the NMES&RT intervention (0.24 Nm·kg^{-1} or an 11% increase) with the smallest difference being in the RT alone intervention (0.05 Nm·kg^{-1} or a 2.44% increase) (Table 4.1 & Figure 4.1). The NMES&RT was the only intervention that showed a statistically significant increase in peak torque (p = 0.003) as a result of the intervention. However the largest percentage change was found in the NMES alone group (11.00%) (Figure 4.1). This was followed closely by the NMES&RT group (10.04%). The confidence interval (CI) for the NMES&RT group (2.09%- 17.98%) is much smaller than the NMES alone group (-1.68%-23.67%) (Figure 4.1) so the mean of the sample for the NMES alone group could be substantially different if the study were to be repeated.

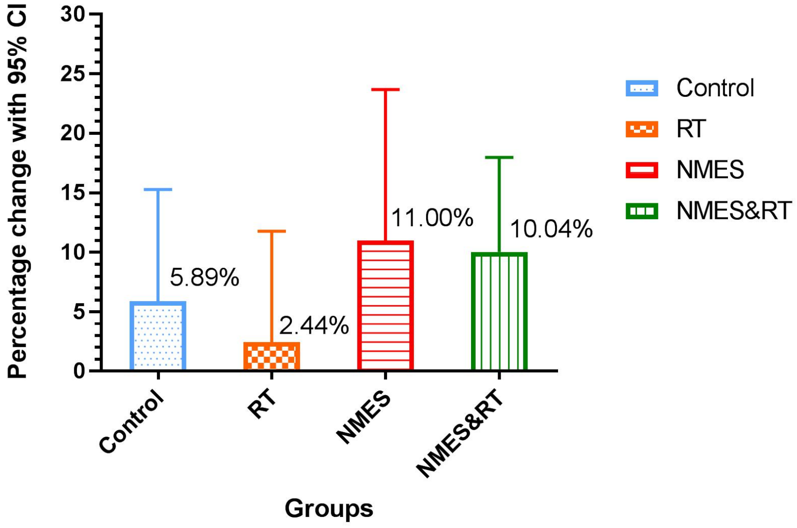

Figure. 4.1. Percent change within groups with a 95% confidence interval (CI)

The ANOVA with repeated measures (Table 4.2) showed a significant main effect of time over all interventions, F(1) = 10.02; p = 0.003, indicating that strength increased significantly over all groups but there was no effect of the intervention, F(3) = 1.47; *p* = 0.243.

Table. 4.2. Differences between interventions using an ANOVA with repeated measures

Measure	**F**	**df**	***p value***
Time	10.02	1	0.003*
Intervention	1.47	3	0.243
Time X intervention	0.99	3	0.411

*Statistical significance at *p*=<0.05

This means that strength was similar in all four groups for both the pre-test and post-test. There was also no interaction effect of time by intervention F(3)= 0.99; *p* = 0.411. The absence of the interaction effect of time by intervention indicates that strength developed similarly over the groups.

These results indicate that time was the only factor within this study and no significant differences between interventions, but the paired t-test (Table 4.1) needs to be kept in mind before we dismiss these interventions and further analysis and assessment needs to be performed. A post-hoc analysis was not performed due to the lack of an interaction effect (p = 0.411) and thus illustrating there were no significant differences between the groups (Table 4.2). The interaction effect demonstrates that at least one group had significant changes from the pre-test to the post-test compared to the other groups.

Figures 4.2 and 4.3 suggest that there were no trends, no identifiable distributions, and no consistent differences between individuals relative peak torques within the control group over time. This is consistent with what would be expected from a group that received no intervention.

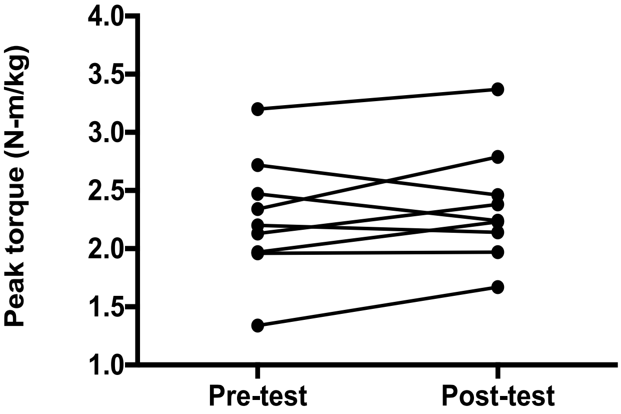

Figure. 4.2. Relative peak torque changes in the control group

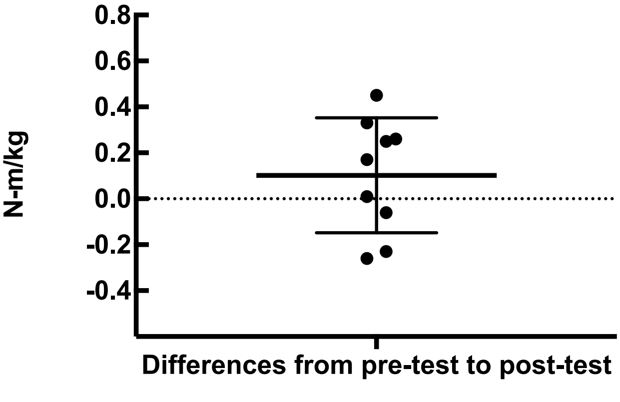

Figure. 4.3. Differences from pre-test to post-test in the control group

Similar results were noted within the RT alone group (Figures 4.4 & 4.5) with no identifiable trends, distributions and no consistent differences. This is not surprising given the fairly large spread of data from the pre to post- test differences (SD = ±0.32) (Table 4.1).

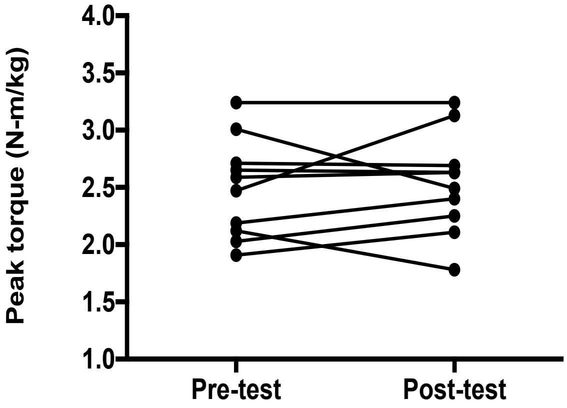

Figure. 4. 4. Relative peak torque changes in the RT group

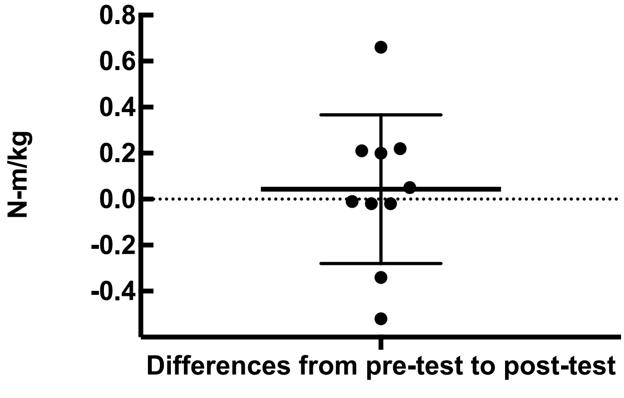

Figure. 4.5. Differences from pre-test to post-test in the RT group

There appears to be a trend of increasing relative strength in the NMES group (Figure 4.6). However, the large spread of data needs to be noted. Indicated by the SD of the mean differences of ±0.36 from the pre-test to post-test (Table 4.1).

