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At the Heart of South Leinster

# An Investigation into The Acute Effects of Utilising a Live Strength Feedback System to Ensure Equal Bilateral Force Distribution When Performing the Nordic Hamstring Exercise, a Randomised Control Trial

**Author:** Diarmuid Tobin

**Student Number:** C00152842

**Award:** Master of Science (MSc)

**Supervisors:** Claire Lodge PhD & Brian O'Rourke MSc

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# Definitions

**- Eccentric Muscle Contraction:** A muscle shortening contraction in the presence of a resistive force that results in elongation of a muscle, used to perform negative work or to decelerate a body part.

**- Angle of Peak Torque:** The joint angle at which the muscles acting on the joint achieve their highest contraction force output.

**-Validity:** Validity for the purpose of this study refers to the comparability of a test device with a confirmed reliable device to determine its efficiency at measuring a similar objective output.

**-Reliability:** Reliability for the purpose of this study refers to a device's ability to consistently measure an objective output metric with minimum variation or error between consecutive recordings.

**-Interpreting the size of an ICC:**

| Size of Correlation (±) | Interpretation |
|---|---|
| .90 to 1.00 | Very High Correlation |
| .70 to .90 | High Correlation |
| .50 to .70 | Moderate Correlation |
| .30 to .50 | Low Correlation |
| .00 to .30 | Negligible Correlation |

(Mukaka, 2012)

**-Isokinetic Dynamometry:** Isokinetic testing assesses the contractive force capabilities of an isolated muscle group against an accommodating resistance at a constant speed through a controlled range of motion.

**-Hamstring Solo Elite:** The Hamstring Solo Elite is a newly designed pressure feedback device that utilises load cell technology to monitor eccentric knee flexor strength.

# Abbreviations

**HSI(s):** Hamstring Strain Injury/Injuries.

**HSE:** Hamstring Solo Elite.

**NHE:** Nordic Hamstring Exercise.

**ST:** Stretch Tolerance.

**Q:H Ratio:** Ratio of Quadriceps Strength to Hamstring Strength.

**1RM:** One Repetition Maximum.

**HHD:** Hand-held Dynamometer.

**N:** Newtons (Measurement of Force).

**Nm:** Newton-Metres (Measurement of Torque).

**mmHg:** Millimetres of Mercury (Measurement of Pressure).

**(r):** Pearson's Correlation Coefficient.

**ICC:** Intraclass Correlation Coefficient.

**°/s:** Degrees per Second (Measurement of Torque Velocity).

**CV:** Coefficient of Variance.

**Rpm:** Revolutions per Minute.

**TE:** Typical Error.

**RCT:** Randomised Control Trial.

**ACL:** Anterior Cruciate Ligament.

**LH:** Long Head.

**DOMS:** Delayed Onset Muscular Soreness.

**RTP:** Return to Play.

**RR:** Relative Risk.

**CNS:** Central Nervous System.

**MBIs:** Magnitude Based Inferences.

# Introduction

Hamstring strain injuries (HSIs) are prevalent in sports that involve sprinting such as soccer, rugby, and athletics (Sconce et al., 2015). HSIs are reported to account for between 12% & 16% of all injuries sustained by athletes in sprint related sports such as track & field (Yeung et al., 2009), soccer (Croisier, 2004), Australian football (Ruddy et al., 2016) and rugby (Moore et al., 2015). HSIs have also been reported by Liu et al. (2012), to account for 12% of all injuries in a competitive season of English professional soccer resulting in an average of 17 days of missed playing/training time. HSI rates in professional soccer have been reported by Bahr et al. (2015) to have increased over the last two decades from 7% to 12-17% . It was also stated by Bahr et al. (2015) that HSIs are putting increased financial pressure on professional sports clubs due to their prolonged recovery time and high recurrence rates. The implications of HSIs in amateur sport do not only include physical and emotional stress but also include financial strain on amateur clubs that very often have to operate on minimal budgets when compared the their professional counterparts.

High-speed running, particularly sprinting, has been widely identified in the literature as the primary offending mechanism for HSIs (Ruddy et al., 2016) . The late swing phase is believed to be the most ‘at risk’ phase of gait for HSIs due to the level of high-velocity eccentric force absorbed by the hamstring muscle to control the rapid deceleration of the extending limb in preparation for heel strike (Liu et al., 2017).

The Hamstring Solo Elite (HSE) is a pressure feedback device that utilises load cell technology to monitor eccentric knee flexor strength. The HSE is a device with a cushioned inclined surface on which the subject kneels with their heels fixed beneath cushioned load cells; these provide instant feedback on the force being exerted by each limb during repetitions of the Nordic Hamstring Exercise (NHE). The HSE is one of the first devices designed to provide live objective feedback for hamstring strength and individual limb force distribution when performing the NHE. The accessibility and convenience of the device as an in-house method of quantifying hamstring strength makes the HSE a more desirable method when compared to much less accessible methods such as isokinetic dynamometry.

Validity and/or reliability testing is carried out to determine the validity of a measurement device or a tester’s ability to consistently measure a variable (Bruton et al., 2000). Reliability is essential in order for data to be recorded consistently and used for analysis. A strength measuring device, such as the HSE, must be reliably consistent in order to determine if any adaptations to training can be solely attributed to the training intervention and not to an inconsistent error associated with the device (Pincivero et al., 1997). Accuracy is essential when assessing performance, so it is vital that the HSE is both a reliable and a valid device. A device that lacks validity and reliability is flawed and practitioners cannot confidently use the device to monitor periodised gains. When a new device such as the HSE is introduced it is essential that the device's validity is first established against a gold standard device that measures the same information such as an isokinetic dynamometer. It is also essential that the device be reliable in a test-retest scenario as any inconsistencies compromise the quality of the data obtained from the device. This is particularly important when the device is used for clinical rehabilitation, as any undetected weakness or misreading could potentially put the patient/athlete at risk of further injury or result in the misinterpretation of clinical findings.

Once found to be valid and reliable, the HSE device has the potential to be utilised in conjunction with a NHE intervention to address between-limb eccentric hamstring strength imbalances. Between-limb imbalances are regarded as a significant risk factor for HSI (Yeung et al., 2009). In support of this finding, eccentric knee flexor strength imbalances between right and left limbs of ≥15% and ≥20% were observed by Bourne et al. (2015), to increase the risk of an athlete sustaining a HSI by 2.4 fold and 3.4 fold, respectively. With the serious implications that a between-limb eccentric strength imbalance can have on HSI risk, it has been proposed by Croisier et al. (2008) that pre-season screening for hamstring strength weakness and imbalances is fundamental for identifying the potential risks of incurring a HSI.

The NHE has been strongly supported in the literature as being extremely effective in reducing HSI occurrences (Al Attar et al., 2016, van der Horst et al., 2015, Thorborg, 2012, Petersen et al., 2011). While the NHE is an effective method for developing eccentric hamstring strength, it is a double leg exercise that can be limited by limb dominance leading to unequal strength gains between the left and right limbs leading to an increase in between-limb strength imbalances. This study investigates the implementation of a pressure feedback system for eccentric hamstring conditioning such as the HSE could be used to identify between-limb eccentric strength imbalances and also be used as monitoring tool to ensure equal force distribution between both limbs during eccentric conditioning exercises such as the NHE.

# Chapter 1: The Validity and Test Retest Reliability of the Hamstring Solo Elite.

# Abstract

## Introduction

Hamstring strain injuries (HSIs) are still prevalent in sports that involve sprinting such as soccer (Sconce et al., 2015). HSIs are reported to account for 12-16% of injuries sustained by athletes, with an average absence of 17 days from sport (Liu et al., 2012). Several risk factors for HSI have been observed by Liu et al. (2012); with strength imbalances between right and left limbs reported to be a significant risk factor. Strength imbalances of ≥15% and ≥20% were observed by Bourne et al. (2015), leading to a 2.4-fold and 3.4-fold increase, respectively, in HSI risk. Therefore, devices that are reliable and can assess strength imbalance and increase strength by giving live quantifiable feedback during exercise would be beneficial.

The aims of this study were:

i) To determine whether the Hamstring Solo Elite is a valid instrument to measure hamstring strength when compared to the Biodex system 3 isokinetic device.

ii) To assess the test-retest reliability of the Hamstring Solo Elite as a strength assessment device.

## Methods

20 male athletes (21±2 years of age, 78.6±4.6kg , 179.6±6.4cm) were recruited from the IT Carlow student base. Subjects attended a familiarisation session to perform repetitions of eccentric knee flexion on the Biodex System 3 isokinetic device and Nordic Hamstring Exercise (NHE) repetitions on the HSE. The subjects were then randomly separated into two equal groups. Group 1 performed 5 reps at 30°/s on the Isokinetic device in session 2 and the 5 NHE repetitions 7 days later while group 2 performed the NHE repetitions in session 2 and the eccentric Isokinetic test 7 days later. Both groups attended a fourth session 7 days after session 3 to perform a further set of 5 NHE repetitions.

The peak torque (Nm) from the isokinetic dynamometer and peak force (N) from the HSE were recorded to determine whether high (>0.7) ICCs (Mukaka, 2012) were observed between the individual left and right limbs. The test-retest reliability of the HSE between 2 consecutive trials and the Percentage Typical error (%TE), Standard Error or Measurement (SEM) and Minimum Detectable Change (MDC) were also calculated.

## Results

Intraclass correlation coefficients demonstrated high ICCs =0.82 (CI 0.58 to 0.93) and 0.84 (CI 0.58 to 0.93) for left and right leg peak torque/force respectively. Very high Intraclass Correlation Coefficients were observed between two trials of the HSE ICCs =0.91 (CI 0.76 to 0.96) and 0.91 (CI 0.78 to 0.96) for left and right leg peak force respectively. %TE between trials of the HSE was calculated to be 6.87% and 6.35 for the left and right limbs respectively while the MDC was calculated to be 42.78N & 47.51N for the respective left and right limbs.

## Conclusion

This study demonstrates high test-retest reliability of the HSE and acceptable validity when the device was compared to the Biodex System 3. The results of this study means the clinician can be confident in the reliability and validity of the HSE in the assessment of hamstring strength. Accurate assessment of hamstring strength is important for monitoring periodised strength gains and screening for hamstring weaknesses that put an athlete at risk of a HSI.

# 1.1 Review of Literature

### 1.1.1 Non-Modifiable Risk Factors

Non modifiable risk factors for HSI are factors that put an athlete at risk of incurring a HSI but cannot be influenced through strength training or manual therapy. Non-modifiable risk factors for HSI predominantly include previous hamstring injury and increasing age (Foreman et al., 2006). While age is regarded as a non-modifiable risk factor, appropriate eccentric conditioning of the hamstrings can minimise the HSI risks associated with increasing age (Bourne et al., 2016a).

*Previous Hamstring Injury*

Previous hamstring injury is commonly reported to be the leading risk factor that predisposes an athlete to a recurring hamstring injury (Opar et al., 2015). The cause has not yet been concurrently decided upon but many believe it to be either residual structural damage to the sarcomeres, a neuromuscular recruitment deficit following a previous tear or a combination of both (Foreman et al., 2006). The inclusion of previous injury amongst the leading risk factors of hamstring injuries is reinforced by Freckleton and Pizzari (2013) who carried out a systematic review and meta-analysis of 13 studies, comprising of a total of 2952 subjects, that all implicated previous injury as a significant risk factor. The meta-analysis strongly supported the consensus that previous injury is a significant relative risk (RR) factor (RR=2.68, 95% CI 1.99 to 3.61, p=0.00).

*Effect of Age on HSI Risk*

It has been widely accepted that age is a predominant risk factor for injury in general and is particularly true for HSI. A study investigating injury risk factors in football players by Arnason et al. (2004) cites increasing age as an influential injury risk factor with subjects >1 standard deviation above the mean age having an injury odds ratio of 2.69 compared to subjects >1 standard deviation below the mean age who had an injury odds ratio of 0.91. In the study the group with the highest injury incidence is also the group with the highest age profile. This finding is supported in many injury risk cohort studies and systematic reviews (Freckleton and Pizzari, 2013, Prior et al., 2009, Foreman et al., 2006), who all state that age is a significant risk factor for HSI even when there is no previous injury history.

While these are considered to be non-modifiable risk factors, it must also be considered that these risk factors for HSIs can have their effects minimised through adequate eccentric hamstring conditioning and the resulting development of long muscle fascicle lengths elicited through eccentric conditioning (Bourne et al., 2016a).

### 1.1.2 Modifiable Hamstring Injury Risk Factors

Several modifiable risk factors have been identified and proposed to precede HSI's according to Liu et al. (2012); these include shortened optimum muscle length, lack of muscle flexibility and strength imbalances between right and left limbs.

#### *Angle of Peak Torque*

The angle of peak torque for the hamstring muscle group is another modifiable risk factor that is often closely monitored as a factor that can predict HSI risk (Sconce et al., 2015). According to Brughelli et al. (2010), the optimum angle of peak torque achieved by the knee flexor group for field sports such as Australian Football is approximately 30° of knee flexion. This angle is particularly important as it is closely associated with the late swing phase in the gait cycle; it is at this stage of gait that the hamstring muscle group experiences the greatest amount of eccentric force and so is the offending mechanism for many HSIs (Liu et al., 2012). It was proposed by Brockett et al. (2001) that eccentric loading of the hamstring muscle group can result in long term improvements in the angle of peak toque achieved during eccentric loading.

#### *Hamstring Muscle Flexibility*

Flexibility is often debated with no clear consensus of whether it has a significant influence on injury susceptibility. It is believed that generally poor lower limb flexibility can predispose an athlete to a lower limb soft tissue injury with a lower stretch tolerance (ST) from the hamstring muscle group being cited as a significant risk factor for HSI (Mackey et al., 2011). Flexibility as an injury risk factor was investigated by Witvrouw et al. (2003) who discovered that there was a significant (P=0.02) relationship between poor hamstring flexibility and hamstring strain injuries in a group of 146 male professional soccer players. The findings by Witvrouw et al. (2003) are in contrast with previous research such as a cohort study by Arnason et al. (2008) and a systematic review by Freckleton and Pizzari (2013) who both stated that flexibility has not been proven to be a significant risk factor for HSI but acknowledged that further specific research of the topic is needed.

### *Lumbar Spine Posture and Anterior Pelvic Tilt*

Postural abnormalities such as excessive lumbar lordosis and an associated anterior pelvic tilt can have major anatomical implications on the hamstring muscle group due to their attachment at the ischial tuberosity. The anterior tilt of the pelvis causes the hamstrings to operate at longer muscle lengths before hip flexion or knee extension add to this elongation of the muscle making it susceptible to injury at long muscle lengths. The relationship between these postural changes and hamstring injuries has been reported by Hennessey and Watson (1993) to be significant (P=0.01). The study observed accentuated lumbar lordosis and anterior pelvic tilt in subjects with hamstring injuries when compared to the uninjured control group. While posture is commonly postulated as an injury risk factor there are few studies that look at the correlation between posture and HSI.

### *Quadriceps to Hamstrings Strength Ratio*

The quadriceps to hamstring strength ratio (Q:H ratio) is another commonly postulated predictor of HSI. The Q:H ratio has been discussed in previous literature such as a systematic review on HSI risk factors by Freckleton and Pizzari (2013) but acknowledges that there is conflicting evidence to support the Q:H ratio being a significant risk factor. It is suggested in a systematic review by Foreman et al. (2006) that the reduced strength of the hamstrings may not produce enough eccentric force to adequately decelerate the extensor force generated by the quadriceps during knee extension in the late swing phase of gait. Given that this phase of gait is responsible for a high percentage of HSI it is reasonable to assume that the Q:H ratio may play a role in hamstring injuries as a Q:H ratio of >1.4 can increase susceptibility to HSI by 17 fold (Yeung et al., 2009). The Q:H ratio as a risk factor is often criticised as it is only detected during isokinetic testing which is deemed by many to be non-sport specific testing method (Arnason et al., 2008).

### *Eccentric Hamstring Strength Between-Limb Imbalances*

It has been hypothesised that an eccentric hamstring strength imbalance between the right and left limbs could by an influential factor that precedes a HSI (Bourne et al., 2015). Seventy seven professional soccer players' were tested by Croisier et al. (2003) for eccentric hamstring strength imbalances between the right and left limbs and injury occurrences were then recorded over a 9 month professional season. It was observed that in the presence of an eccentric hamstring strength imbalance (>10%), HSI was predicted to increase from 3% to

15% when compared with no eccentric hamstring strength imbalance (<10%) being present. Furthermore, Croisier et al. (2008) proposed that pre-season screening for hamstring strength weakness and imbalances is fundamental for identifying the potential risks of incurring a HSI which may include gross weakness and/or strength imbalances between limbs. Eccentric knee flexor strength imbalances between right and left limbs of ≥15% and ≥20% were also observed by Bourne et al. (2015), to increase the risk of an athlete sustaining a HSI by 2.4 fold and 3.4 fold, respectively.

Shortened optimum muscle length and lack of muscle flexibility have been shown to improve through the use of an eccentric hamstring loading program according to McHugh et al. (2014). It is important that these modifiable risk factors can be objectively measured in order to determine if they are successfully manipulated through hamstring strength and/or flexibility training.

### 1.1.3 Validity of 'The Nordic Hamstring Exercise' to Assess Eccentric Hamstring Strength.

The Nordic hamstring exercise (NHE) was described by Brockett et al. (2001), as involving the athlete starting in a kneeling position with their ankles fixed in position and an open hip angle, the athlete then slowly lowers their torso towards the ground (while maintaining a constant open hip angle) against the gravitational moment until the force overcomes the athlete's peak eccentric strength and they drop to the ground resting on their hands. The NHE has been widely used as an efficient exercise to increase eccentric knee flexor strength. Several studies including Brockett et al. (2001), Brukner (2015),Iga et al. (2012), Mjolsnes et al. (2004) and Petersen et al. (2011), have reported that the NHE can significantly reduce HSI occurrence rates. Significant increases in flexibility and a significantly better angle of peak torque were observed by McHugh et al. (2014) when compared to baseline measurements following a 4 week NHE intervention.

HSI's are frequently experienced just prior to foot strike during a sprinting action where the hamstrings undergo a forceful eccentric contraction as the hip flexes and knee extends simultaneously. The Nordic hamstring exercise is deemed to be a sport specific strength exercise as it allows eccentric knee flexor strength to be developed in a positon, and at muscle lengths, similar to the common injury mechanism albeit at a slower velocity than that of the common injury mechanism.

In a recent study by van der Horst et al. (2015), it was observed that implementation of a 25 session Nordic hamstring exercise program over a 13 week period with 292 players from 40 amateur soccer teams, HSIs were significantly reduced (P=0.005). The study concluded that the Nordic hamstring exercise program significantly reduced hamstring injury incidence rates but has no significant effect on the severity of the injuries. The study did not test pre and post intervention strength to quantify the strength increase observed as a result of the prescribed intervention when compared with the control group.

The NHE was tested as a potential field-based indicator of eccentric knee flexor strength by Sconce et al. (2015) who reported that the angle at which "breaking point", (the point at which the athlete loses their contraction and falls) is reached, correlated strongly (r=0.81, P<0 .001) with the peak torque achieved during an isokinetic eccentric knee flexor test. Interestingly, the study also stated that there was a weak relationship (r=0.480, P=0.06) between the "breaking point" angle and the isokinetic angle of peak torque. This shows that the Nordic hamstring exercise may be a useful indicator of eccentric strength but a poor predictor of angle of peak torque. Assessing hamstring strength in this manner, however, is highly subjective due to the lack of any objective strength measures such as those provided by an instrumented pressure feedback system such as the HSE.

The HSE device measures the force distributed by each limb simultaneously during a performance of the Nordic hamstring exercise. This can be practically applied to both a conditioning and injury rehabilitation setting by providing immediate and reliable feedback to the conditioning or rehabilitation staff that objectively quantifies individual limb strength. This device may provide an accessible means for determining global eccentric hamstring weakness and/or between limb imbalances which have both been cited as potential risk factors for HSIs (Liu et al., 2012).

### 1.1.4 Methods of Strength Measurement

Various devices and methods have been used to record objective strength measures for research purposes, athletic performance, assessment and medical rehabilitation monitoring. When using these devices, it is essential that the device has adequate validity (the comparability of the test device with a confirmed reliable device to determine its efficiency at measuring a similar objective output). It is also vital that the device displays good reliability (a device's ability to consistently measure an objective output metric with minimum variation or error between consecutive recordings) to ensure that the data displayed by the device is accurate and can be confidently utilised by the clinician.

The most common devices used for objective strength measurement are hand-held dynamometry and isokinetic dynamometry testing. Isokinetic testing is characterised by assessing an isolated muscle group against an accommodating resistance at a constant speed through a controlled range of motion (Feiring et al., 1990). Isokinetic dynamometry is a common method of objectively assessing strength by recording peak torque, average torque, work and power as well as the angle of peak torque (Maffiuletti et al., 2007).

#### *Isokinetic Dynamometry*

The Isokinetic dynamometer is widely considered to be the optimum method of strength assessment (Opar et al., 2013) and is commonly used to quantify the concentric, eccentric and isometric strength of several muscle groups. Isokinetic testing has been used as a clinically reliable method to assess muscle strength for more than 40 years and is still often used as a standard reference when comparing other methods of muscle strength assessment (Stark et al., 2011).

Isokinetic testing provides more objective feedback during strength testing than other traditional methods such as one rep max (1RM). This means of testing gives no insight in to the specific area/muscle group responsible for the eventual failure of the max repetition and therefore makes it difficult to target and address these weaknesses with a specific strength training intervention (Verdijk et al., 2009). Isokinetic testing gives a variety of detailed measurements that allow the practitioner to highlight specific areas of weakness and taper a strength/rehabilitation program based on the data recorded by the isokinetic device (Alvares et al., 2015). Details such as peak torque, Q:H ratio (in the lower extremity), time to peak torque and angle of peak torque are all valuable details when prescribing an intervention program and are also valuable as comparisons when the subject is re-assessed post-intervention to determine if the prescribed program has had the desired effect (Almosnino et al., 2012). The device's ability to target specific muscle groups such as the knee flexors/extensors allow for targeted and specific assessments to be carried out.

However, this means of assessment is not readily accessible in all conditioning or clinical settings due to the high cost of the device. The isokinetic device is also not practical when assessing a large group of athletes regularly, as it requires considerable time to set up and execute the testing protocol (Opar et al., 2013) while also requiring expertise in interpreting results to determine what areas of the data collected need addressing. The isokinetic dynamometer's ability to record several measurements simultaneously makes it a useful and effective method of muscle strength assessment. Previous research by Feiring et al. (1990), Drouin et al. (2004) & Maffiuletti et al. (2007) examined the test retest reliability of isokinetic dynamometer metrics including peak torque, angle of peak torque, work, velocity and angular positioning recorded by the dynamometers, for trial-to-trial/day-to-day consistency at various speeds and positions. Each of the studies found isokinetic dynamometry to be a reliable ($r=0.95$, $r=0.99$ and $r=0.86$ respectively) means of muscle strength assessment. It was noted by Drouin et al. (2004) that the reliability displayed in the study only represents speeds of 300°/s and below as discrepancies were observed at higher speeds.

Inter-machine reliability was tested by Alvares et al. (2015) for any significant differences between the Biodex System 3 pro and Cybex Humac Norm Model 770 isokinetic dynamometers. The study compared isometric, concentric and eccentric peak torque at 60°/s for the knee flexors and extensors. Reproducibility for the peak torques involved demonstrated high reliability (ICC=0.88-0.92) and no significant differences were observed between the two isokinetic devices ($P>0.05$).. The study concluded that inter-device reliability between the Biodex System 3 pro and Cybex Humac Norm Model 770 isokinetic dynamometers demonstrated high reliability.

While the above evidence does state that isokinetic dynamometry is an extremely accurate and reliable means of assessing strength, the practical limitations are vast. The availability, cost and time consuming nature of testing with these devices means that there is a need for a more convenient and accessible device to measure strength outputs in a practical setting such as a clinic or gym.

### *Hand-held Dynamometry*

A hand-held dynamometer (HHD) is a portable device that is used to measure muscle function at joints such as the hip, shoulder, knee and ankle (Thorborg et al., 2010, Bohannon, 1986, Martin et al., 2006, Spink et al., 2009). The HHD was created as a more precise and objective alternative to manual muscle testing by quantifiably measuring force in Newtons (N) or pressure (mmHg) between the therapists hand and the patients' limb being tested. If the HHD demonstrates reliable accuracy when compared with isokinetic devices then it could serve as a portable, efficient and cost effective alternative to isokinetic testing (Stark et al., 2011).

Hand-held dynamometry was used by Thorborg et al. (2010) to assess the devices reliability to clinically assess max strength at the hip joint, this study examined the test-retest reliability of the device for hip flexion, extension, abduction and adduction. In conclusion, the device displayed good to high reliability (ICC=0.74-0.99) at the 95% confidence interval.

A systematic review by Stark et al. (2011) compared a total of 19 studies carried out between 1988 & 2006 to determine if there was an ICC of >0.6 between a HHD and an isokinetic dynamometer. They found that 13 of the studies demonstrated reliability of (ICC >0.6), of the 6 studies that reported a correlation above the threshold set by the authors (>0.6); the methods of the studies are questionable secondary to non-reporting of, or absence of random test allocation, tester training and blind testing. The study concluded that hand held dynamometry is a valid and reliable method of strength assessment.

While the above review summarises that HHDs are reliable in measuring muscle strength, it must be noted that the studies observed in the review did not standardise their muscle testing techniques and positions. The studies also tested several different muscle groups during different types of contractions which also raises the question of interrater reliability when using a HHD for strength assessment. When compared to an isokinetic dynamometer such as the Biodex, the HHD's limitations include the inability of the device to control the speed of the contraction and the amount of feedback it can provide as it generally only provides a peak force reading in Newtons (N). Despite the convenience and accessibility of the HHD an isokinetic dynamometer is a far more detailed test method that is not subject to interrater reliability as the protocols can be easily standardised allowing for more consistent data collection. The HHD is also limited as the reliability of the device depends on the tester's ability to generate enough force to match or overcome the subjects' muscle contraction force. As mentioned by Stark et al. (2011) this may put the tester at risk of injury while carrying out the required manual resistance. This limitation can be addressed through the use of external fixated dynamometers which remove the need for manual resistance by a clinician resulting in a safer and more reliable test method.

### *Externally Fixed Dynamometry & Pressure Feedback Systems*

The use of externally fixed dynamometry, where a dynamometer is fixed to an apparatus in a certain position to assess a target muscle group, is a relatively new concept and therefore has not yet been supported by the research literature examining its use or reliability. Externally fixed dynamometry has been previously used by Wollin et al. (2016) to test its inter and intra-tester reliability for measuring unilateral isometric knee flexor strength in a position of hip extension and knee flexion which is specific to the terminal swing phase of gait.

It was proposed by Opar et al. (2013), that a novel device that can monitor the eccentric strength of each limb independently, during performance of the Nordic hamstring exercise (NHE), could make screening of eccentric strength and unilateral imbalances more efficient and feasible in a group setting. This method incorporated the use of load cells to measure the strength performance of each limb during the NHE. Thirty subjects had their eccentric knee flexor strength tested on a novel pressure feedback system by Opar et al. (2013), they performed 2 sets of 3 reps of the NHE on the device on two separate occasions. The two performances were tested for ICCs at 95% confidence intervals.  The NHE was chosen as it is a common hamstring strengthening exercise used in training programs making it practical to monitor the eccentric force exerted by the knee flexors (Opar et al., 2013). The study also used the device to assess residual weakness in athletes with a previous hamstring injury within 12 months prior to testing. The study found that the device displayed high-very high reliability (ICC=0.83-0.90) and a typical error of 21.7-27.5 N at a 95% confidence level when measuring peak eccentric knee flexor force in healthy athletes and also detecting eccentric knee flexor weakness, strength asymmetry and residual weakness in previously injured athletes. This study shows that the device displays consistent test-retest reliability but doesn't necessarily explore the validity of the device when compared to a gold standard device such as an isokinetic dynamometer.

The Hamstring Solo Elite is a device that provides feedback during the performance of commonly used eccentric hamstring strengthening exercises, such as the NHE. This may improve the efficacy of eccentric strength training. Externally fixed dynamometry, such as the proposed HSE device, is a relatively new concept which means that there is a gap in the literature to date supporting its reliability. Externally fixed dynamometry may be a useful means of assessing strength in a safer and more consistent position without the need for manual resistance from the tester. However, externally fixed dynamometry doesn't control the speed of the contraction while the feedback provided also lacks important details such as angle of peak torque that an isokinetic dynamometer can provide which may be crucial in determining return to play outcomes or injury risk factors.

When validating a new device, it is best to compare it to industry considered reference standard device. Importantly, there is inherent measurement error associated with any device (including those considered reference standard and already validated). An important factor to consider in the validation process is the standard measurement error associated with the reference device. This Standard error of measurement estimates how repeated measures of a person on the same device tend to be distributed around his or her “true” score. For present purposes, the standard measurement error was taken into account when defining the smallest worthwhile change and comparing internal consistencies of both devices.

**Aims:**

(i) Validation of the HSE device as compared to an isokinetic dynamometer.

(ii) To establish the test-retest reliability of the HSE device.

**Hypotheses**

1. The Hamstring Solo Elite is a valid device for measuring eccentric hamstring strength when compared to the Biodex isokinetic dynamometer.

2. The Hamstring Solo Elite's outputs display high ICCs (0.7-0.9) for test-retest reliability when compared over two consecutive tests.

# 1.2 Methods

### 1.2.1 Participants

20 male participants were recruited from the student body at the Institute of Technology Carlow. The participants were field sport athletes who competed in GAA, rugby or soccer. The participants were experienced in lower limb strength training i.e., they took part in at least 2 lower limb strength sessions per week over the last 12 months. The participants were 21±2 years of age, weighed 78.6±4.6Kg and were 179.6±6.4cm in height and were free of any lower limb injuries. Each of the participants signed an informed consent (see appendix A) and completed a thorough medical screening form (see appendix B) in the presence of the tester. Participants were instructed to abstain from lower limb strength training for the duration of the data collection process. Participants were informed that they were free to withdraw from testing at any stage, and to contact the tester should any concerns arise. In the current study, 1 subject withdrew due to an injury sustained outside of testing.

### 1.2.2 Experimental Design

Participants reported to the isokinetic laboratory for 4 separate sessions. They were randomly separated into 2 even groups of 10 participants to determine the order in which their testing was to be carried out (Figure 1). The participants were split into their respective groups to randomise the order in which the performed each strength test to reduce the likelihood of a familiarisation or learning effect of the testing procedures skewing the data. The groups were divided using a random number generator to ensure randomisation of the groups was adequate.

The participants performed a generic 3 minute warm-up on a Watt-Bike at 60 rpm to increase lower limb blood flow and increase muscle temperature before commencing any strength assessment protocols. The first session was a familiarisation session for all of the participants on both devices. The following 3 sessions were used to either measure eccentric strength of the left and right limbs on the isokinetic dynamometer or 1 of 2 test-retest measurements using the Hamstring Solo Elite, depending on the order of testing assigned to the particular group. All sessions were carried out 7 days apart to allow adequate strength recovery.

Group 1 had their eccentric strength measured using the Isokinetic device during session 2 and then had their eccentric strength measured on the Hamstring Solo Elite 7 days later. Group 2 had their eccentric strength measured using the Hamstring Solo Elite during session 2 and then had their eccentric strength measured using the Isokinetic device 7 days later during session 3. Both groups then attended a fourth session 7 days after session 3 to have their eccentric strength measured a second time using the Hamstring Solo Elite.