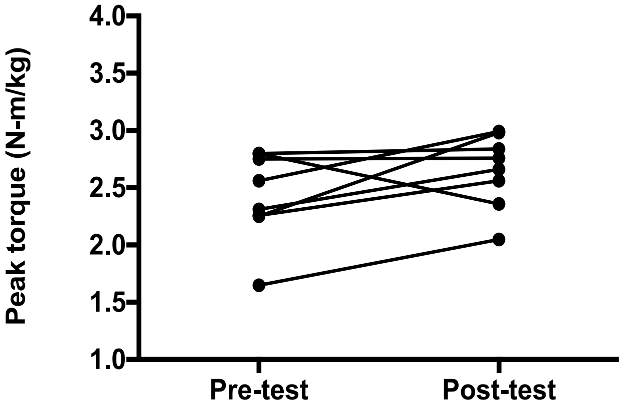

Figure. 4.6. Relative peak torque changes in the NMES group

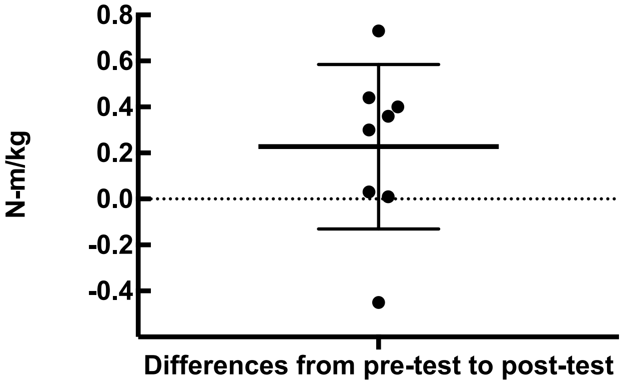

Figure. 4.7. Differences from pre-test to post-test in the NMES group

There were consistent and similar changes from the pre-test to post-test in the NMES&RT group compared to the other groups (SD= ±0.16) (Table 4.1). There is also a noticeable positive trend for the NMES&RT intervention as can be seen in all participants increasing their strength relative to their body weight (Figure 4.8).

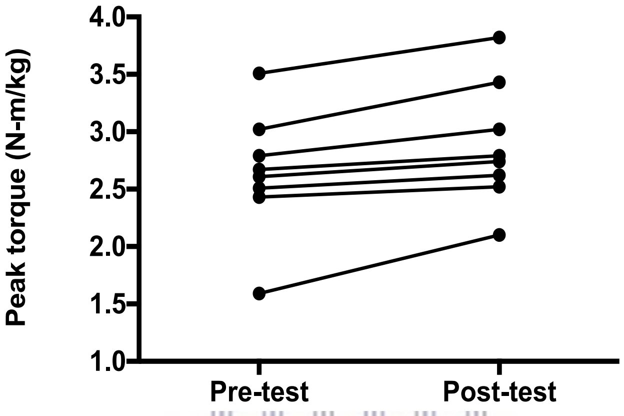

Figure. 4.8. Relative peak torque changes in the NMES&RT group

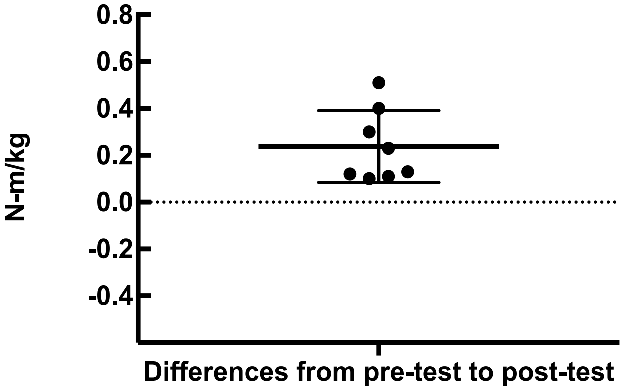

Figure. 4.9. Differences from pre-test to post-test in the NMES&RT group

From these figures a trend in the NMES&RT intervention and the strength development of the hamstring in a lengthened state eccentrically can be seen.

4.1.1 Magnitude-based inferences (MBI)

MBI were used to identify the magnitude of the effect of each intervention, with 90% confidence intervals being used for the change scores as recommended by Batterham and Hopkins (2006). The between group differences (mean %), and the standardized effect size (*d*) for each between group analysis was calculated using Hopkins' pre-post parallel intervention spreadsheet (Hopkins 2017). The effect sizes were categorized as follows: 0.00-0.19 = negligible; 0.20-0.59 = small; 0.60-1.19 = moderate; 1.20-1.99 = large; 2.00-3.99 = very large; 4.0 = extremely large (Batterham & Hopkins, 2006).

This deeper analysis into the data comparing the interventions using MBI (Table 4.3 & Table 4.4) facilitated the ability to see that the differences between the NMES vs NMES&RT interventions (*d* = 0.02) as well as Control vs RT interventions (*d* = -0.12) are unclear and negligible (Table 4.3 & 4.4). The largest effect size was the NMES intervention compared to the RT intervention (*d* = 0.44) and the NMES&RT intervention compared to the RT intervention had an effect size of 0.39 but with a smaller confidence level (0.2) compared to NMES vs RT (0.3) (Table 4.4).

This variation can also be seen in those two pairwise comparisons' confidence intervals, -0.02 to 0.80 for the RT vs NMES&RT comparison and -0.23 to 1.11 for the NMES vs RT comparison, which of course means we have a slightly more specific and less dispersed range for the NMES&RT vs RT comparison compared to the NMES vs RT comparison (Table 4.4). The RT vs NMES (*d* = 0.44) and the RT vs NMES&RT (*d* = 0.39) comparison showed a small positive effect, the most likely positive effect between all interventions (Table 4.4). The comparisons between the control group and NMES (*d* = 0.26) and Control group vs NMES&RT (*d* = 0.24) also showed a small positive effect but slightly smaller effect sizes compared to RT vs NMES (*d* = 0.44) and RT vs NMES&RT (*d* = 0.39) (Table 4.3 & Table 4.4).