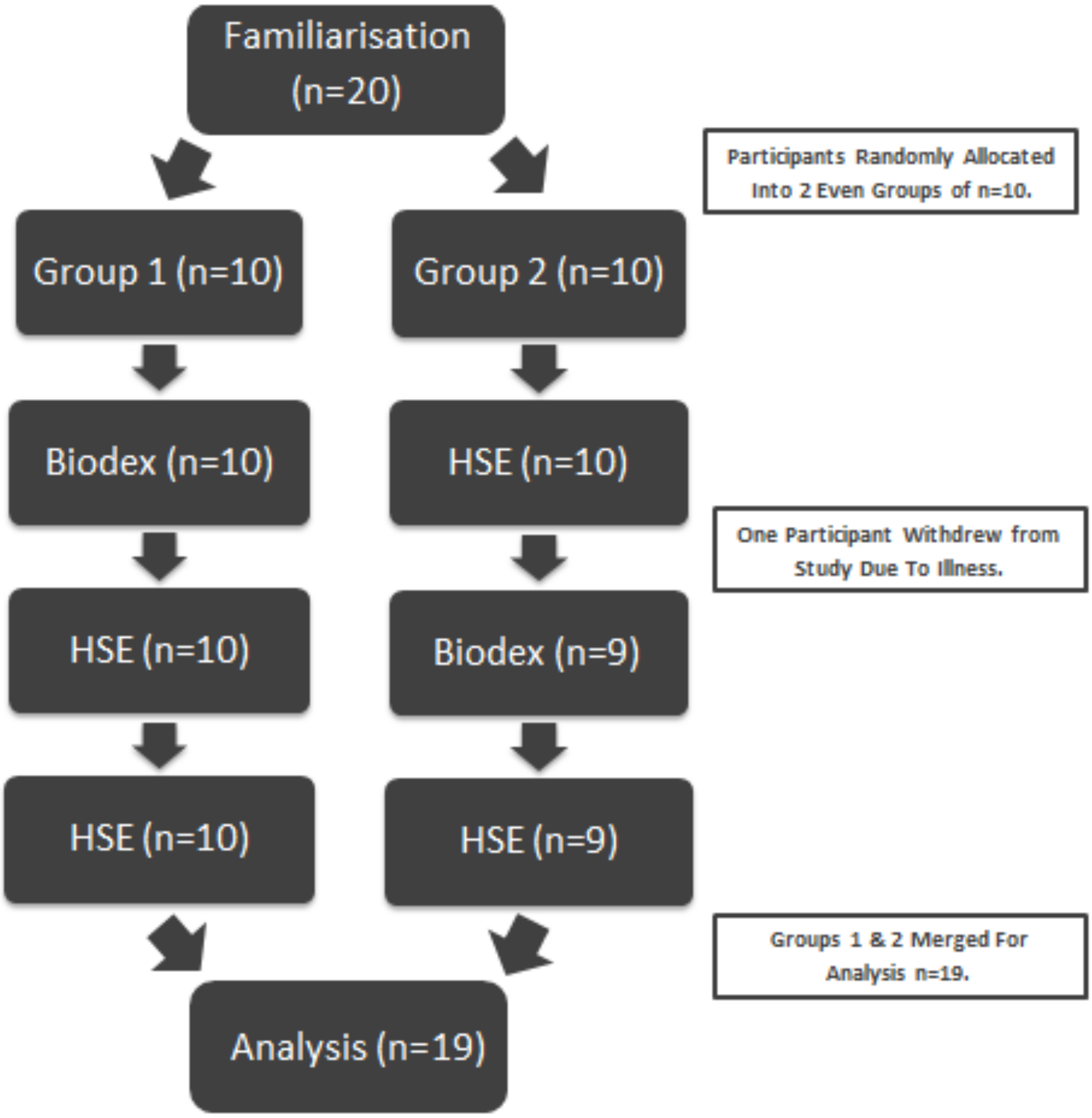

Figure 1: Flow Chart of Data Collection Procedure

### 1.2.3 Familiarisation

All participants were first required to attend a familiarisation session. During the familiarisation session the participants were required to perform repetitions of eccentric knee flexion on the Biodex System 3 (Figure 2) isokinetic device at 30°/s, with maximum effort, until they could perform consistent repetitions (minimum: 5 repetitions, maximum: 10 repetitions) with a coefficient of variance (CV) value of <15 for both legs. The CV value is an important consideration as it represents variations in the force being exerted in each repetition, giving an overall quantification of repetition quality. During the familiarisation session the participants were also required to perform repetitions of the NHE, with maximum effort, on the HSE pressure feedback system until the repetitions could be consistently performed without technique errors such as flexing at the hips of arching of the lumbar spine (Figure 3). Verbal cueing reinforced technique during test repetitions.

*Figure 2: Biodex System 3 eccentric knee flexion apparatus setup.*

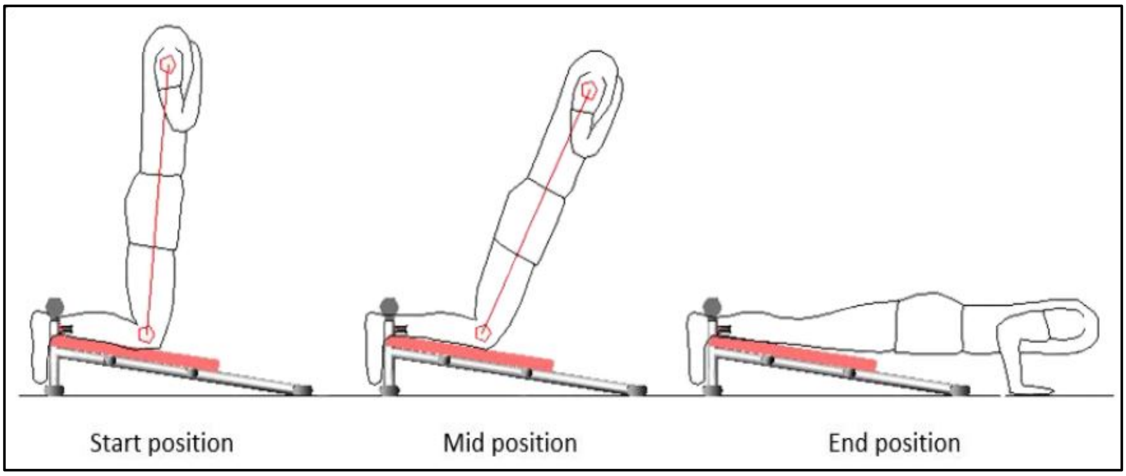

*Figure 3: Graphical representation of Nordic hamstring exercise technique.*

### 1.2.4 Isokinetic Test Protocol

Data collection on the Biodex System 3 consisted of one set of 5 maximum eccentric knee flexion repetitions at a slow speed of 30°/s on both legs individually (Figure 2). The eccentric speed of 30°/s was chosen as it has previously been used to assess eccentric knee flexor strength by Aagaard et al. (1998) and mimics the slow velocity of knee extension experienced during repetitions of the NHE. The participants were securely fixed to the device and performed one sub-maximal practice repetition to ensure the participants was comfortable performing eccentric knee flexion repetitions. The participants were then instructed to perform a maximal knee flexion contraction against the extension force applied by the device until the isokinetic arm returned to the start position for 5 repetitions with 10 seconds rest between repetitions to match the time taken by participants to reset their body position between repetitions of the NHE. Maximal peak torque (Nm) of the 5 repetitions for both limbs was recorded for data analysis. Repetitions were only recorded if the CV value was observed to be <15.

### 1.2.5 Nordic Hamstring Exercise Protocol

Data collection on the HSE consisted of the performance of one set of 5 NHE repetitions as slowly as possible with 10 seconds between repetitions. The participants' details of height and weight were collected prior to the familiarisation session and entered into their individual profiles within the HSE data collection app that connects to the Hamstring Solo device via Bluetooth connection. They were then given visual (Figure 3) and detailed verbal coaching cues on performance technique before commencing.

The participants were then positioned in a kneeling position on the cushioned surface of the Hamstring Solo and with their ankles fixed beneath the load cells just superior to the medial and lateral malleoli. They were then instructed through verbal commands to "lower their torso as slowly as possible towards the ground by only extending at the knee joint until they could no longer sustain the eccentric hamstring contraction and landing on their palms on the floor". The participants were also instructed to "maintain a straight line from the shoulder to the knee" to the best of their ability "by not allowing bending at the hips" to occur during the repetitions. There was no minimum range of motion set and repetitions were excluded if they showed a lack of control on descent or excessive hip movement during the repetition. After each repetition the peak force (N) from the left and right limbs was recorded through wireless data acquisition from the load cells.

### 1.2.6 Statistical Analysis

The peak toque (Nm) recorded by the isokinetic device and the peak force (N) recorded by the Hamstring Solo Elite were analysed to determine if there was a high intraclass correlation coefficient (ICC) of >0.7 between both devices for both limbs. The statistical analysis was performed using the IBM SPSS Statistics, version 22 (IBM, Armonk, NY, USA). ICCs were calculated using the peak torque and peak force recorded from both the Isokinetic device and the Hamstring Solo Elite respectively, to determine the validity of the device when compared to the Biodex Isokinetic device. ICCs were calculated using the peak force recorded from 2 separate trials of the Hamstring Solo Elite to determine if the device demonstrates acceptable test-retest reliability. Classification of observed ICCs was based on thresholds stated by Mukaka, (2012) as a very high correlation of 0.9-1.0, a high correlation of 0.7-0.9, a moderate correlation of 0.5-0.7, a low correlation of 0.3-0.5 and a Negligible correlation of 0.00-0.30. Percentage Typical Error (TE%) was calculated as a CV value of the measurements observed from the HSE. Standard Error of Measurement (SEM) for the device was calculated using the formula: {SEM = So x Sqroot(1-r)} where So is the Observed Standard Deviation and r is the Reliability. SEM was then used to determine the Minimum Detectable Change (MDC) at a confidence level of 95%, "MDC = 1.96 x SEM x square root of 2".

# 1.3 Results

### 1.3.1 Inter-Device Validity

Table 1: Descriptive statistics and inter-device validity data (n = 19)

| Bilateral Limb Testing Eccentric Knee Flexion | Biodex System3~ Peak Torque (Nm)* | Hamstring Solo Elite Peak Force (N)* | ICC (95% CI) |
|---|---|---|---|
| **Left** | 184.71±33.61 | 268.56±51.45 | 0.82 (0.58, 0.93) |
| **Right** | 185.45±34.29 | 268.72±57.12 | 0.84 (0.59, 0.96) |

Abbreviations: **ICC**, intraclass correlation coefficient; **Nm**, Newton-meters; **N**, Newtons.

*****Values are mean ± standard deviation. **~**Biodex System3 tested eccentric knee flexion at 30°/s

ICCs between the Biodex System3 and HSE for each variable are displayed in (Table 1). ICCs between both devices was obtained to determine if a high (>0.7) correlation was observed between the peak torque and peak force recorded by the Biodex and the HSE respectively. Correlations were tested using the peak torque recorded by the Biodex for the left and right limbs respectively (184.71±33.61Nm & 185.45±34.29Nm) and the peak force recorded by the HSE for the left and right limbs respectively (268.56±51.45N & 268.72±57.12N). The validity between the Biodex and HSE's respective Peak torque and peak force was observed through a high correlation of (>0.8). ICCs displayed between the devices were 0.82 (CI 0.59 to 0.94) and 0.84 (CI 0.59 to 0.96) for the left and right limbs respectively.

### 1.3.2 Test-Retest Reliability

Table 2: Descriptive statistics and Test-retest reliability data for the Hamstring Solo Elite (n = 19)

| Bilateral Limb Testing Eccentric Knee Flexion | Between-session reliability | | ICC (95% CI) | TE **(%)** | SEM **N** | MDC **N** |
|---|---|---|---|---|---|---|
| | **Session 1*** | **Session 2*** | | | | |
| **Left** | 268.56±51.45 | 269.99±48.75 | 0.91 (0.76, 0.96) | 6.35% | 15.44 | 42.78 |
| **Right** | 268.72±57.12 | 269.57±48.84 | 0.91 (0.78, 0.96) | 6.87% | 17.14 | 47.51 |

Abbreviations: **ICC**, Intraclass Correlation Coefficient; %**TE**, Percentage Typical error; **SEM**, Standard error of Measurement; **MDC**, Minimum Detectable Change; **N**, Newtons.

***Values are mean ± standard deviation.**

Descriptive statistics and the HSE test-retest data for each variable are displayed in (Table 2). ICCs between both trials on the device was obtained to determine if a high (>0.7) correlation was observed between the peak force recorded on two consecutive trials of the HSE. ICCs were tested using the peak force recorded during the first trial with the HSE for the left and right limbs respectively (268.56±51.45N & 268.72±57.12N) and the peak force recorded during the second trial with the device for the left and right limbs respectively (269.99±48.75N & 269.57±48.84N). The HSE displayed high test-retest reliability between the two trials that were performed. The ICCs displayed between both trials were 0.91 (CI 0.76 to 0.96) and 0.91 (CI 0.78 to 0.96) for the left and right limbs respectively. Percentage Typical Error (TE%) between trials was calculated to be 6.35% and 6.87% for the left and right limbs respectively. The Standard Error of Measurement (SEM) was calculated as being 15.44N & 17.14N for the left and right limbs respectively. Minimum Detectable Change (MDC) of 42.78N & 47.51N for the left and right limbs respectively at a 95% confidence interval.

# 1.4 Discussion

The HSE displayed high (>0.70) inter-device validity with the Biodex System3 isokinetic dynamometer. When peak eccentric knee flexor strength was assessed for the left and right limbs by both devices, it resulted in an observed correlation of 0.82 (CI 0.586 to 0.938) and 0.84 (CI 0.586 to 0.938) respectively. The above results indicate that we can accept the hypothesis that the HSE is a valid device for measuring eccentric hamstring strength when compared to the Biodex isokinetic dynamometer.

An externally fixed dynamometer that assesses eccentric hamstring strength, such as the HSE, has not been validated against an isokinetic dynamometer such as the *Biodex System3* until now and therefore the literature lacks comparative ICCs for this study. However, the validity of a similar concept when compared to isokinetic dynamometry has been previously investigated and also validated against a HHD by Toonstra and Mattacola (2013). The study observed differences in isometric hamstring contractions and reported no significant differences (*P*=1.0) between the isokinetic dynamometer and the portable fixed dynamometer. The high correlations observed in the current study are important in validating the device as it supports the HSE's validity when compared to the Biodex, a reliable gold standard means of assessing strength that has previously shown ICCs ranging from 0.86 to 0.95 (Maffiuletti et al., 2007, Feiring et al., 1990, Drouin et al., 2004).With the device displaying similar validity to the Biodex it infers that the HSE may be utilised as a valid means of assessing eccentric knee flexor strength through the performance of the NHE. The NHE has been supported by the literature as a valid means of strengthening and assessing the strength of the hamstring eccentrically (Sconce et al., 2015, van der Horst et al., 2015).

The significant correlations observed between the Biodex and the Hamstring Solo Elite may be due to the fact that both the HSE and Biodex measured peak eccentric knee flexor strength for the purpose comparison in this study. The subjects' strength training experience was important when performing consistent maximal contractions during testing. This was vital to ensure that the correlation values being observed between both devices represented the accuracy of the devices and not the subjects' ability to consistently perform maximal strength repetitions.

The HSE displayed very high (>0.9) test-retest reliability for consecutive measurements of the Nordic hamstring exercise. When eccentric knee flexor strength was assessed for each limb on two consecutive sessions by the HSE it resulted in a high correlation of 0.91 (CI 0.76

to 0.96) and 0.91 (CI 0.78 to 0.96) for the left and right limbs, respectively. These ICCs observed support the hypothesis that the HSE displays acceptable test-retest reliability over two consecutive tests.  These ICCs are similar to the ICCs observed in previous research carried out on Isokinetic (0.86-0.95) and hand-held (0.90) dynamometers (Stark et al., 2011, Maffiuletti et al., 2007). The %TE observed was 6.87% & 6.35% for the left and right limbs respectively. This finding shows the relatively low variation in repetitions recorded by the HSE and  is similar to that observed by Opar et al. (2013) with a %TE of 8.5% & 5.8% being reported for the left and right limbs respectively. The MDC for the HSE was observed as being 42.78N & 47.51N for left and right limbs respectively, which is in contrast to the higher MDC of 76.2N & 60.1N reported by Opar et al. (2013) for left and right limbs respectively. This MDC shows that the HSE can reliably measure any changes of greater than 42.78N & 47.51N for the respective left and right limbs without error affecting the observed result. This allows clinicians to determine a threshold at which the progressions observed can be confidently attributed to the intervention applied by them.

The test-retest reliability of the Hamstring Solo Elite device is similar to the ICCs observed in previous research carried out on Isokinetic (0.86-0.95) and hand-held (0.90) dynamometers (Stark et al., 2011, Maffiuletti et al., 2007). The test-retest reliability of an  isokinetic dynamometer to assess eccentric knee flexor strength at speeds of 60°/s and 120°/s  was investigated by Li et al. (1996) who observed similar ICCs of 0.83 for both speeds. This investigation contrasted with the current study in the speeds investigated and also both males and females were included in the sample set used. The test-retest reliability of a similar device measuring eccentric hamstring strength was observed by Opar et al. (2013) with similar results (ICCs=0.85-0.89) to this study being observed. The very high test-retest reliability result means that the device shows a good level of consistency when assessing eccentric hamstring strength during the performance of the Nordic hamstring exercise.

From an engineering point of view, the use of accurate and highly calibrated load cell technology in the HSE's design means that the device should display mechanical consistency when tested repeatedly. This was confirmed by the consistent muscle contractions performed by the subjects leading to high correlation values when test-retest reliability was examined. Reliability is essential for a device such as this with any changes in strength observed being attributed to an intervention rather than an associated error with the device. This has significant implications in a clinical setting where accuracy is essential to prevent a misrepresentation of clinical findings.

The main limitations of the study are the relatively low sample size (n=19) when compared to the sample size tested by Opar et al. (2013) of (n=30). A difficulty affecting the possible sample size is recruiting subjects with a significant enough training age to perform consistent maximal eccentric repetitions from the cohort available. Participant compliance in abstaining from lower limb strength sessions between testing is another limitation that may have a positive or negative effect on the data recorded in repeated sessions. Without the ability to monitor participant compliance outside of testing, the results may be affected by varying levels of subject fatigue while testing or minor injuries elsewhere in the kinetic chain that may also negatively affect results. Compliance is particularly pertinent to the group that had 14 days between HSE testing which may have resulting been affected by increases or decreases in strength over the 14 day period. Future research should look to increase the sample size tested and also carry out greater familiarisation to encourage more consistency in repetitions performed during data collection.

The device itself is also limited as it cannot control repetition speed or provide an angle of peak torque which is useful when targeting strength improvements at a specific joint angle where injury is common e.g. late swing phase of gait as previously alluded to in the literature. The device also does not provide a coefficient of variance (CV) value to determine if a repetition is valid; which is an important feature of isokinetic dynamometers. Regardless of these limitations, with adequate familiarisation and sufficiently trained individuals, these factors are likely to be outweighed by the accessibility and functionality of the HSE as a method of objectively assessing eccentric hamstring strength.

## 1.5 Conclusion

The HSE is a valid and reliable device for assessing eccentric hamstring strength. The device has been proposed as a more affordable and accessible means of assessing eccentric hamstring strength and as a result of its compact and portable design it has the potential to be utilised in both clinical and athletic environments. The implementation of this device to assess hamstring strength as a daily screening, injury rehabilitation or strengthening tool can now be done so with the reassurance that the device is an accurate and reliable strength-monitoring instrument.

# Chapter 2: The Acute Effects of a Progressively Loaded Nordic Hamstring Program Utilising a Live Strength Feedback System to Ensure Equal Bilateral Force Distribution, a Randomised Control Trial.

# Abstract

**Introduction:** Hamstring strain injuries (HSIs) are one of the most prevalent injury types in sports that involve high-speed running and sprinting such as soccer (Sconce et al., 2015). Risk factors for HSI include hamstring weakness (Liu et al., 2012) and between-limb eccentric hamstring strength imbalances (Bourne et al., 2015). The Nordic Hamstring Exercise (NHE) is an effective means of developing eccentric hamstring strength and reducing HSI occurrence rates (Sconce et al., 2015, van der Horst et al., 2015). A real-time pressure feedback, available with a system such as the HSE, during the performance of the NHE allows the athlete to monitor individual limb force distribution during repetitions of the exercise. This feature may allow between-limb imbalances to be corrected while performing the NHE and thus increasing eccentric hamstring strength ,correcting eccentric strength imbalances and reducing HIS risk..

**Aims:**

To investigate the effects of a progressively loaded 5 week NHE intervention using a live strength feedback system compared without live feedback and a control group on:

1. eccentric hamstring peak torque, average peak torque and angle of peak torque.
2. between limb eccentric hamstring strength imbalances .

**Methods:** 62 Participants (22±3 years, 84.7±8.2kg, 178.7±10.4cm) were recruited from the Soccer, Rugby and GAA teams in the Institute of Technology Carlow. The participants attended a familiarisation session to perform repetitions of eccentric knee flexion at speeds of 30°/s and 120°/s on the Biodex System3 isokinetic device. The subjects returned 7 days later to repeat the isokinetic protocol to assess their baseline eccentric hamstring peak torque, angle of peak torque and average peak torque for each limb, and any between limb imbalances. Subjects were then strength matched and randomly divided into 3 equal groups. Group 1 (HSE group performed a 5 week progressively loaded NHE program using the HSE device which allowed subjects to monitor between limb force imbalances during their exercises. Subjects in this group were encouraged to ensure even force distribution. Group 2 (Solo group) followed the same program using a stationary device to fix the heels but were not able to monitor between limb force imbalances.. Group 3 was the control group who did no additional hamstring conditioning. Each of the groups had their baseline measurements reassessed post-intervention to determine any effects elicited from the respective interventions. Two-way ANOVA statistical tests were used to determine the main effects for time (pre vs post intervention) and group (Control, HSE, Solo). Magnitude based inferences were used to determine what effect, if any, did the utilisation of the HSE during the intervention have on between-limb eccentric hamstring strength imbalances.

**Results:** There was an observed main effect for time, with increased hamstring strength post intervention ($F_{5,98} = 8.85$; $P < .004$; $\eta^2$ 0.070). There was also an observed main effect for intervention group, with increased hamstring strength between groups ($F_{6,92} = 8.29$; $P < .001$; $\eta^2$ 0.123). Following Tukey post hoc analysis, significant differences between groups for increased peak torque were observed between the elite and control group ($P$=0.03) while the Solo group also displayed a significant increase in peak torque ($P$=0.01) when compared to the control group. No significant difference was observed between the Elite and Solo groups ($P$=0.37).

There was an observed main effect for time, with increased hamstring strength post intervention ($F_{5,78} = 8.79$; $P < .004$; $\eta^2$ 0.069). There was also an observed main effect for intervention group, with increased hamstring strength between groups ($F_{5,82} = 6.54$; $P < .002$; $\eta^2$ 0.140). Following Tukey post hoc analysis, significant ($P<0.05$) differences between groups for peak torque were observed between the elite and control group ($P$=0.04) while the Solo group also displayed a significant increase in peak torque ($P$=0.01) when compared to the control group. No significant difference was observed between the Elite and Solo groups ($P$=0.39).

There was an observed main effect for time, with increased hamstring strength post intervention ($F_{8,92} = 9.59$; $P < .002$; $\eta^2$ 0.075). There was also an observed main effect for intervention group, with increased hamstring strength between groups ($F_{8,90} = 6.41$; $P < .002$; $\eta^2$ 0.098). Following Tukey post hoc analysis, significant ($P<0.05$) differences between groups for average peak torque were observed between the elite and control group ($P$=0.04) while the Solo group also displayed a significant increase in average peak torque ($P$=0.01) when compared to the control group. No significant difference was observed between the Elite and Solo groups ($P$=0.40).

Magnitude based inferences show the HSE has a likely beneficial effect in correcting between-limb imbalances for peak torque, average peak torque and angle of peak torque. The Solo group had no beneficial effect in correcting any between-limb imbalances.

**Conclusion:** The Nordic Hamstring exercise is an effective means of increasing hamstring strength. With the integration of a live strength feedback system, , the NHE can be an effective means of increasing eccentric knee flexor strength while reducing between-limb strength imbalances.

# 2.1 Literature Review

### 2.1.1 Literature Search Strategy

To examine the scientific evidence base, a rigorous literature review was undertaken. The databases (PubMed, Google Scholar) were searched. The search included the terms [‘Eccentric’ AND ‘Hamstring’ AND ‘Strength’ OR ‘Imbalance’ AND ‘Isokinetic’ OR ‘Pressure Feedback]. English language journals with full text available were only included in this search. The data range included from 2000- present to examine the most recent research. Abstracts were examined and articles that included the above search terms were selected for full review. From the search 180 articles were retrieved. After initial reading of the abstracts 70 were excluded. The remaining 110 articles were included in the review. The articles were reviewed using the PRISMA framework (statement and checklist) for systematic literature review.

### 2.1.2 Implications of Hamstring Strain Injuries

Professional clubs regard their players as their most vital assets in achieving success as a club. The leading cause of time lost from competition in multi-sprint sports is HSIs (Hickey et al., 2016). The impact of prevalent injuries such as HSIs can negatively affect team performance and in turn affect the morale of the entire team (Woods et al., 2004).

Foreman et al. (2006) reported that the overall cost of injury to a premier league club in the 1999-2000 season was as high as £74.7 million. However, more recent research from Ekstrand et al. (2016) shows the true progression of the financial burden on clubs as incidence rates have increased; with the average cost of a player being injured as high as €500,000 per month. With the high prevalence and recurrent nature of HSIs, this means that HSIs alone bear huge financial implications on professional sport. The cost to the club may also be further increased through reduced match attendance resulting from the absence of first choice players.

The broad variations in return to play duration following HSIs have been reported to vary from 1 day up to 104 weeks depending on severity (Moen et al., 2014). HSIs are responsible for greater than one quarter of all injury absences per season in professional football clubs according to Ekstrand et al. (2016). The average playing time lost to HSIs has been closely investigated by Heiderscheit et al. (2010) who determined the average time lost per HSI is 26 days with a minimum of 4 competitive game days missed as a result. With up to 6 HSIs in a squad of 25 soccer players per season (Ekstrand et al., 2016), this results in 156 days of player absence each season resulting from HSIs alone.

The prolonged nature of HSIs can put significant emotional stress on athletes who cannot play which in turn affects the morale of the individual and the team (Blake et al., 2014, Murphy et al., 2012). Physically and in contrast to professional athletes, amateur players generally have an occupation to support them financially. This means that any loss of physical function resulting from injuries such as HSIs may have major implications on their ability to carry out their occupational obligations putting mental and financial pressure on athletes. Other physical implications include the predisposition to future injury such as ACL injuries resulting from altered hamstring function (Zebis et al., 2015).

The incidence rates and implications of HSIs again mean that there is a high demand for effective hamstring injury prevention strategies but in order to design effective injury management strategies the cause or causes of the problem must be first identified.

### 2.1.3 Epidemiology of Hamstring Strain Injuries

As outlined, muscle injuries are a common burden on athletes taking part in sport at all levels. In particular, hamstring strain injuries (HSIs) are an ever-increasing problem and are closely linked with sports that involve sprinting and sudden changes of direction (Foreman et al., 2006). HSIs are the most prevalent of all the injury subtypes and are reported to account for 12-15% of all injuries (Liu et al., 2012). Despite significant advances in injury prevention practices, HSIs instances continue to rise field sports such as professional soccer. Ekstrand et al. (2016) has observed an annual 4% increase in HSIs between 2001 and 2014. This study also observed that HSIs accounted for 12% of all injuries in professional soccer during the observed period. It is suggested that, despite preventative measures being implemented, the physical demands of the game are now greater than ever with a 30% increase in high-speed running being observed in premier league football teams over the duration of the study.

Similar HSI rates have also been reported in rugby Moore et al. (2015), reported HSIs to be responsible for 15% of all injuries incurred by an international rugby team over 3 years. These findings were consistent with other professional sports such as Australian Football where a 16% incidence rate for HSIs was observed by Orchard et al. (2013) and Cricket where HSI incidence rates had increased from 3% to 11% over the initial 6 years of the study (Orchard et al., 2016). The increased HSI incidence in cricket has been attributed to the introduction of the T20 (TwentyTwenty) Cricket championship which greatly increased player load and exposed the players to short high-intensity games.

HSI prevalence is notable in amateur sports such as Gaelic Games where Hurling has been reported to have a 17% HSI incidence rate (Blake et al., 2014) and in Gaelic Football where a staggering 21% incidence rate has been observed by Roe et al. (2016). It was observed that HSIs were 7 times more prevalent in match play when compared to training suggesting that current Gaelic Football training demands are not offering sufficient injury protection to players during competitive games and instead have become more injurious in the later years of the above study.

### 2.1.4 Hamstring Anatomy

Hamstrings have double joint functions (knee and hip) and injuries can originate from maladapted movements at either joint. The hamstring muscle group is comprised of predominantly type II muscle fibres. The hamstrings are comprised of three separate muscles (biceps femoris, semitendinosis, and semimembranosus). The biceps femoris (most lateral muscle) is comprised of two heads (long and short). The long head originates from the distal portion of the sacrotuberous ligament and the posterior aspect of the ischial tuberosity. The short head of biceps femoris originate from the linea aspera of the femur and does not cross the hip joint. Both heads form the muscle belly and pass distally and insert on the lateral side of the head of the fibula, the lateral condyle of the tibia, and the deep fascia of the lower leg. The biceps femoris has a dual innervation: the long head is innervated by the tibial portion, and the short head by the peroneal portion of the sciatic nerve. The medial hamstring muscles are semimembranosus and semitendinosis. The semitendinosis has a common origin with the long head of the biceps femoris from the ischial tuberosity. It inserts proximally into the medial surface of the tibia and the deep fascia of the lower leg and distally to form a member of the pes anserinus with the gracilis and sartorius. The semimembranosus originates via a thick tendon from the ischial tuberosity proximal and medial to the biceps femoris and the semitendinosis and inserts into the medial-posterior aspect of the tibia via fibrous expansions. The semitendinosis and semimembranosus muscles are innervated by the tibial portion of the sciatic nerve (Drake et al. 2009).

### 2.1.5 Hamstring Strain Injury Mechanisms

In order to develop effective rehabilitation and prevention strategies for HSIs, we must first identify and understand the offending mechanisms for HSIs. By understanding the mechanisms by which HSIs occur it is possible to focus injury prevention practices around types of muscle contraction and the knee/hip joint positions in which these injuries most commonly occur (Yu et al., 2017). Identifying the biomechanical factors that put the hamstrings at risk of injury such as knee and hip position along with biomechanical considerations such as pelvic positioning can lead to more specific and effective HSI prevention.

The most commonly identified HSI mechanism is high-speed running. High-speed running, particularly sprinting, has been widely identified in the literature as the primary offending mechanism for HSIs (Yu et al., 2008, Van Hooren and Bosch, 2016, Ekstrand et al., 2016). This mechanism of injury is evident through the high incidence rates in sports that involve sprinting and high speed running such as soccer, rugby and Gaelic games (Ekstrand et al., 2016, Roe et al., 2016, Moore et al., 2015). In professional soccer alone, more than 60% of all reported HSIs occurred during high-velocity running (Woods et al., 2004). Rugby reported similar findings with more that 68% of all HSIs being attributed to high-speed running alone (Brooks et al., 2006). It has been reported by Askling et al. (2007) that all competitive sprint athletes who incurred a first-time HSI did so at maximum or close to maximum velocity sprinting.