Table. 4.3. MBI results for between-group comparisons of the control group

Between-group comparisons	**Control vs. RT**	**Control vs. NMES**	**Control vs. NMES&RT**
Change score difference	-0.05	0.13	0.14
SEM	0.13	0.15	0.10
± 90% CL	0.20	0.30	0.20
Effect size (d)	-0.12	0.26	0.24
CI	-0.58 to 0.34	-0.29 to 0.82	-0.07 to 0.54
Qualitative inference	Negligible/unclear	Small positive	Small positive

Table. 4.4. MBI results for comparisons between the intervention groups

Between-intervention comparisons	**RT vs. NMES**	**RT vs. NMES&RT**	**NMES vs. NMES&RT**
Change score difference	0.18	0.19	0.01
SEM	0.16	0.12	0.14
± 90% CL	0.3	0.2	0.3
Effect size (d)	0.44	0.39	0.02
CI	-0.23 to 1.11	-0.02 to 0.80	-0.48 to 0.52
Qualitative inference	Small positive	Small positive	Negligible unclear

4.2 Active straight leg raise (ASLR)

Hamstring length was tested in two ways: Active SLR (ASLR) and passive SLR (PSLR). The data for the active straight leg raise (ASLR) was also tested for normality using a Shapiro-Wilk test. The pre-test provided no evidence against the assumption of normality (*p* = 0.225) but the post-test did with *p* = 0.008. However as it is a post-test from the same participants per group, and the only test to provide evidence against the assumption of normality it was checked visually using a stem-and-leaf plot as well as the Q- Q plot (Ghasemi & Zahediasl, 2012) with these demonstrating a normal distribution of data (Figure 4.10) and thus parametric tests were also used.

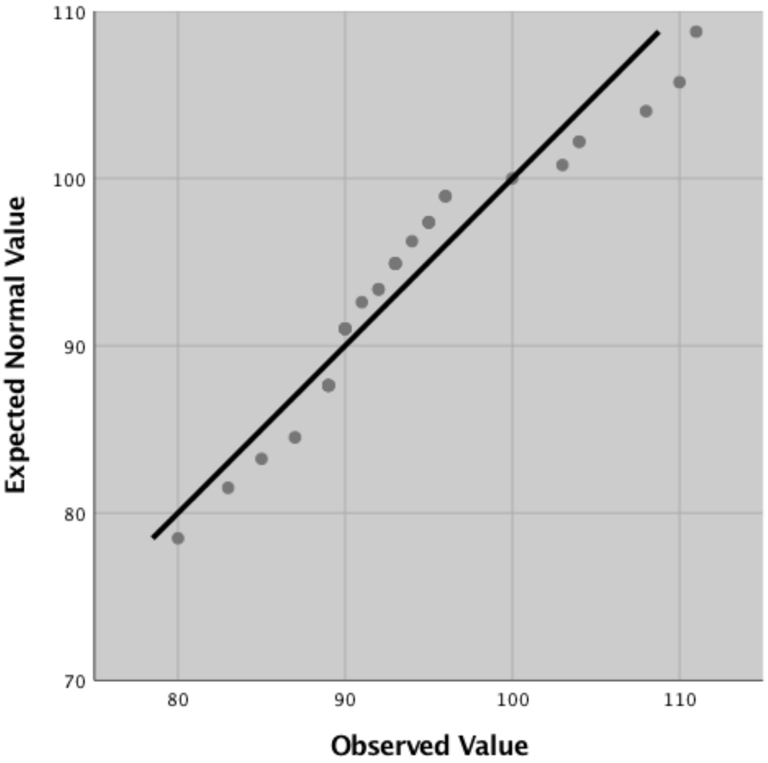

Figure. 4.10. Q-Q plot for ASLR post-test data

A paired t-test was used to identify within-group changes for each group. For the ASLR, the control intervention had the greatest increase in length from pre-test to post-test (11.89°) with the NMES alone intervention having the smallest increase (3.75°). However it is pertinent to note that all interventions showed an increase in hamstring length (Table 4.5). Although none of them are statistically significant when statistical significance is set at *p*<0.0125. The control intervention almost reached statistical significance (*p* = 0.013) (Table 4.5).

Table. 4.5. Paired t-tests including means and standard deviations for the pre-test and post-test ASLR (degrees) as well as differences within each intervention from the two testing phases

Group	**Pre-test mean (± SD)**	**Post-test mean (± SD)**	**Mean difference (± SD)**	**t value**	***p value***
Control (n=9)	78.11° (± 11.97)	90. 00° (± 4.44)	11.89° (± 11.27)	-3.16	0.013
RT Alone (n=10)	87.70° (± 6.75)	91.70° (± 3.62)	4.00° (± 8.01)	-1.58	0.149
NMES Alone (n=8)	89.75° (± 12.89)	93.50° (± 7.71)	3.75° (± 7.52)	-1.41	0.201
RT & NMES (n=8)	91.63° (± 16.28)	100.25° (± 8.97)	8.62° (± 14.05)	-1.74	0.126

*Statistical significance at *p*<0.0125

An ANOVA with repeated measures showed an effect of time F(1) = 15.9; *p* = 0.000, indicating that over all groups hamstring length (using an ASLR) increased significantly. There was also an effect of intervention, F(3) = 3.10; *p* = 0.041, indicating that there was a significant difference in hamstring length between the groups during either the pre-test or post-test. Figure 4.11 clearly shows that there were differences between the control group and the other groups at the pre-test, providing an explanation for this effect of intervention (Table 4.6). There was no interaction effect of time by intervention on hamstring length (using an ASLR), F(3) = 1.26; *p* = 0.306 (Table 4.6).

Table. 4.6. Differences between interventions of the ASLR using an ANOVA with repeated measures

Measure	**F**	**df**	***p value***
Time	15.93	1	0.000*
Intervention	3.10	3	0.041*
Time X intervention	1.26	3	0.306

*Statistical significance at *p*=<0.05

This indicates that hamstring length (using an ASLR) developed similarly over all the groups. As there was no interaction effect no post-hoc test was used. It is very interesting to note that the control intervention had the lowest statistical value as well the greatest increase in hamstring length using an ASLR (Table 4.5 & Figure 4.11).