Various studies have been carried out to explore the biomechanical aspects of sprinting with the aim of identifying the phase or phases of the gait cycle at which the hamstring muscle group is most susceptible to injury (Schache et al., 2012, Liu et al., 2017, Yu et al., 2017). Some initial research by Mann and Sprague (1980) into the activity of the hamstring muscle group during gait had suggested that the hamstrings experienced its greatest amount of force during the initial stance phase thus putting the hamstrings at their greatest risk of injury during this phase. This theory has since been proven to be outdated by a vast quantity of evidence citing the late swing phase of gait as the phase at which the hamstrings are most susceptible to injury  (Liu et al., 2017, Liu et al., 2012, Yu et al., 2008). The late swing phase is believed to be the most 'at risk' phase of gait for HSIs due to the level of high-velocity eccentric contractions generated by the hamstring muscle group during this phase (Guex et al., 2016b). The eccentric contraction experienced by the hamstring muscle group is caused by the deceleration of the rapidly extending limb in preparation for heel strike. The hamstring muscle group is also at an elevated risk of injury at this point as Daly et al. (2015) suggest that anterior pelvic tilt also occurs at this phase of gait putting greater strain on the hamstrings. Anterior pelvic tilt has previously been discussed as a risk factor for HSI and with all hamstring muscles originating at the ischial tuberosity of the pelvis it is clear that an anterior tilt of pelvis whilst the hamstring muscle group are experiencing a high eccentric load could lead to an increase in HSI risk. For these reasons, the primary focus of injury prevention and rehabilitation being based around eccentric hamstring conditioning.

Evidence suggests that kicking is another common mechanism for HSIs with Gabbe et al. (2005) reporting that 19% of HSIs in amateur Australian football players occurred during the act of kicking. Similarly, in other sprint-related sports that also include kicking, such as soccer and rugby, significant incidences of HSIs during kicking have been reported. In a Rugby-based study by Brooks et al. (2006) more than 10% of HSIs occurred during kicking. While this is much lower than in Australian football one must consider that kicking is only carried out by certain position-based individuals in rugby compared to all members of an Australian football or Soccer team. With evidence to suggest kicking as a mechanism for HSIs, conditioning methods that mimic the demands of kicking must address the control of eccentric hamstring contractions during high velocity hip flexion as well as knee extension.

Many traditional hamstring-strengthening methods such as the squat or deadlift don't necessarily place the hamstrings under the same strain conditions that are experienced during high-speed running. However, more eccentric based exercises such as Romanian Deadlifts and the NHE, where the hamstring is lengthened and still must produce maximal or near maximal force, are more effective in preparing the hamstring muscles for the demands of high-speed running. These eccentric type exercises biomechanically replicate the force demands placed on the hamstring muscles as highlighted above, allowing coaches to achieve their desired specificity in preparation.

### 2.1.6 Non-Modifiable Risk Factors

Non-modifiable risk factors for HSI are factors that put an athlete at risk of incurring a HSI but cannot be influenced through strength training or manual therapy. Non-modifiable risk factors for HSI predominantly include previous hamstring injury and increasing age (Foreman et al., 2006).

*Previous Hamstring Injury*

Previous hamstring injury is commonly reported to be the leading risk factor that predisposes an athlete to a recurring hamstring injury. The cause has not yet been concurrently decided upon but many believe it to be either residual structural damage to the sarcomeres, a neuromuscular recruitment deficit following a previous tear or a combination of both (Foreman et al., 2006). It has been hypothesised by Fyfe et al. (2013) that neuromuscular inhibition, resulting from a previous HSIs, is a significant factor in HSI recurrence. The concept of neuromuscular inhibition is supported by Opar et al. (2015) who found that professional AFL players who had a previous HSI displayed smaller strength gains following a pre-season eccentric hamstring strengthening program. The inclusion of previous injury amongst the leading risk factors of hamstring injuries is supported by a systematic review by Freckleton and Pizzari (2013) who carried out a meta-analysis of 13 studies, comprising of a total of 2952 subjects, that all implicated previous injury as a significant risk factor. The meta-analysis strongly supported the consensus that previous injury is a significant relative risk (RR) factor (RR=2.68, 95% CI 1.99 to 3.61, p=0.00). As previously discussed, controlling athlete workload, particularly in adolescence, can reduce the likelihood of incurring an initial HSI which will then exist as a predisposing factor for further HSIs.

Overall, many of the HSI risk factors discussed can be addressed or prevented through optimal eccentric conditioning of the hamstring group and the development of good postural balance. Similarly, the effects of non-modifiable risk factors can be offset or initially prevented through the implementation of correct injury prevention practices, correct periodisation and the controlling of game/training workload expose in the athlete’s adolescence.

*Effect of Age on HSI Risk*

It has been widely accepted that age is a predominant risk factor for injury in general and is particularly true for HSI (Gabbe et al., 2006). A study investigating injury risk factors in football players by Arnason et al. (2004) cites increasing age as an influential injury risk factor. In the study, the group with the highest injury incidence is also the group with the highest age profile. This finding is supported in many injury risk cohort studies and systematic reviews (Freckleton and Pizzari, 2013), (Foreman et al., 2006) & (Prior et al., 2009) who all state that age is a significant risk factor for HSI even when there is no previous injury history. It has been hypothesised that an increased HSI rate with increasing age can be associated with the players’ greater training age meaning a greater overall exposure to high intensity running that may include previous injuries which has been identified as a significant HSI risk factor (Ruddy et al., 2016). While age as a risk factor is non-modifiable, education and the exposure of athletes to proper condition methods and injury prevention measures at an early age can limit the effect that age has on HSI risk. Furthermore, correct monitoring of player load and controlled game/training time exposure can also suppress the effects of increased HSI risk as seen in many adolescent GAA players who are exposed to large volumes of load leading to injuries that are likely to become recurrent in later years.

### 2.1.7 Modifiable Hamstring Injury Risk Factors

Several modifiable risk factors have been identified and proposed to precede HSI’s according to Liu et al. (2012); these include shortened optimum muscle length, lack of muscle flexibility and strength imbalances between right and left limbs. Shortened optimum muscle length and lack of muscle flexibility have been shown to improve through the use of an eccentric hamstring loading program according to McHugh et al. (2014). It is important that these modifiable risk factors can be objectively measured in order to determine if they are successfully manipulated through hamstring strength and/or flexibility training. One must also consider that there are other modifiable risk factors for HSI; some of which can be manipulated through manual therapy such as poor lumbar posture and anterior pelvic tilt.

*Strength Imbalances*

It has been hypothesised that an eccentric hamstring strength imbalance between the right and left limbs could be an influential factor that precedes a HSI Bourne et al. (2015). Eccentric strength has been shown to have a protective effect against HSIs due to the forceful eccentric contraction that occurs in the late swing phase of gait which has been cited as the most common mechanism of injury for HSIs (Thorborg, 2012). Seventy seven professional soccer players' were tested by Croisier (2004) for eccentric hamstring strength imbalances between the right and left limbs, injury occurrences were then recorded over a 9 month professional season. It was observed that in the presence of an eccentric hamstring strength imbalance (>10%) HSI was predicted to increase from 3% to 15% when compared with no eccentric hamstring strength imbalance (<10%) being present. Furthermore, Croisier et al. (2008) proposed that pre-season screening for hamstring strength weakness and imbalances was fundamental for identifying the potential risks of incurring a HSI. Eccentric knee flexor strength imbalances between right and left limbs of ≥15% and ≥20% were also observed by Bourne et al. (2015), correlating to an athlete being 2.4 and 3.4 times, respectively, more likely to suffer a HSI.

Strength imbalances between muscle groups such as the quadriceps to hamstring relationship may also predispose an athlete to HSIs. The quadriceps to hamstring strength ratio (Q:H ratio) is another commonly postulated predictor of HSIs. The importance of this ratio as a HIS risk factor has been supported in previous literature such as a systematic review on HSI risk factors by Freckleton and Pizzari (2013) but acknowledges that there is conflicting evidence to support the Q:H ratio being a significant risk factor. It is suggested in a systematic review by Foreman et al. (2006) that the reduced strength of the hamstrings may not produce enough eccentric force to adequately decelerate the extensor force generated by the quadriceps during knee extension in the late swing phase of gait. Given that this phase of gait is responsible for a high percentage of HSI it is reasonable to assume that the Q:H ratio may play a role in hamstring injuries as a H:Q ratio of <0.6 can increase susceptibility to HSI by 17 fold (Yeung et al., 2009). The Q:H ratio as a risk factor is often criticised as it is only detected during isokinetic testing which is deemed by many to be non-sport specific testing method (Arnason et al., 2008). The inclusion of the Q:H ratio as a risk factor is also limited as traditionally it has only considered concentric strength of the quadriceps and hamstrings. This means it can be argued that the Q:H ratio lacks specificity with regards to known hamstring injury mechanisms, which are predominantly linked to forceful eccentric contractions of the hamstring muscle group.

### *Angle of Peak torque*

Angle of peak torque for the hamstring muscle group is another modifiable risk factor that is often closely monitored as a factor that can predict HSI risk (Sconce et al., 2015). The optimum angle of peak torque achieved is approximately 30° of knee flexion which is important as this angle is closely associated with the late swing phase in the gait cycle; it is at this stage of gait that the hamstring muscle group experiences the greatest amount of eccentric force and so is the offending mechanism for many HSI (Liu et al., 2012). Hamstring strength at 30° also plays a key role in stabilisation of the knee joint and, in particular, prevents anterior translation of the tibia which is responsible for anterior cruciate ligament injuries (Ardern et al., 2010). It was proposed by Brockett et al. (2001) that eccentric loading of the hamstring muscle group can result in long term improvements to the angle of peak toque achieved during eccentric loading. Despite a lack of conclusive research that includes muscle flexibility as a significant risk factor, it is likely that flexibility does play a role through its involvement in other risk factors such as postural abnormalities and angle of peak torque.

### *Hamstring Muscle Flexibility*

Flexibility is often debated with no clear consensus of whether it has a significant influence on injury susceptibility. It is believed that generally poor lower limb flexibility can predispose an athlete to a lower limb soft tissue injury with a lower stretch tolerance (ST) from the hamstring muscle group being cited as a significant risk factor for HSI (Mackey et al., 2011). Flexibility as an injury risk factor was investigated by Witvrouw et al. (2003) who discovered that there was a significant (P=0.02) relationship between poor hamstring flexibility and hamstring strain injuries in a group of 146 male professional soccer players. These findings are in contrast with previous research such as a cohort study by Arnason et al. (2008) and a systematic review by Freckleton and Pizzari (2013) who both stated that flexibility has not been proven to be a significant risk factor for HSI but acknowledged that further specific research of the topic is needed. Although there has been no conclusive evidence to include hamstring flexibility as a significant risk factor it can be argued that muscle flexibility directly influences other known risk factors such as optimum muscle length and postural abnormalities e.g. anterior pelvic tilt. Therefore, hamstring muscle flexibility is still an injury risk factor that must be monitored and can easily be modified.

### *Lumbar Spine Posture and Anterior Pelvic Tilt*

Postural abnormalities such as excessive lumbar lordosis and an associated anterior pelvic tilt may have major anatomical implications on the hamstring muscle group due to their attachment at the ischial tuberosity. The anterior tilt of the pelvis causes the hamstrings to operate at longer muscle lengths before hip flexion or knee extension add to this elongation of the muscle making it susceptible to injury at long muscle lengths. Postural abnormalities such as anterior pelvic tilt affect the length-tension of agonist/antagonist muscle groups which compromises optimal muscle length and flexibility. The relationship between these postural changes and hamstring injuries has been reported by Hennessey and Watson (1993) to be significant (P=0.01). The study observed accentuated lumbar lordosis and anterior pelvic tilt in subjects with hamstring injuries when compared to the uninjured control group. While posture is commonly postulated as an injury risk factor there are few studies that look at the correlation between posture and HSI. As these postural changes in the pelvis usually involve the excessive dominance of the quadriceps muscle group over the hamstring muscle group, it can be hypothesised that adequate condition for the hamstring muscle group is not being implemented to cope with the physical demands of sport where the quadriceps muscle group undergo more forceful contractions with greater loads than that experienced by the hamstring muscle group.

### *Weekly Running Volume Exposure*

High-speed running has been cited as the most common injury mechanisms for HSIs (Askling et al., 2007). Kinematic functions that occur during high-speed running, such as muscles reaching peak lengths and maximum force combined with the high accumulation of forceful eccentric contractions, may lead to injury of the contractile unit (Schache et al., 2012, Yu et al., 2008). It has been suggested the hamstring injury risk ratio significantly increases in subsequent weeks following an acute increase in running exposure when compared to an athlete's average weekly running exposure (Ruddy et al., 2016). The findings of the study by Ruddy et al. (2016) are in keeping with concept of high acute-chronic workload ratios leading to increased injury susceptibility as proposed by Malone et al. (2016) and Gabbett

(2016). Running exposure is only a significant risk factor when it is implemented as a training error and therefore can easily be prevented through correct conditioning and periodisation.

### 2.1.8 Hamstring Conditioning & Injury Prevention

The exact phase of gait at which HSIs most commonly occur and how to prevent these injuries are topics that are still debated in the literature with contrasting evidence that supports concentric, isometric and eccentric hamstring conditioning (Van Hooren and Bosch, 2016, Petersen et al., 2011, Farthing and Chilibeck, 2003). Although hamstring conditioning commonly involves a multi-faceted approach that incorporates a variety of contraction type exercises, that vast majority of research into hamstring conditioning is based on the physiological and practical benefits of eccentric conditioning (Al Attar et al., 2016, Timmins et al., 2016, Bourne et al., 2016a, Bourne et al., 2016b).

*Hamstring Conditioning*

As previously discussed, the most commonly cited mechanism for HSIs is eccentric loading of the hamstrings during the late swing phase of gait (Yu et al., 2017). This had led to the primary focus of HSI prevention strategies being based on eccentric conditioning methods and their effect in reducing HSIs. The preventative effect of eccentric hamstring conditioning on HSI occurrence has been investigated through randomised control trials (RCTs) that have tested thousands of athletes in a variety of sports (Petersen et al., 2011). Soccer, with its' progressively worsening HSI incidence rates, has been commonly used to observe the effects of eccentric training on these HSI incidence rates. The findings of one of the largest ever RCTs on the effects of eccentric hamstring conditioning, in 592 soccer players, reported a 72% reduction in HSIs in the intervention group after 13 weeks of eccentric hamstring conditioning (van der Horst et al., 2015). These studies are of a high standard but were heavily reliant on compliance to the program by the participating football clubs limiting the amount of usable data obtained from the research. Almost identical results were observed by Petersen et al. (2011), whose study included 942 soccer players and involved a 10 week eccentric hamstring conditioning program, with a 70% reduction in HSIs observed in the intervention group. This finding is further supported by Al Attar et al. (2016) who observed a

50% reduction in HSI occurrence in soccer players whose injury prevention program included eccentric hamstring conditioning when compared to the control group. Amidst the ongoing discussion over exact injury mechanisms and conditioning approaches in the literature, there is a strong body of evidence advocating and justifying the inclusion of eccentric conditioning in injury prevention programs means that eccentric hamstring strength, as previously proposed, is an essential element in reducing the incidence of non-contact HSIs.

As proposed by Thorborg (2012), hamstring eccentrics are indeed hamstring essentials when reducing HSI incidence rates. Practically, eccentric conditioning increases the gross strength of the hamstring muscle group thus addressing the risk factor of gross eccentric hamstring weakness and preventing hamstring fatigue that can increase HSI risk (Greig and Siegler, 2009). Eccentric conditioning has also been proposed to increase flexibility of the hamstring muscle group, another consideration for injury risk (McHugh et al., 2014). While increased eccentric strength is an important effect of eccentric conditioning, it is believed that changes in optimal angle of force production by the hamstring muscle group is a vital physiological adaptation to this type of conditioning that leads to a reduced risk of HSI (Willisch et al., 2015, Brockett et al., 2001).

It is believed that beneficial changes to the individual muscle fibres and overall muscle structure are observed as a result of eccentric hamstring conditioning. The physiological adaptations that lead to this increase in optimal hamstring length have been investigated at muscle fibre level by Timmins et al. (2016) and Guex et al. (2016a). The research into these physiological adaptations has observed the structural characteristics of the muscle that affect muscle force production. These adaptations include muscle thickness, fascicle length and pennation angle of the muscle fibres as proposed by Blazevich et al. (2007) who observed the structural response of the architectural muscle structures to loading and stress. While Blazevich et al. (2007) observed these structural changes in quadriceps muscles resulting from concentric and eccentric loading, it formed the basis of recent research by Timmins et al. (2016) who investigated these effects in hamstring muscle following eccentric loading using a functional MRI system. It was observed that eccentric loading has a beneficial effect on the architecture of the biceps femoris long head (LH) muscle by significantly increasing muscle fascicle length and reducing pennation angle.

These architectural changes lead to an increase in muscle optimum length for force production and directly reducing injury risk. These findings are supported by Guex et al. (2016a) who observed similar significantly beneficial effects to the biceps femoris LH muscle using ultrasound diagnostics following eccentric conditioning at long lengths when compared to the same conditioning at shorter muscle lengths. Both authors respectively investigated the architectural changes to the biceps femoris LH muscle as it is responsible for 80% of all hamstring injuries. These findings put further emphasis on the importance of including eccentric condition in HSI prevention programs. It is also important to note, as reported by Timmins et al. (2016), that although these beneficial effects are developed in a relatively short period (4 weeks) the detraining effects were observed to return to pre-intervention levels after just 28 days. This finding expresses the importance of maintaining theses effects through regular eccentric conditioning.

The architectural and physiological benefits of eccentric hamstring training are clearly supported in the literature to contribute to a reduction in HSI risk. All of these effects compound to ultimately increase the eccentric contractile strength of the hamstring muscle group. Increased eccentric hamstring strength has been cited as a significant factor in improving performance and also reducing non-contact ACL injuries (Zebis et al., 2015, Alentorn-Geli et al., 2009, Clark et al., 2005).

The various methods of eccentric conditioning differed in their biomechanical relevance to common injury mechanism. Hip dominant exercises such as the Romanian Deadlift (Farthing and Chilibeck, 2003) only involved eccentric hip flexion while the knee joint is kept in extension did not accurately replicate the eccentric demands place on the knee joint during high-speed running and did not result in as effective strength gains and injury reduction rates as the knee dominant exercise such as the NHE utilised by van der Horst et al. (2015).

### *Hamstring Injury Prevention*

Development and implementation of effective HSI management and prevention strategies are crucial to prevent injury from impacting players' availability to play and the financial burden on clubs.

The development of effective HSI prevention strategies has been widely investigated through clinical trials such as van der Horst et al. (2015) and Al Attar et al. (2016) who have concurrently reported that there are significant preventative effects resulting from the utilisation of eccentric hamstring exercises such the Nordic hamstring exercise. Significant clinical trials such as these are, in essence, redundant if these preventative exercises are not adopted and implemented by medical and coaching staff. As shown by Bahr et al. (2015), despite significant clinical trials that support the implementation of the Nordic Hamstring exercise, the majority of Champions league teams are not using the exercise in their HSI prevention practices. This insinuates that a major challenge in reducing HSI incidence and recurrence could be to try and educate coaching staff to use evidence-based practice and dedicate sufficient time and resources to regular injury prevention strategy development. Further research supporting the NHE as an effective intervention to reduce HSIs may contribute to greater adoption of the exercise by coaches in a variety of sports.

### 2.1.9 Exercise Selection for Eccentric Hamstring Conditioning & Rehabilitation

Traditionally, hamstring rehabilitation has been based on the concept of initially introducing isometric contractions until they can be performed free of pain and then progressing to concentric contraction type exercises with the end goal being eccentric contraction type exercises. This concept has been proven to be inefficient and less effective than modern approaches that introduce eccentric loading early in the rehabilitation program (Hickey et al., 2016, Brukner, 2015, Askling et al., 2014). It has been reported by Hickey et al. (2016) that progressing HSI rehabilitation programs based on pain free isometric contractions can lead to an elongated return to play time. The author observed that pain during isometric contractions can often be slow to resolve whilst the athlete can often tolerate eccentric loading despite not being pain free during isometric contractions. Based on the observations made by Hickey et al. (2016) it is suggested that HSI rehabilitation programs should be progressed based on the athlete’s tolerance to loading exercises rather than pain on clinical tests. As previously discussed, the benefits of eccentric conditioning include increased eccentric strength, increased fascicle length and a reduced pennation angle in hamstring muscle fibres. Introducing eccentric conditioning early in the rehabilitation process allows the injured hamstring muscle to gain increased exposure to eccentric loading which has been proven to reduce HSIs (van der Horst et al., 2015). The early utilisation and gradual progression of eccentric hamstring conditioning leads to improved HSI risk factors such as eccentric hamstring strength and muscle fascicle length, both of which facilitate a favourable shift toward an optimal stress strain ratio for the muscle.

A variety of eccentric hamstring conditioning exercises and programs have been implemented with the aim to increase eccentric hamstring strength and reduce HSI occurrence and recurrence. However, one exercise in particular has been strongly supported in the literature as being the most effective and accessible eccentric hamstring conditioning exercise. This exercise is the Nordic Hamstring Exercise and it has been shown to be extremely effective in reducing HSI occurrence (Al Attar et al., 2016, van der Horst et al., 2015, Thorborg, 2012, Petersen et al., 2011). The preventative effects of the NHE have been reported to range from a 40% to a 60% reduction in HSI occurrence and a further 70% reduction in HSI recurrences (Al Attar et al., 2016, van der Horst et al., 2015). The Nordic hamstring exercise is deemed to be a sport specific strength exercise as it allows eccentric knee flexor strength to be developed in a positon, and at muscle lengths similar to the common injury mechanism of terminal knee extension that occurs just prior to heel strike (Iga et al., 2012). The NHE has also been reported to have beneficial effects on hamstring muscle flexibility and angle of peak torque (McHugh et al., 2014) which, it can be hypothesised, result from the adaptations to eccentric exercise observed in the muscle fascicles as proposed by Timmins (2016).  While the NHE exercise has been widely accepted as an effective method of reducing HSI occurrence, annual increases in HSI incidence rates (Ekstrand et al., 2016) have led to the effectiveness of the NHE being questioned. However, research by Bahr et al. (2015) into the implementation of the NHE in injury prevention practices has shown that despite strong clinical evidence advocating the use of the NHE, the majority (83.3%) of professional football teams do not utilise the NHE as a tool to reduce HSIs. One of the most common anecdotal reasons cited for noncompliance is the delayed onset of muscular soreness (DOMS) experienced following the NHE and the volume of exercises prescribed to be completed. While this effect is only a temporary adaptation to eccentric loading, it is a factor that could limit the uptake of the NHE particularly when an athlete has a history of HSIs and may be overly cautious or fearful when experiencing any hamstring soreness or tightness. The key to improving uptake of the NHE is education for both coaching staff and athletes along with reassurance of athlete by supervising the NHE until they have gained confidence in the exercise. New research emerging from Presland et al. (2017) suggests that there is a solution to this issue of muscle soreness by proposing a NHE program that requires less repetitions and lower session frequency while still observing similar benefits when compared to more heavily loaded programs such as that of van der Horst et al. (2015). If this research can improve the uptake of the NHE in HSI prevention strategies then, based on the current research, a significant reduction in HSI occurrence rates may be observed in the future.

While the NHE has been shown to be a highly effective means of improving eccentric hamstring strength there are other considerations that must be taken into account when selecting an exercise to improve eccentric strength. One such consideration is the individual muscle recruitment patterns associated with the exercise that is being used. The influence of exercise selection on individual hamstring muscle recruitment patterns has been investigated by Bourne et al. (2016b) who observed that eccentric hip extension exercises selectively activated the long hamstring muscles such as biceps femoris LH while knee dominant eccentric exercises such as the NHE selectively recruited the semitendinosus. This has implications when the goal of the eccentric training is to target a specific hamstring muscle such as addressing atrophy of the semitendinosus following a hamstring graft ACL repair (Ardern et al., 2010) or seeking to achieve hypertrophy in the biceps femoris muscle following a HSI (Opar et al., 2015). Despite the findings indicating that eccentric hip extension has greater selective recruitment of the biceps femoris LH, which is responsible for up to 80% of HSIs, it is important to note that despite the biceps femoris LH not being selectively recruited during the NHE, the study observed that it still experienced its greatest amount of overall load during the NHE. This indicates that exercise-based selective recruitment of the individual hamstring muscles is beneficial when the goal is to isolate the effects of conditioning to that muscle but, as supported by the literature, the NHE remains the most effective means of eccentrically loading the collective hamstring muscle group simultaneously (Schuermans et al., 2014).

While the NHE has been widely accepted as an effective method of eccentrically strengthening the hamstring muscle group there are some limitations to the traditional uses of this exercise. The NHE is a double leg exercise that can be limited by limb dominance leading to unequal strength gains between the left and right limbs. This may be especially likely in athletes that may, through a residual weakness following a HSI (Opar et al., 2015), subconsciously avoid fully recruiting the previously injured limb putting it at risk of a recurrent HSI as. Traditionally this exercise has been utilised with no means of quantifying any limb dominance during repetitions of the NHE.

### 2.1.10 The Potential Benefits of Utilising a Pressure Feedback System in Eccentric Hamstring Conditioning

Between-limb imbalances are regarded as a significant risk factor as previously discussed and have major implications on HSI risk (Yeung et al., 2009). There are several sources of imbalance between the left and right limbs such as hamstring to quadriceps ratio, angle of peak torque, fascicle length and eccentric strength which have each been cited as factors that can potentially influence HSI risk (Fyfe et al., 2013). The main causes of these imbalances vary from natural limb dominance to residual structural and physiological deficits resulting from a previous HSI (Opar et al., 2015, Fyfe et al., 2013). The implications of between-limb eccentric hamstring strength imbalance is evident in research by (Bourne et al., 2015) who reported an 2.1 times increase in relative risk (RR) for professional rugby players with a 15% between-limb imbalance and a 3.2 times increase in RR when a between-limb imbalance of 20% was observed.

The development of a between-limb imbalance is most commonly as a result of limb dominance (Opar et al., 2015), limb dominance cannot be easily identified during conventional conditioning such as the NHE which may further compound the imbalance by unbalanced limb force distribution during these exercises. If greater loading is experienced by the dominant limb it may lead to greater strength adaptations, greater fascicle length adaptations and a greater improvement in pennation angle as proposed by Timmins et al. (2016) and Guex et al. (2016a). Another common source of between-limb strength deficits is based on the proposed theory by Fyfe et al. (2013) that there is neuromuscular inhibition in previously injured hamstrings leading to reduced capacity for adaptation to eccentric loading. With traditional conditioning methods being unable to identify this residual weakness an athlete may complete a full rehabilitation protocol and RTP with a significant between-limb imbalance leading to a heightened risk for HSI recurrence (Tol et al., 2014, Croisier et al., 2008). There are various lab based methods of quantifying imbalances such as isokinetic dynamometry, EMG monitoring and force plate technology but each of these methods is expensive and generally not accessible or convenient in a sporting environment.

The effects of these limb dominant strength adaptations and residual strength deficits may be reduced through appropriate eccentric training. In order for these imbalances to be addressed they must first be identified but access to isokinetic dynamometers is limited and expensive in the vast majority of sporting and clinical scenarios. After the deficits have been identified they must be closely and regularly monitored to determine if the training adaptations are correcting the imbalance.

Visual feedback such as that obtained through the use of the HSE has been proposed to improve performance in a variety of ways. With the addition of visual feedback the visual proprioceptive centres provide afferent information to the central nervous system (CNS) with regards to force output exerted by each limb. The neural input contributed by the visual receptors is then integrated by the CNS to trigger a motor response. The motor response to alter force distribution of each limb is then performed as a cognitively programmed response involving the motor cortex, basal ganglia and the cerebellum. The proprioceptive monitoring of force exertion by the muscle is controlled by co-activation of alpha-motor neurons and gamma motor neurons which constantly monitor muscle length and tension. The eccentric overload experienced by the muscle spindles is believed to have a postsynaptic excitatory effect on the spindle afferents. The stimulation of these alpha-motor neurons is then believed to elicit an increase in force production (Lephart et al., 1997).

Previous research by Kellis and Baltzopoulos (1996) explored the use of visual feedback in eccentric resistance exercise on an isokinetic dynamometer and observed significantly higher peak torque values for flexion and extension in their visual feedback group when compared to their non-visual feedback group. Visual feedback has also been used in real time monitoring of isometric strength training with research by Limonta et al. (2015)

showing that when their visual feedback stimulus was removed force accuracy was significantly reduced during subsequent isometric contractions.

### 2.1.11 Monitoring Hamstring Risk Factors

With the high incidence and recurrence rates of HSIs it is clear that there is an inherent complexity associated with HIS prevention strategies. This complexity is likely to be the result of multiple injury risk factors that can often coexist Liu et al. (2012). Practitioners strive to address the modifiable risk factors through various conditioning strategies such as the NHE (van der Horst et al., 2015). In order to determine if an injury prevention strategy is effective, it is vital that regular monitoring of risk factors is carried out to quantify and progress made.

As discussed previously, the most common methods of strength monitoring to date have been isokinetic dynamometry and handheld dynamometry. While previous methods of monitoring risk factors have provided important feedback to shape injury prevention practices, it is important that practitioners can determine the magnitude of improvement that leads to meaningful results.

The NHE has been shown to increase eccentric hamstring strength and, as a result, reduces HIS occurrence rates (Al Attar et al., 2016, van der Horst et al., 2015, Thorborg, 2012, Petersen et al., 2011) . However, the NHE does not address all HSI risk factors and in order to tackle the complexity of HSIs, a multi-variate approach must be implemented Liu et al. (2012). This present study proposes that the implementation of a pressure feedback system for eccentric conditioning such as the HSE could be used to increase eccentric hamstring strength and also address between-limb eccentric strength imbalances. The HSE has the potential to be used as a monitoring tool that ensures equal force distribution between both limbs during eccentric conditioning exercises such as the NHE. The utilisation of such a system may prevent strength adaptations from being biased towards the dominant limb while also providing live feedback to quantify any existing imbalances allowing the athlete to selectively recruit the weaker limb and illicit greater eccentric adaptations to reduce the deficit.

**Aims:**

(i) To determine if a progressively loaded 5 week NHE intervention results in significant ($P<0.05$) increases in eccentric hamstring peak torque, average peak torque and improves angle of peak torque.

(ii) To investigate the effects of a pressure feedback system on between-limb eccentric hamstring strength imbalances following a 5 week NHE intervention.

**Hypotheses:**

1. A 5 week progressively loaded NHE intervention significantly ($P<0.05$) increases eccentric hamstring peak torque, average peak torque and improves angle of peak torque.

2. Utilising a pressure feedback system to ensure equal force distribution will have a corrective effect on between-limb imbalances during a progressively loaded NHE intervention.

# 2.2 Methods

Table 3: PICO Study Characteristics

| PICO* Indicators | Results according PICO |
|---|---|
| **Design** | Clinical trials and observational studies (cohort and case-control designs) |
| **Population** | Participants (male collegiate field-sport athletes with a minimum of 12 months of lower-limb strength training experience) must be free of HIS for previous 3/12. |
| **Intervention** | Progressively loaded 5 week Nordic Hamstring Exercise program. |
| **Comparisons** | Using a pressure feedback system to assess limb-force distribution vs No feedback vs Control (No Eccentric Conditioning). |
| **Outcome measures** | Pre vs Post Intervention Peak Torque |
| | Pre vs Post Intervention Average Peak Torque |
| | Pre vs Post Intervention Angle of Peak Torque |
| | Pre vs Post Intervention Between-limb % Imbalances for each of the above Metrics. |

***** The PICO process (an acronym for patient problem or population (P), intervention (I), comparison (C) and outcome(s) (O)).