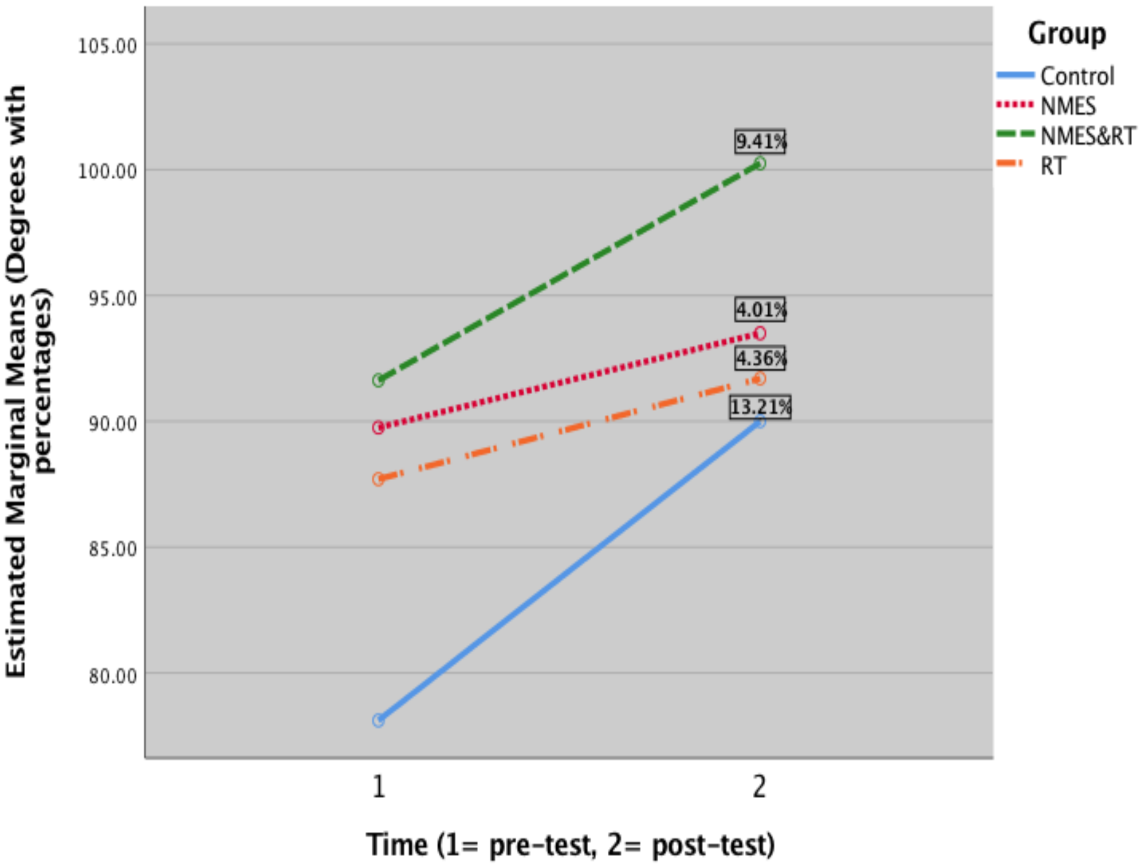

Figure. 4.11. Estimated marginal means of ASLR for all groups for the pre- and post-tests.

4.2 Passive straight leg raise (PSLR)

Analysis for the passive straight-leg raise (PSLR) showed it was also normally distributed using a Shapiro-Wilk test for both the pre-test (p = 0.072) and post-test (p = 0.119) and thus parametric testing was also used.

Once again, there was an increase in the mean for the hamstring length in all interventions (Table 4.7). A paired t-test was used to identify within group changes for each group. The control group had the greatest increase in hamstring length (15.11°) as well as the only statistically significant result (*p* = 0.006) (Table 4.7). The NMES alone intervention had the smallest mean increase (3.75°) which corresponds to the ASLR test results as these two interventions had the greatest and least increase respectively in the ASLR test too.

Table. 4.7. Paired T-tests including means and standard deviations for the pre-test and post-test PSLR (degrees) as well as differences within each intervention from the two testing phases

Group	Pre-test mean (± SD)	Post-test mean (± SD)	Mean difference (± SD)	t value	*p* value
Control (n=9)	85.00° (± 12.85)	100.11° (± 6.88)	15.11° (± 12.06)	-3.76	0.006*
RT alone (n=10)	91.20° (± 9.34)	101.50° (± 3.84)	10.30° (± 10.80)	-3.02	0.015
NMES alone (n=8)	93.00° (± 12.75)	96.75° (± 5.12)	3.75° (± 9.87)	-1.08	0.318
RT&NMES (n=8)	93.63° (± 14.24)	102.38° (± 7.52)	8.75° (± 8.88)	-2.79	0.027

*Statistical significance at $p<0.0125$

An ANOVA with repeated measures showed an effect of time, F(1) = 28.04; *p* = 0.000, indicating that over all groups' hamstring length (using a PSLR) increased significantly from pre-test to post-test. No effect of intervention, F(3) = 0.71; *p* = 0.56, was seen indicating that hamstring length (using a PSLR) was similar in all four groups for both the pre-test and post- test, as well as no interaction effect of time by intervention on hamstring length (using a PSLR), F(3) = 1.67; *p* = 0.193 (Table 4.8). The absence of the interaction effect of time by intervention indicates that hamstring length (using a PSLR) developed similarly over all the groups. As there was no interaction effect no post-hoc test was used. The control intervention was the only intervention to reached statistical significance for hamstring length using a PSLR (*p* = 0.006).

Table. 4.8. Differences between interventions of the PSLR using an ANOVA with repeated measures

Measure	**F**	**df**	***p* value**
Time	28.04	1	0.000*
Intervention	0.71	3	0.555
Time X intervention	1.67	3	0.193

*Statistical significance at *p*=<0.05

In summary, these results showed that the NMES&RT intervention had the most effect on the eccentric lengthened state hamstring strength and it was the only intervention that indicated a statistically significant increase in strength, as identified from the t-test (Table 4.1). The effects of various interventions (as seen in Figures 4.2-4.9) show a clear increase in strength as a result of the NMES&RT intervention. No other intervention showed a increase in eccentric lengthened state hamstring strength for all participants. Therefore these results suggest that the most effective intervention was the NMES&RT intervention even though the omnibus ANOVA showed that there was no intervention effect between the groups and there were no statistically significant differences between groups using an ANOVA.

When looking at the hamstring length, using two methods (ASLR and PSLR), the results were not what was expected, as it was hypothesized that the NMES&RT intervention would have the largest increase. Although all interventions in both tests had a mean increase in hamstring length, the control group had the greatest mean increase for both tests and the NMES alone intervention had the least. Furthermore, the only statistically significant result was in the control intervention (from pre-test to post-test of $p = 0.006$) for the PSLR (Table 4.7) with a statistical significance at $p<0.0125$.

Chapter 5

DISCUSSION

The aim of this study was to identify the changes in lengthened state eccentric hamstring strength following a randomized control trial comprising of four arms, namely: resistance training alone (RT), neuromuscular electrical stimulation alone (NMES), NMES combined with RT (NMES&RT), and a control group (C). It was hypothesized that the NMES&RT group would be the most effective intervention, leading to the greatest lengthened state eccentric strength increases of the hamstrings as this group would receive the most stimulus (exercise and NMES).

Reduction of hamstring injuries are of vital importance due to the number of hamstring injuries and re-injuries that occur as well as the injury burden of these injuries, which can be reported as the total number of days lost per 1000 hours of exposure (Bahr et al., 2018; Brukner, 2015; Ekstrand et al., 2016; Elliot et al., 2011; Malliaropoulos et al., 2011; Orchard & Seward 2002; Tyler et al., 2017). Tyler et al. (2017) demonstrated the potential of lengthened state eccentric training to reduce hamstring injuries.