### 2.2.1 Participants

62 Participants (22±3 years of age, weighed 84.7±8.2Kg and 178.7±10.4cm in height) were recruited from the Soccer, Rugby and GAA teams in the Institute of Technology Carlow. The participants were experienced in lower limb strength training i.e., they took part in at least 2 lower limb strength sessions per week for the previous 12 months.. Each of the participants signed informed consent (Appendix A) and completed a thorough medical screening form (Appendix B) in the presence of the tester. Participants were informed that they were free to withdraw from testing at any stage, and to contact the tester should any concerns arise. The study and its associated procedures were approved by the Institute of Technology Carlow Ethics Committee.

### 2.2.2 Exclusion Criteria

Participants who had incurred a lower-limb injury in the 12 weeks previous to testing were excluded from the study. Participants were also excluded if their health screening form highlighted any health conditions that would contraindicate performing maximal strength testing. Participants with a history of low-back, hip or knee injuries were also excluded from the study.

### 2.2.3 Sample size

The required sample size was calculated by performing power calculations based on recommendations by Walter et al. 1998, and data from previous research papers that used similar measurement methods in comparable populations (Bourne et al., 2016a, Farthing and Chilibeck, 2003). To achieve an acceptable level of significance ($P<0.05$), *G*Power* sample calculation software determined that at least 19 participants were needed in each group for data analysis.

### 2.2.4 Procedures:

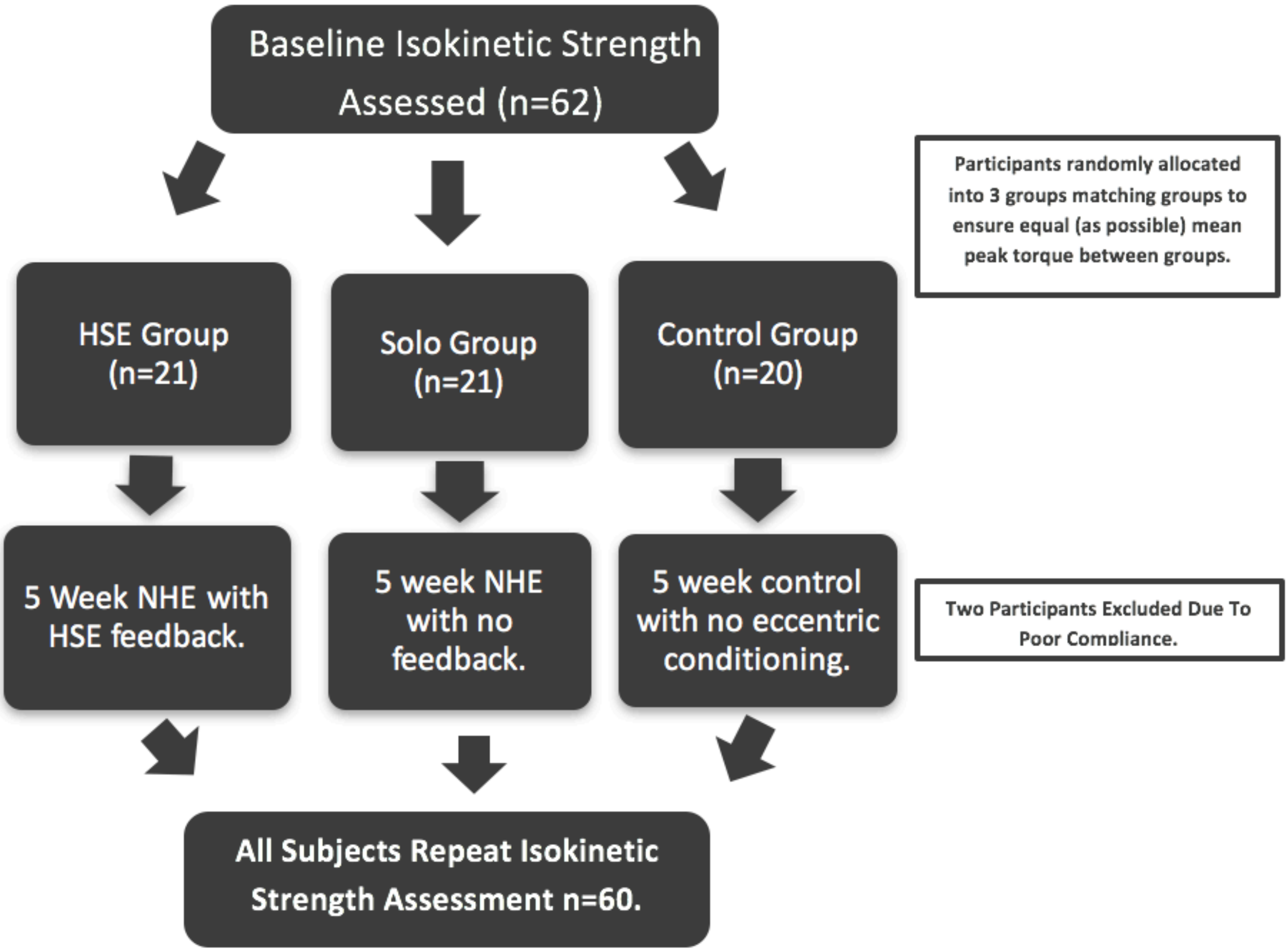

Figure 4: Flow Diagram of Data Collection Protocol.

The order in which the testing protocol was carried out is depicted in *Figure 4* above. All participants first attended a baseline eccentric strength measurement session where their eccentric hamstring strength was measured bilaterally using an isokinetic dynamometer (Biodex System3). The participants performed a generic 3 minute warm-up on a Watt-Bike Model B® at 60-80 rpm to increase lower limb blood flow and increase muscle temperature before commencing any strength assessment protocols. Data collection on the Biodex System 3 consisted of one set of 5 maximum eccentric knee flexion repetitions both at 30°/s and at 120°/s (Aagaard et al., 1995) for both legs individually. The participants were securely fixed to the device and performed 3 submaximal practice repetitions ensuring they were familiar with the nature of the test (See Figure 5). The participants were then instructed to perform a maximal knee flexion contraction against the extension force applied by the device until the isokinetic arm returned to the start position. Peak torque (Nm), Average Peak Torque (Nm), Angle of Peak Torque (°) and Between-Limb Strength Imbalances for both limbs was recorded for data analysis. Isokinetic data was only recorded if the coefficient of variance (CV) value was observed to be <15%. In the event of a participant displaying a CV value above 15%, the participant returned 48 hours later to be retested.

*Figure 5: Biodex System 3 eccentric knee flexion apparatus setup.*

The participants were divided into 3 strength matched groups and each group was assigned to one of three interventions. Participants were ranked in order of baseline Peak Torque divided equally into each group. For example the three strongest participants, following baseline measurements, were split and randomly assigned to one of the three interventions. This method was adopted to ensure that each group had similar pre-intervention strength levels preventing any bias of strength adaptations in a particular intervention group. The tester was present at all testing and strengthening sessions to ensure compliance was maintained and reinforce correct technique was being displayed by the participants. Compliance was aided by incorporating the NHE strength sessions into compulsory resistance training classes attended by the participants as part of their respective college degrees.

Group one was a control group who did not take part in any eccentric hamstring strength exercises during the 5 week intervention and were also instructed to remove any eccentric hamstring exercises from their regular gym activities for the duration of their intervention. A 5 week intervention was chosen as it was the longest availability period for the cohort being tested and significant eccentric strength increase have been report by McHugh et al., 2014, following 4 weeks of eccentric hamstring conditioning.

Group two took part in a 5 week progressively loaded Nordic Hamstring Exercise program using the HSE pressure feedback system (Figure 7) which was initiated within 7 days of baseline isokinetic testing. The participants performed a generic 3 minute warm-up on a Watt-Bike Model B® at 60-80 rpm to increase lower limb blood flow and increase muscle temperature before commencing any strength assessment protocols. The testing procedure on the Hamstring Solo Elite consisted of the performance of the assigned volume (Table 4) of Nordic hamstring exercise repetitions as slowly as possible. The participants were given visual (Figure 6) and detailed verbal coaching cues on performance technique before commencing.

Table 4: Progressively Loaded Nordic Hamstring Exercise Program.

| **Week 1** | **Week 2** | **Week 3** | **Week 4** | **Week 5** |
|---|---|---|---|---|
| One Session<br>(3 sets of 5 reps) | Two Sessions<br>(3 sets of 6 reps) | Two Sessions<br>(3 sets of 8 reps) | Two Sessions<br>(3 sets of 10 reps) | Two Sessions<br>(3 sets of 10 reps) |

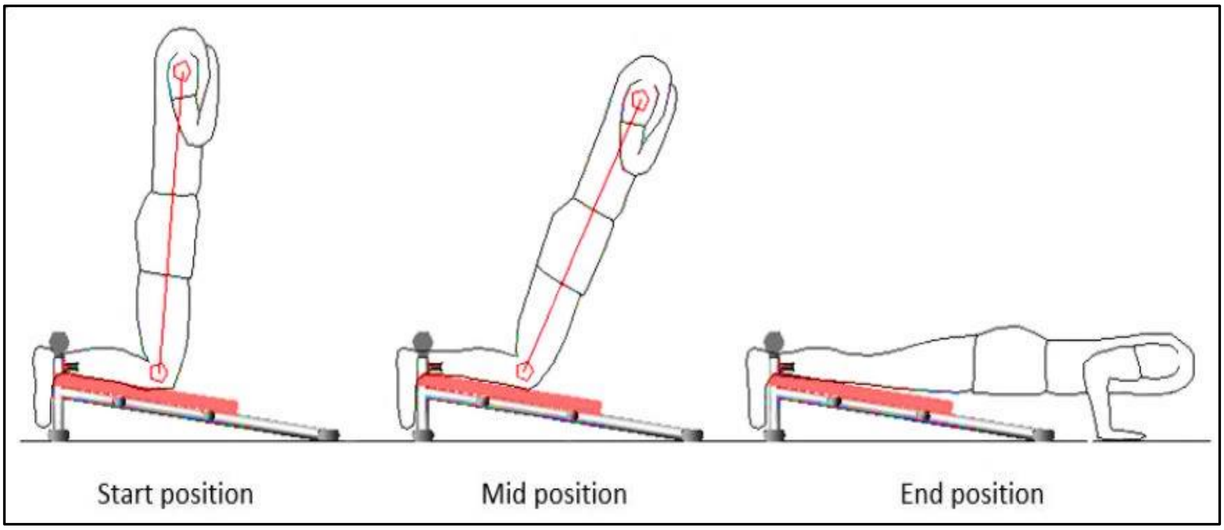

Figure 6: Graphical representation of Nordic hamstring exercise technique.

The participants were positioned in a kneeling position on the cushioned surface of the Hamstring Solo and with their ankles fixed beneath the load cells just superior to the medial and lateral malleoli. The ankle fixators were lowered against the participant's heels and this setting was consistent for each test. The participants were then instructed to "lower their torso as slowly as possible, while using the live feedback on the app provided to maintain even force distribution by both limbs (Figure 7), towards the ground until they could no longer sustain the eccentric hamstring contraction and land on their palms on the floor". The technique required the participants to maintain a straight line from the shoulder to the knee by minimising hip flexion and lumbar lordosis (to the best of their ability) during the repetitions.

Figure 7: Hamstring Solo Elite pressure feedback device.

Group 3 took part in a 5 week progressively loaded Nordic Hamstring Exercise program using the Hamstring Solo stationery device with no pressure feedback functions (Figure 8) which initiated within 7 days of baseline isokinetic testing. The participants performed a generic 3 minute warm-up on a Watt-Bike Model B® at 60-80 rpm to increase lower limb blood flow and increase muscle temperature before commencing any strength assessment protocols. The testing procedure on the Hamstring Solo Elite consisted of the performance of the assigned volume (Table 4) of Nordic hamstring exercise repetitions as slowly as possible. The participants were given visual (Figure 6) and detailed verbal coaching cues on performance technique before commencing.

The participants were positioned in a kneeling position on the cushioned surface of the Hamstring Solo and with their ankles fixed beneath the load cells just superior to the medial and lateral malleoli. The ankle fixators were lowered against the subject's heels and this setting was consistent for each test. The participants were then instructed to lower their torso as slowly as possible towards the ground until they could no longer sustain the eccentric hamstring contraction and land on their palms on the floor (Figure 6). The technique required the participants to maintain a straight line from the shoulder to the knee by minimising hip flexion and lumbar lordosis (to the best of their ability) during the repetitions. Following completion of each of the respective 5 week interventions, the three groups repeated the isokinetic eccentric strength protocol to determine any effect(s) that each of the interventions had on eccentric hamstring strength.

*Figure 8: Non-instrumented Hamstring Solo device.*

### 2.2.5 Statistical Analyses

Eccentric knee flexor peak toque (Nm), average peak torque (Nm) and angle of peak torque were recorded by the isokinetic device. The collected data was analysed to determine if there was a significant difference ($P<0.05$) between the control group and each of the respective interventions. The statistical analysis was performed using the IBM SPSS Statistics, version 22 (IBM, Armonk, NY, USA). The strength parameters mentioned above were normally distributed for each group meaning two-way ANOVA statistical tests were used to determine the main effects for time (pre vs post intervention) and group (Control, HSE, Solo). To determine observed effects, effect sizes ($\eta^2$) were calculated and interpreted using the Cohen d classification (0.01 = small effect, 0.06 = medium effect, 0.14 = large effect). Tukey's Post-Hoc tests were then carried out to determine where any significant differences occurred.

Between-limb imbalances for the above mentioned isokinetic measurements were also recorded by the isokinetic dynamometer. These imbalances showed high variability between participants and so were not normally distributed. In order to determine the magnitude of the effects, if any, that the pressure feedback device had on between-limb imbalances post-intervention, magnitude based inferences (MBIs) as proposed by Batterham and Hopkins (2006) were used for analysis.

The combination of a null hypothesis and magnitude based inferences statistical approach to examine different outcome measures within the study was in keeping with analysis carried out in studies such as Delaney et al. (2017) and Cockburn et al. (2010). The primary aim of the current study was to determine the effect that the pressure feedback system had on between-limb strength imbalances. This aim could not be addressed through the use of a null hypothesis as it doesn't give a practical inference for the effect observed from each intervention as MBIs do. MBIs allow the magnitude of an effect to be emphasised while also estimating precision which is in contrast to using an arbitrary p value to test a null hypothesis which focuses on absolute effect (Rowlands et al. 2008). As a result, null hypothesis testing does not emphasise the real world significance of an observed outcome that MBIs do (Batterham and Hopkins 2006).

# 2.3 Results

For the below results ANOVA tests were used to determine if the intervention had any significant effect on baseline eccentric peak torque, average peak torque and angle of peak torque. Combined values for the left and right hamstrings were used in the analysis of the above-mentioned parameters. The ANOVA tests analysed the mean strength measures between the left and right limbs to determine the overall strength changes, between the respective groups, for both limbs collectively. For between-limb imbalance analysis, Magnitude-Based Inferences (MBIs) were used to provide a quantitative and qualitative representation of any differences between pre and post-intervention imbalances. Each outcome measure is presented individually below.

### 2.3.1 Pre vs Post-Intervention Peak Torque

Baseline peak torque values for eccentric knee flexor strength at 30°/s were 178.75 ± 34.9 Nm, 190.1 ± 35.56 Nm and 172± 32.93 Nm for the Elite, Solo and Control groups respectively. Changes in peak torque at 30°/s can be seen in Figure 9 below. There was an observed main effect for time, with increased hamstring strength post intervention ($F_{5,98}$ = 8.85; $P <$ .004; $\eta^2$ 0.070). There was also an observed main effect for intervention group, with increased hamstring strength between groups ($F_{6,92}$ = 8.29; $P <$ .001; $\eta^2$ 0.123). Following Tukey post hoc analysis, significant differences between groups for increased peak torque were observed between the elite and control group (*P*=0.03) while the Solo group also displayed a significant increase in peak torque (*P*=0.01) when compared to the control group. No significant difference was observed between the Elite and Solo groups (*P*=0.37).