5.1 Peak Torque

NMES has been described as having numerous effects and benefits, such as being a strength-training tool, a rehabilitative and preventive tool, a testing tool of neural and muscular function, and a post-exercise recovery tool (Maffiuletti et al., 2011). Peak torque was assessed on a Biodex System 4 Pro™. The participant's peak torque was divided by their body weight in order to obtain Newton-meters per kilogram ($Nm \cdot kg^{-1}$), also known as relative peak torque.

NMES has been shown to increase strength more that RT alone in the healthy population (Canning & Grenier, 2014; Filipovic et al., 2011; Herrero et al., 2010; Paillard, 2008). However, in this study there were no significant differences in the relative peak torque results between the four groups using an analysis of variance (ANOVA) ($p = 0.441$) (Table 4.2). This could be due to the relatively low number of participants, especially with participants being spread across four groups and not two or three. There was however a significant effect of time ($p = 0.003$) (Table 4.2). This indicates that there was a significant increase in strength across all groups from pre-test to post-test. The lack of significant differences between groups could be due to a number of reasons, one being that all groups may have been effective at strengthening the lengthened state eccentric strength of the hamstrings. However, the control group would not be expected to show an intervention effect, as the participants within this group did not undergo any intervention to increase their lengthened state eccentric hamstring strength. We may then deduce that, due to there being no familiarization to the testing protocol prior to the pre-test, all the participants may have experienced a learning effect of the testing protocol. With repeated strength tests, such as the pre and post- tests employed in this study, the learning effect can be described as an improvement in strength or results simply due to familiarization of the protocol and thus a ‘learning’ improvement taking place as opposed to just true training effects (McArdle et al., 2010). The difference in results between studies could also be due to the large variation in protocols used such as, impulse frequency, duty cycle, duration of sessions, duration of training period, different outcome measures, different tools used to assess outcomes, and different muscle groups assessed.

Looking at each group individually, it can be seen that only the NMES&RT group had any significant changes in peak torque $p = 0.003$ (Table 4.1) but as mentioned this was not significantly different from any other group, which can be seen in Table 4.2. As multiple hypothesis testing was done on the peak torque variable there is an increased risk of a Type I error, even though measures were taken in an attempt to decrease this risk such as, the p value (<0.05) being divided by the amount of groups (four) leading to a 'stricter' analysis ($p<0.0125$). Deductions from both these tests still need to be made carefully. This means that NMES&RT does increase lengthened state eccentric strength of the hamstrings but when compared to NMES, RT, and even athletes that just continue with general sport training (C), no statistical differences were found.

It can also be noted that the NMES&RT group was the only group that had all participants' have an improvement in the lengthened state eccentric strength of their hamstrings (Figures 4.8 & 4.9). This may not be statistically significant but it is notable as this will assist in identifying clinical significance. Clinical significance is stated as being a "decision based on the practical value or relevance of a particular treatment, and this may or may not involve statistical significance as an initial criterion." (Fethney, 2010, p.93).

Magnitude based inferences (MBI) was then used in an attempt to identify the magnitude of changes and not simply looking at *p* values and overreliance on statistical significance alone. MBI showed small positive results for both the NMES group and the NMES&RT group when compared with the C group and RT group (Table 4.3 and 4.4). This shows that including NMES, whether isometrically (NMES) or superimposed (NMES&RT) will lead to increases in strength, albeit small, with no significant differences between them. This demonstrates that adding NMES, using either of these methods, does seem to show small positive effects on the eccentric lengthened state strength of the hamstrings but the differences between them are unclear and cannot be determined from this study. This contradicts some previous work by Herrero et al. (2005) where the authors found combined NMES to be more beneficial than NMES alone. However, the strength training protocol they used was very different to the one carried out in this study, plus this study used the combined technique and not superimposed. In contradiction, Canning and Grenier (2014) found that NMES alone increased muscle strength more than superimposed NMES. The difference in results could be due to fact that the study performed by Canning and Grenier (2014) only employed a step down exercise in addition to the NMES and which was potentially not enough of a load to increase strength compared to NMES alone. In addition, they only applied the NMES over the vastus medialis and attempted to assess the strength of this muscle, but the vastus medialis does not contract alone and there will be other quadriceps involvement. Further research would be needed to infer definitive conclusions between NMES alone and NMES&RT.

Multiple studies have used MBI's to understand the clinical/practical benefits of various protocols and the 'size of the effect' (Ayala, De Ste Croix, Sainz de Baranda, & Santonja, 2015; Mendiguchia et al., 2015; Scott, Taylor, Chesterton, Vogt, & Eaves, 2018). Small effects were expected in this study as the participants were trained individuals and trained individuals typically show slightly smaller increases in strength when compared to untrained individuals (Filiopovic et al., 2012; Herrero et al., 2010). The small effects could also have been due to the relatively small sample size that they used. This small sample size needs to be considered when discussing these results. These results could strengthen the case for the recommendation by Herrero et al. (2015) to use superimposed NMES&RT if individuals are looking to increase strength. This recommendation follows numerous studies that have identified superimposed NMES&RT to lead to strength gains in multiple muscle groups (Colson et al., 2000; Willoughby & Simpson, 1996; Willoughby & Simpson, 1998). If we consider clinical significance, including NMES into training protocols does have value, as identified in this study and others (Canning & Grenier, 2014; Colson et al., 2000; Filipovic et al., 2011; Herrer et al., 2005; Herrero et al., 2010; Paillard, 2008; Willoughby & Simpson, 1996; Willoughby & Simpson, 1998;).

There are possible reasons for all three of the intervention groups not having more profound improvements in their relative peak torque; the intervention may have been too short for the RT group to adapt and display strength improvements. There was no familiarization period for the NMES groups. This may have lead to increased muscle damage for the first few sessions, as NMES can lead to profound muscle damage especially if individuals are unfamiliar with NMES (Maffiulleti et al., 2011; Nosaka et al., 2011). This is important as NMES has different physiological effects compared to traditional strength training (Nosaka et al., 2011; Paillard, 2008). Further to that, hamstrings seem to be more sensitive to the damaging effects of NMES (Vanderthommen et al., 2012), which needs to be kept in mind. Further studies identifying best practice for NMES on the hamstrings specifically may be warranted. The protocol used in this study, as mentioned, may have lead to increased muscle damage and not enough time for physiological adaptions (supercompensation) (Turner, 2011). Potentially this means that individuals may be able to increase strength more with a superior protocol.

The guidelines proposed by Filipovic (2011) were largely followed in this study as well as the recommendation by Parker et al. (2003) to apply NMES thrice a week as opposed to twice. However, very few studies have followed these guidelines and it remains to be seen if these guidelines are indeed the most effective for strength improvements.

A full review of the literature was conducted, but no previous literature has been found that compares RT, NMES, and superimposed NMES (NMES&RT) with regard to strength improvements alone on the hamstrings. Some studies have looked at the combined method compared to RT and NMES alone (Herrero et al., 2006). Canning and Grenier (2014) did study the effects of superimposed NMES compared to RT alone and NMES alone but only on the vastus medialis muscle and not the hamstrings.

These results show that there were no statistically significant differences between groups when assessing relative peak torque, although there does seem to be clinically significant results for both NMES groups (NMES and NMES&RT). Even though there are only small effects this would be expected (Filiopovic et al., 2012; Herrero et al., 2010). The results obtained in this study do not seem to be as positive for NMES as some others have shown (Canning and Grenier, 2014; Herrero et al., 2006; Herrero et al., 2010; Maffiuletti et al., 2002). Adding NMES to training regimes does have value and is merited if used but from these results it can be seen that it is not a necessity.

5.2 Active straight leg raise (ASLR)

Hamstring flexibility was assessed using both an active straight leg raise (ASLR) test as well as a passive straight leg raise (PSLR) test. Both tests have been used to assess hamstring flexibility, usually in an attempt to identify predictors of hamstring injury (Askling et al., 2010; Henderson et al., 2010; Witvrouw et al., 2003).

Eccentric training has been shown to increase muscle flexibility in trained and untrained individuals, especially when assessing the hamstrings using a straight leg raise and passive knee extension tests (Abdel-aziem et al., 2018; Askar et al., 2015; Guex et al., 2016; Leslie et al., 2017; Potier et al., 2009). Using an ASLR there was an effect of time (*p* =

0.000) as well as an effect of intervention (*p* = 0.041) but there was no interaction effect (*p* = 0.306) (Table 4.7). From these results we can deduce that there was a change in hamstring length from pre-test to post-test among all participants (effect of time) and there was at least one group that differed from the other groups at either the pre-test or post-test (effect of intervention) but the intervention did not play a significant role in these differences (lack of the interaction effect). The difference at one time point from one or more groups is easily identifiable in Figure 4.10 with the control group having comfortably the lowest mean at pre-test (78.11°) (Table 4.6). These results lead to the belief that no intervention in this study affects hamstring length. So if an individual is looking to increase hamstring range of motion (ROM) using an ASLR there is no difference if they were to perform RT, NMES training, NMES&RT, or continuing sports training only.

5.3 Passive straight leg raise (PSLR)

Hamstring flexibility assessed by a PSLR re-iterated the results obtained from the ASLR. The ANOVA showed an effect of time (*p* = 0.000) but no effect of intervention (*p* = 0.555) or interaction effect (*p* = 0.193) (Table 4.9). This shows that there was a difference over all participants but the intervention had no effect, as shown by the ASLR too. The only significant result found was in the paired t-test with the control groups' pre-test, post-test result (*p* = 0.006) (Table 4.8). This suggests that the control group was the only group that improved their hamstring flexibility when a PSLR was used.

These results should be analyzed with caution due to the increased risk of a Type I error. It also would not be expected to have the control group to show a significant improvement, which was larger than any of the three intervention groups. There is a high likelihood that there is a confounding factor affecting these results. One explanation for these results in the control group could be the phenomenon of regression to the mean as at the pre-test the control group had the lowest range of motion of all groups in both the ASLR and PSLR comfortably (78.11° and 85.00° respectively) (Table 4.6 and 4.8). Regression to the mean could be explained as; on an initial measurement if a variable is on an extreme to a typical average (above or below), the second measurement of the variable will tend to be closer to the average. Fluctuations above and below the average are common on multiple measurements in this phenomenon (Everitt, 2002).

There does seem to be no effect of any of these interventions on hamstring flexibility using an ASLR or PSLR. There were increases in flexibility of the hamstring muscle across all groups in both the ASLR and PSLR tests but no significant increases, besides the control group in the PSLR (Table 4.8). This contradicts previous work (Abdel-aziem et al., 2018; Askar et al., 2015; Guex et al., 2016; Leslie et al., 2017; Potier et al., 2009) but this could be due to the majority of those studies using the passive knee extension test as opposed to straight leg raise tests, the short intervention period of this study (four weeks), the 'stricter' analysis used during the paired t-tests' as it was not an aim of this study to identify if eccentric training increases flexibility but to see if there is a particular training regime more effective to do so. There would have been multiple groups that would have reached statistical significance if the *p* value were left at <0.05. So this study cannot refute the previous studies where eccentric training was found to significantly increase hamstring flexibility.

If individuals are looking to increase hamstring flexibility specifically, they may be advised to perform methods other than those used in this study. Even though eccentric training does lead to increased flexibility (Abdel-aziem et al., 2018; Askar et al., 2015; Guex et al., 2016; Leslie et al., 2017; Potier et al., 2009). Practitioners such as, physiotherapists, sport scientists, biokineticists and the like, may want to consider advising individuals to add foam rolling or dynamic stretching to individuals looking to increase hamstring flexibility (Behm, Blazevich, Kay, & McHugh, 2015; Su, Chang, Wu, Guo, & Chu, 2017). One important factor with regard to hamstring flexibility and hamstring stretching that should be noted, for clinicians that are vital in the prehabilitation and rehabilitation of hamstring injuries such as, physiotherapists and biokineticists - one hamstring muscle may be affected differently compared to other hamstring muscles (biceps femoris, semimembranosus, and semitendinosus) following different stretching maneuvers such as; passive knee extension and passive hip flexion i.e. the biceps femoris may react differently to a passive hip flexion stretch compared to the semimembranosus (Miyamoto, Hirata, & Kanehisa, 2017).

Is lengthened state eccentric training or including NMES the sole answer to reducing hamstring injuries and re-injuries? The short answer is no. The hamstring muscle group is highly complex with high variation in function, which is still being studied and understood (Higashihara et al., 2018; Higashihara et al., 2010; Kyröläinen et al., 1999; Schache et al., 2012; Yu et al., 2008). Hamstring injuries are also multifactorial and require a holistic approach to prevention and rehabilitation (Freckleton, Cook, & Pizzari, 2014; Van der Horst, van de Hoef, Reurink, Huisstede, & Backx, 2016). Not only are the types of exercises performed in hamstring injury prevention programs important but also when they are performed. There seems to be no differences in strength if exercises are performed before football training or if they are performed after football training. However, there are architectural adaption differences such as muscle thickness, pennation angle, and fascicle length when exercises are done before compared to after football training (Lovell et al., 2018). Pennation angle is the angle of muscle fibres in relation to a muscle's longitudinal axis. Pennation allows for an increase in muscle fibres in a smaller cross-sectional area and thus is very important in force generating capacity (McArdle et al., 2010). Fascicle length can simply be described as the length of a muscle fibre and this has an influence on the shortening velocity of the muscle fibres (Abe, Kumagai, & Brechue, 2000; Fukutani & Kurihara, 2015). These architectural adaptions support strength gains and affect muscle contraction characteristics, as mentioned (Fukutani & Kurihara, 2015; Lovell et al., 2018). Thus this should be kept in mind by clinicians and trainers when deciding on methodologies for hamstring injury prevention programs and they should have a specific goal in mind when deciding on the timing of exercises.

Another example of hamstrings not being able to be assessed on one characteristic alone such as, only strength, only flexibility etc. is hamstring muscles that are classified as ‘weak and short’ (low eccentric strength and short fascicles) are over 4 times more likely to suffer a future hamstring injury than individuals that can be classified as having ‘strong and long’ hamstrings (high eccentric force and long fascicles) (Timmins et al., 2016). This demonstrates the need for increasing eccentric strength of the hamstrings as well as increasing fascicle length.

Exercise selection is vital for hamstring injury rehabilitation as well as prehabilitation. Different exercises activate the different hamstring muscles at various levels (Bourne et al., 2017). This requires practitioners to be very specific especially during rehabilitation when they are attempting to focus on a specific hamstring muscle. Prior to implementing hamstring rehabilitation or prehabilitation programs to individuals or teams, practitioners need to be sure as to which hamstring muscles they would like to target and at which muscle lengths. This will be able to guide the implementation of these programs.

The need for a multidisciplinary approach to reduce the occurrence of these injuries cannot be understated. Physiotherapists, team doctors, coaches, biokineticists, and/or sport scientists need to work together to tackle the multifactorial nature of hamstring injuries and the return to play of these injuries (Van der Horst, Backx, Goedhart, & Huissteede, 2017). Physiotherapists and physical therapists have published incredible work with regard to hamstring rehabilitation, prehabilitation, and practical applications and their expertise within this field should be used extensively (Ashokan & Vishal, 2018; Freckleton et al., 2014; Guex & Millet, 2013; Mendiguchia et al., 2015; Schmitt et al., 2012).

Chapter 6

SUMMARY & CONCLUSION

6.1 Summary

The present study examined the differences in lengthened state eccentric strength of the hamstrings and hamstring flexibility following a four- week intervention between four different protocols. Namely; neuromuscular electrical stimulation superimposed with resistance training (NMES&RT), NMES alone (NMES), resistance training alone (RT), and a control group (C). The NMES&RT group was the only group to have a statistically significant increase in relative peak torque (*p* = 0.003) (Table 4.1). Despite this no group was statistically significantly different from another. With only an effect of time being apparent (Table 4.2). Both NMES groups (NMES and NMES&RT) showed further positive results using magnitude-based inferences (MBI). The NMES and NMES&RT groups demonstrated small positive effects when compared to RT and the C group but unclear and negligible differences between NMES and NMES&RT.

The control group, using the passive straight leg raise, was the only group with a statistically significant result (*p* = 0.006) with regards to hamstring flexibility, for both the active and passive straight leg raise (Table 4.8). However, no differences between groups were found for either the active or passive straight leg raise (Table 4.7 & Table 4.9).

6.2 Limitations

When critically examining this study there are a number of limitations that need to be considered namely:

1. The length of the intervention – the intervention was only 4-weeks long. A longer intervention might have shown different results for all intervention groups
2. The sample size – there was a fairly small sample size. This is a common limitation in exercise science studies and is very prevalent in this study particularly. The small sample size lead to a decreased statistical power. The small sample size also did not allow for multi- variate analysis. This study does warrant a larger sample size
3. Limitations in the intervention – only body weight exercises were performed in the intervention. More advanced, higher load exercises as proposed by Bourne et al. (2017) and Lorenz and Reiman (2011) may be more beneficial and potentially lead to greater increases in strength in all experimental groups. Especially in this population (trained individuals)
4. Measurement reliability – there were two separate testing clinicians (mainly a limitation with the SLR's as there is a subjective factor). Although measures were taken to ensure standardization, such as, the clinicians did not 'cross-over' testing phases i.e. clinician one tested all participants in the pre-test and clinician two tested all participants in the post-test

5. Sport intervention – All participants continued with normal sporting activity and some sports might lead to an increase in hamstring strength (such as high-speed running). Although participants were told to avoid hamstring specific strengthening they may have been involved in other activities, which had the potential to increase hamstring strength and thus being a confounder in this study.

6.3 Future work and recommendations

1. This study warrants further investigation into NMES with and without RT for strengthening of the hamstrings in a lengthened state eccentrically with a larger sample size. The small sample size does not allow for firm conclusions but there is a suggestion of a positive effect by using NMES, in this study, which should be investigated further
2. A longer intervention period (≥four weeks) is warranted as neural adaptions predominate in the early stages of training and as training continues other physiological adaptions may occur (muscular, endocrine etc.) (McArdle et al., 2010)
3. Future work should also look at these interventions in the elite population as small percentages in the elite population can make substantial differences. Margins at the elite level are a lot smaller than in the general population and any small gain is worthwhile investigating within the elite population (Turner, 2011)

4. There should also be exercises with higher loads rather than just body weight exercises. As the loads employed in this study may have been too low to elicit large strength increases and future studies should include so-called ‘weighted’ exercises
5. There should be identification on the effect of NMES on the endurance on the lengthened state eccentric strength of the hamstring as endurance of the hamstrings are reduced after a cardiovascular test (Cohen, Zhao, Okwera, Matthews, & Delextrat, 2015). This could be vital in reducing hamstring injuries especially since hamstring injuries are prevalent in high speed running sports where there is cardiovascular component such as, football, American and Australian football, and others (Elliot et al., 2011; Malliaropoulos et al., 2011; Orchard and Seward 2002; Tyler et al., 2017)

6.4 Conclusion

In conclusion these results indicate that adding NMES to a hamstring training or prehabilitation program, whether isometrically or superimposed, is beneficial for increasing strength and assisting with decreasing hamstring injury risk slightly. Although there were no statistically significant differences between the groups both the RT and C group had negligible and unclear differences when compared to all other groups, whereas NMES and NMES&RT had small positive differences when compared to RT and C. NMES offers small positive effects in trained individuals with a very low likelihood of negative results or regression of hamstring strength in this population. With this in mind, NMES in any form is not a ‘must-have’ but it is advisable to use if available, as these effects are small but they demonstrate clinical significant. It could prove particularly useful when a new training stimulus is perhaps needed. The present study only looked at the lengthened state eccentric strength of the hamstrings and offers a potential strategy to increase that strength in a shorter period. However, it is very important to note that hamstring injuries are multifactorial and clinicians need to be assessing and implementing a multitude of factors. With all this in mind NMES requires training and it is not to be used as a senseless tool where the electrodes just get applied and used. The use of NMES should encourage critical thinking leading to more questions from the clinician and not less. This does add to the body of NMES research, with at least mildly positive and clinically significant results.

None of the interventions in this study lead to significant changes in hamstring flexibility using an active or passive measure. However, all groups in both the active and passive straight leg raise tests had in increase in their mean from pre-test to post-test. This shows there are no negative effects in hamstring flexibility, in the trained population, with any strategy employed in this study. These results could be generalized to the wider population in terms of region and not just of trained athletes within the City of Cape Town, as there are no obvious differences that may affect lengthened state eccentric strength of the hamstrings with an intervention of RT, NMES, or NMES&RT between the City of Cape Town and other regions of South Africa or even the World. The one factor that could affect these results in other regions of the World is the different sports played in

South Africa and other regions of the World. These results, however, cannot be generalized to females as they have a slightly different physiological response to exercise compared to males (McArdle et al., 2010). These results may also not be generalizable to untrained individuals and further research would need to be conducted on this population. As untrained individuals may be unfamiliar with these exercise protocols it may be expected that they would have a larger increase in lengthened state eccentric strength due to neural adaptions and familiarization (McArdle et al., 2010).

All results from this study need to be interpreted cautiously due to the relatively small sample size. However, further studies regarding NMES and hamstring strength is warranted.

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Appendix A: Pre-Participation Questionnaire

UNIVERSITY OF THE WESTERN CAPE

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Pre-Participation Questionnaire

Name:

Age:

Which sport do you play:

How many days a week do you partake in physical activity: < 3 3-5 > 5

For how long: < 30 30-60 60-90 > 90

At what intensity would you say it is: < 65% (Light) 65-75% (Moderate) > 75% (Vigorous)

Do you have a pacemaker: Yes No

Are you epileptic: Yes No

Appendix B: Information Sheet

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INFORMATION SHEET

Project Title: The effect of neuromuscular electrcal stimulation on hamstring prehabilitation

What is this study about?

This is a research project being conducted by Jaime Valadao at the University of the Western Cape. We are inviting you to participate in this research project as this will be a good opportunity for you to assist in research to possibly reduce occurrence of hamstring injuries. The purpose of this research project is to identify the most effective form of hamstring strengthening.

What will I be asked to do if I agree to participate?

You will be asked to undergo an initial test on an isokinetic dynomometer and be part of one of four groups. Three of these groups will undergo an exercise intervention, two of which will have neuromuscular electrical stimulation administered and then one group will partake in traditional exercise. This intervention will take place three times a week for four weeks. After the intervention you will undergo the same test as initially performed. All the testing and training will take place in the Biokinetics Clinic at the University of the Western Cape, Gym B at the University of the Western Cape and venues which suit you.

Would my participation in this study be kept confidential?

The researcher undertakes to protect your identity and the nature of your contribution. To ensure your anonymity, your name will not be included on the surveys and other collected data; a code will be placed on the survey and other collected data; through the use of identification key, the researcher will be able to link your survey to your identity; and only the researcher will have access to the identification key.

To ensure your confidentiality, we will store the collected data in safe place. Only the researchers will have access to this. Your identification will be given a code and no names will be used.

If we write a report or article about this research project, your identity will be protected.

What are the risks of this research?

There may be some risks from participating in this research study.

All human interactions and talking about self or others carry some amount of risks. We will nevertheless minimise such risks and act promptly to assist you if you experience any discomfort, psychological or otherwise during the process of your participation in this study. Where necessary, an appropriate referral will be made to a suitable professional for further assistance or intervention. As with all research involving physical activity, there is a risk that a musculoskeletal injury may occur to the research participants. However, every effort will be made to minimise this by ensuring an appropriate and adequate warm up is undertaken and proper screening is conducted as to any previous injuries/conditions participants may have, which may be exacerbated by exercise. The intensity of exercise required in this research is light to moderate, which further reduces the injury risk.

What are the benefits of this research?
The benefits to you include the possibility of strengthening and preventing injury to your hamstrings.

Do I have to be in this research and may I stop participating at any time?
Your participation in this research is completely voluntary. You may choose not to take part at all. If you decide to participate in this research, you may stop participating at any time. If you decide not to participate in this study or if you stop participating at any time, you will not be penalized or lose any benefits to which you otherwise qualify. Should you pick up an injury of any sort that will prevent you from taking part in the study you will be excluded from the study. This is to prevent you from injuring yourself further.

What if I have questions?
This research is being conducted by Jaime Valadao, a student in the Department of Sport and Exercise Science at the University of the Western Cape. If you have any questions about the research study itself, please contact Jaime Valadao at: tel.: 072 600 8218, email: jvaladao8@gmail.com. Should you have any questions regarding this study and your rights as a research participant or if you wish to report any problems you have experienced related to the study, please contact:

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BIOMEDICAL RESEARCH ETHICS ADMINISTRATION
Research Office
New Arts Building,
C-Block, Top Floor, Room 28
This research has been approved by the University of the Western Cape's Research Ethics Committee (REFERENCE NUMBER: BM16/4/3)

Appendix C: Consent Form

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CONSENT FORM

Project Title: The effect of neuromuscular electrcal stimulation on hamstring prehabilitation

The study has been described to me in language that I understand. My questions about the study have been answered. I understand what my child's participation will involve and I agree to allow them to participate of my own choice and free will. I understand that their identity will not be disclosed to anyone. I understand that I may withdraw them or them may withdraw themselves from the study at any time without giving a reason and without fear of negative consequences or loss of benefits.

Participant's name……………………….

Participant's signature……………………………….

Date………………………

BIOMEDICAL RESEARCH ETHICS ADMINISTRATION
Research Office
New Arts Building,
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Appendix D: Explanation of Tests

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Project Title: The effect of neuromuscular electrcal stimulation on hamstring prehabilitation

Active Straight leg Raise

The participant will be in a supine position with the hip medially rotated and adducted, with the knee extended. The participant will then actively lift their leg as far as they can or until the participant complains of tightness in the hamstring. The angle of the hip will then be measured with a goniometer.

Passive Straight leg Raise

The participant will be in a supine position with the hip medially rotated and adducted, with the knee extended. The clinician then passively lifts the participant’s leg by the ankle until the participant complains of tightness in the hamstring. The angle of the hip will then be measured with a goniometer.

Modified Thomas Test

The participant sits at the edge of the bed and then lies down while holding the non-tested leg in maximal flexion against the chest while the tested leg should be hanging off the bed. The hip angle is then measured to test the length of the illiopsoas and then the angle of the knee is tested to test the rectus femoris.

Appendix E: Explanation of Exercises

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Project Title: The effect of neuromuscular electrcal stimulation on hamstring prehabilitation

The Diver

With the participant standing they simulate a dive (lifting the uninvolved leg) flex the hip of the involved leg and stretching the arms forward attempting maximal hip extension of the lifted leg with the pelvis horizontal. The knee should be at approximately 10-20° on the standing leg and 90° in the lifted leg, then returning to the starting position and repeating.

The Glider

With the participant standing and holding on to a support with their legs slightly split. The participants weight should be on the heel of the involved leg (front) with approximately 10-20° flexion in the knee. The participant then glides backwards on the uninvolved leg (on a friction mat/towel/paper) and then slowly returning to the starting position (gliding the foot back to the front using the arms if necessary)

The Slider

The participant performs a supine double-leg bridge and then lowers their torso to the floor by extending their knees and sliding their foot till full extension the slowly returning the starting position.

Single leg Hamstring Bridge

The participant lies in a supine position with his involved leg on an elevated surface (bench etc.) and performs a bridge then slowly returns to the starting position.