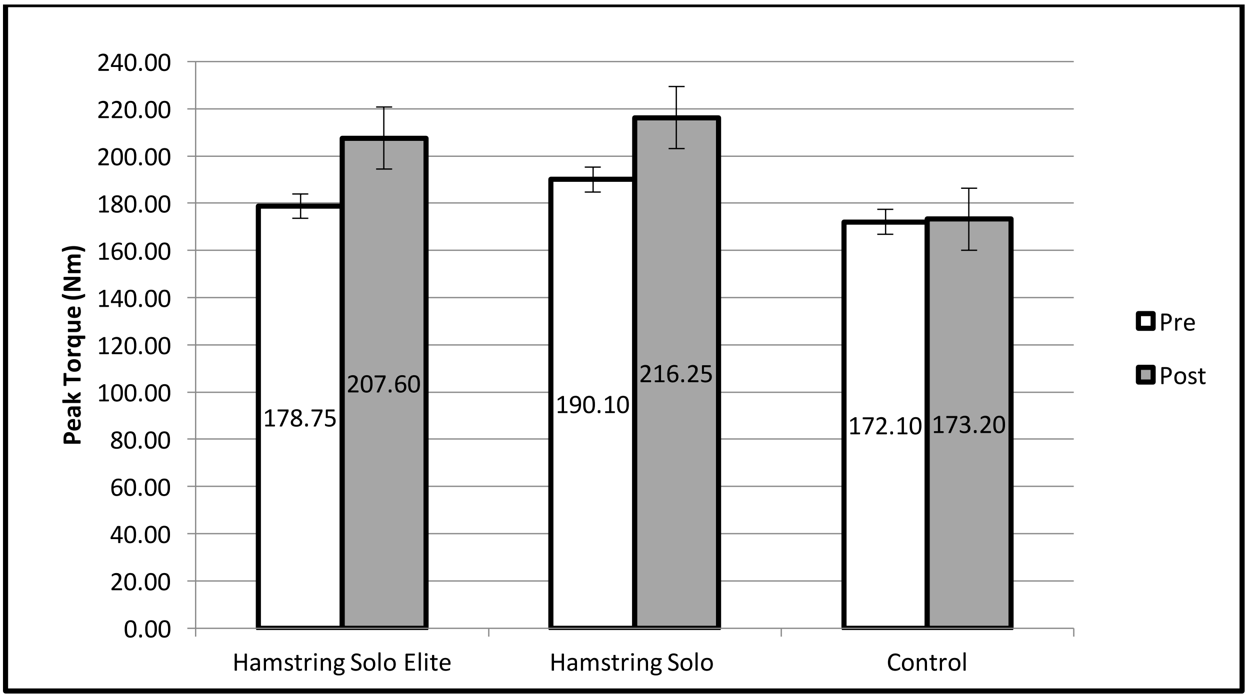

*Figure 9: Pre vs Post intervention isokinetic peak torque measurements at 30°/s (n=60).*

Baseline peak torque values for eccentric knee flexor strength at 120°/s were 184.1 ± 36.63 Nm, 200.68 ± 32.61 Nm and 184.43± 30.53 Nm for the Elite, Solo and Control groups respectively. Changes in peak torque at 120°/s can be seen in Figure 10. There was an observed main effect for time, with increased hamstring strength post intervention ($F_{5,78}$ = 8.79; $P < .004$; $\eta^2$ 0.069). There was also an observed main effect for intervention group, with increased hamstring strength between groups ($F_{5,82}$ = 6.54; $P < .002$; $\eta^2$ 0.140). Following Tukey post hoc analysis, significant (P<0.05) differences between groups for peak torque were observed between the elite and control group (*P*=0.04) while the Solo group also displayed a significant increase in peak torque (*P*=0.01) when compared to the control group. No significant difference was observed between the Elite and Solo groups (*P*=0.39).

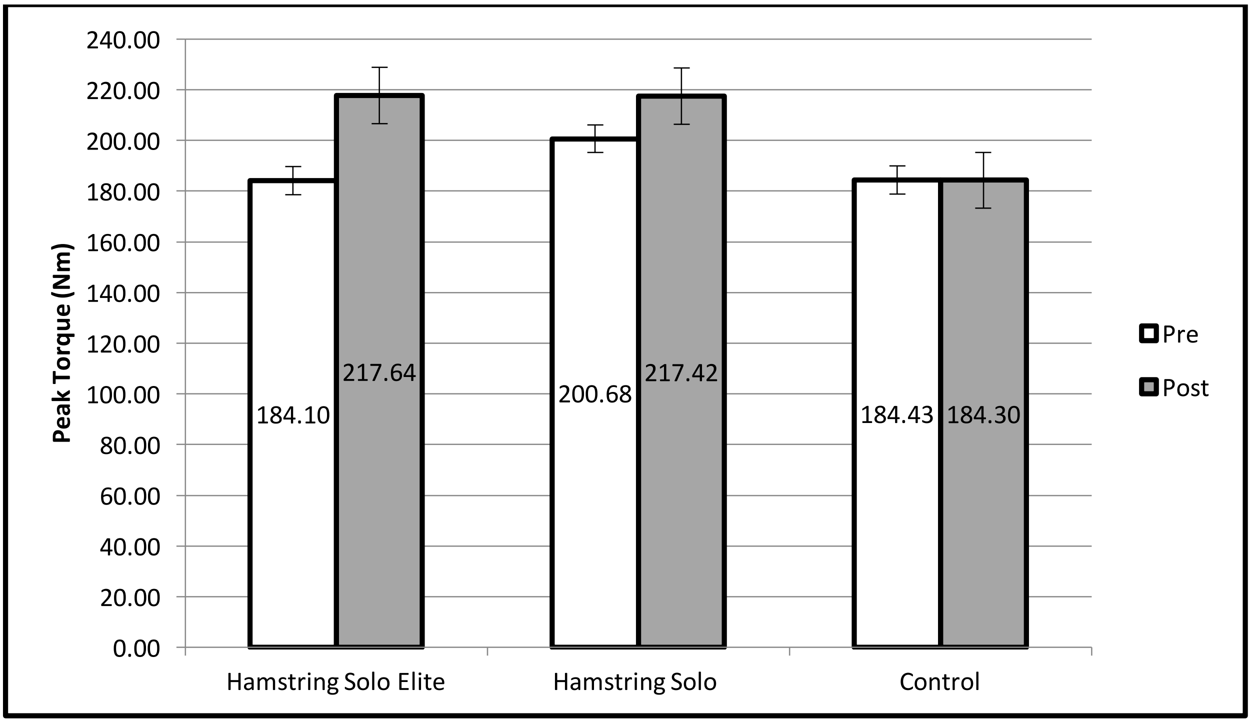

*Figure 10: Pre vs Post intervention isokinetic peak torque measurements at 120°/s (n=60).*

### 2.3.2 Pre vs Post-Intervention Average Peak Torque

Baseline average peak torque values for eccentric knee flexor strength at 30°/s were 161.1 ± 36.01 Nm, 174.19 ± 36.98 Nm and 158.55± 34.29 Nm for the Elite, Solo and Control groups respectively. Changes in average peak torque at 30°/s can be seen in Figure 11. There was an observed main effect for time, with increased hamstring strength post intervention ($F_{8,92}$ = 9.59; $P < .002$; $\eta^2$ 0.075). There was also an observed main effect for intervention group, with increased hamstring strength between groups ($F_{8,90}$ = 6.41; $P < .002$; $\eta^2$ 0.098). Following Tukey post hoc analysis, significant ($P<0.05$) differences between groups for average peak torque were observed between the elite and control group ($P$=0.04) while the Solo group also displayed a significant increase in average peak torque ($P$=0.01) when compared to the control group. No significant difference was observed between the Elite and Solo groups ($P$=0.40).

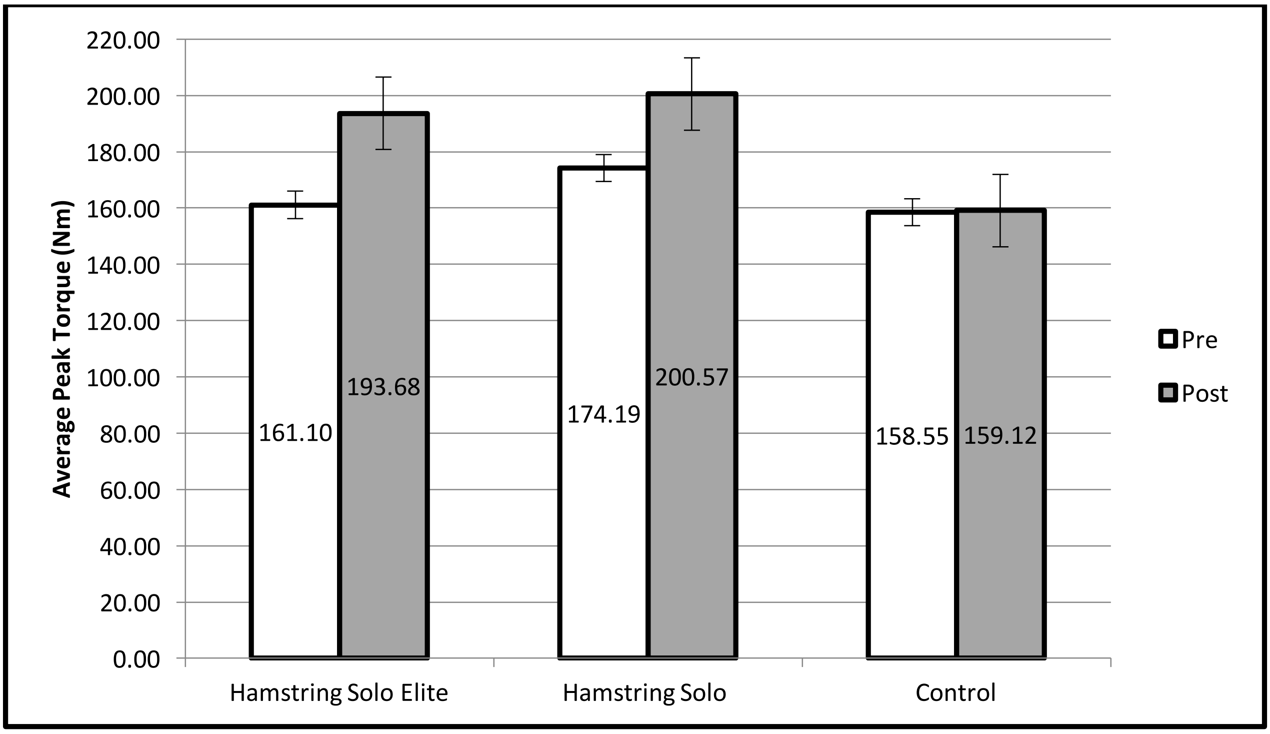

*Figure 11: Pre vs Post intervention isokinetic average peak torque measurements at 30°/s (n=60).*

Baseline average peak torque values for eccentric knee flexor strength at 120°/s were 166.7 ± 33.3 Nm, 183.95 ± 34.23 Nm and 166.63± 34.39 Nm for the Elite, Solo and Control groups respectively. Changes in average peak torque at 120°/s can be seen in Figure 12. There was an observed main effect for time, with increased hamstring strength post intervention ($F_{9,88} = 8.64$; $P < .003$; $\eta^2$ 0.078). There was also an observed main effect for intervention group, with increased hamstring strength between groups ($F_{8,82} = 7.84$; $P < .002$; $\eta^2$ 0.087). Following Tukey post hoc analysis, significant (P<0.05) differences between groups for average peak torque were observed between the elite and control group (*P*=0.04) while the Solo group also displayed a significant increase in average peak torque (*P*=0.02) when compared to the control group. No significant difference was observed between the Elite and Solo groups (*P*=0.49).

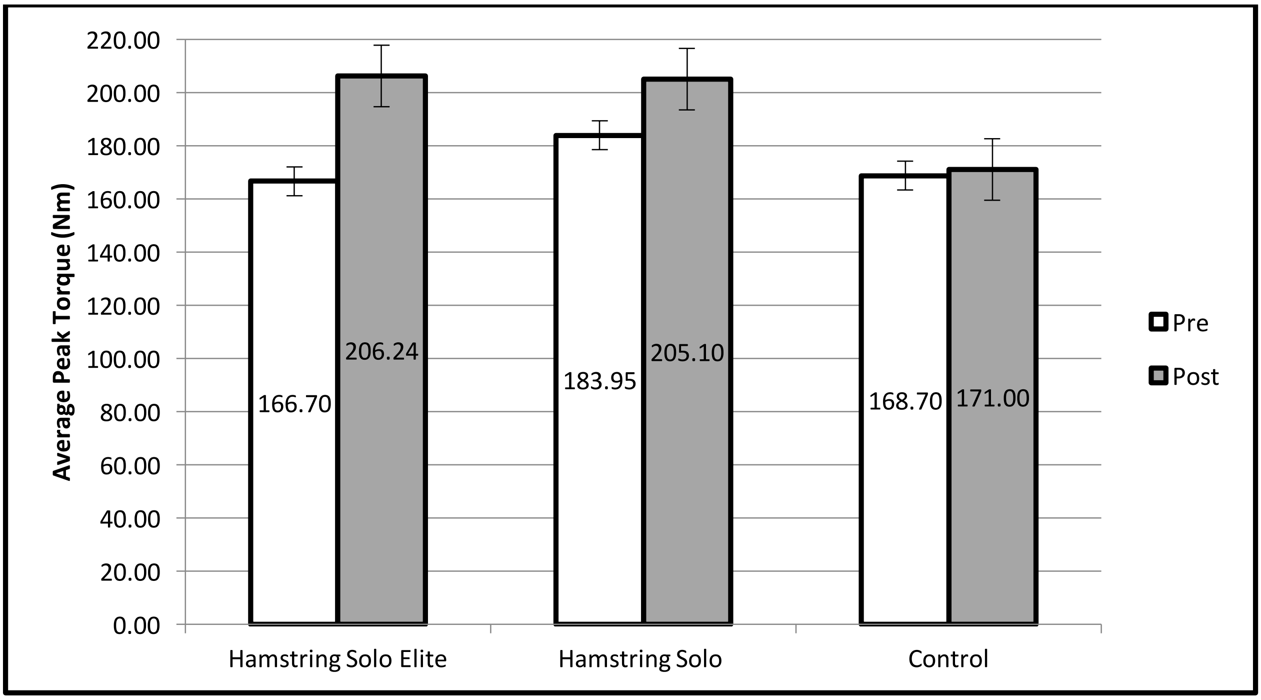

*Figure 12: Pre vs Post intervention isokinetic average peak torque measurements at 120°/s (n=60).*

### 2.3.3 Pre vs Post-Intervention Angle of Peak Torque

Baseline angle of peak torque values for eccentric knee flexor strength at 30°/s were 28.24 ± 8.12 degrees, 27.19 ± 8.54 degrees and 25.73± 8.1 degrees for the Elite, Solo and Control groups respectively. Changes in angle of peak torque at 30°/s can be seen in Figure 13. There was no observed main effect for time, with angle of peak torque post intervention ($F_{5,118}$ = 1.85; $P > .207$; $\eta^2$ 0.020). There was also no observed main effect for intervention group, with increased hamstring strength between groups ($F_{5,116}$ = 1.62; $P > .310$; $\eta^2$ 0.24). Following Tukey post hoc analysis, no significant differences between groups for increased angle peak torque were observed between the elite and control group ($P$=0.83) while the Solo group also displayed no statistically significant difference in angle of peak torque ($P$=0.93) when compared to the control group. No significant difference was also observed between the Elite and Solo groups ($P$=0.94).

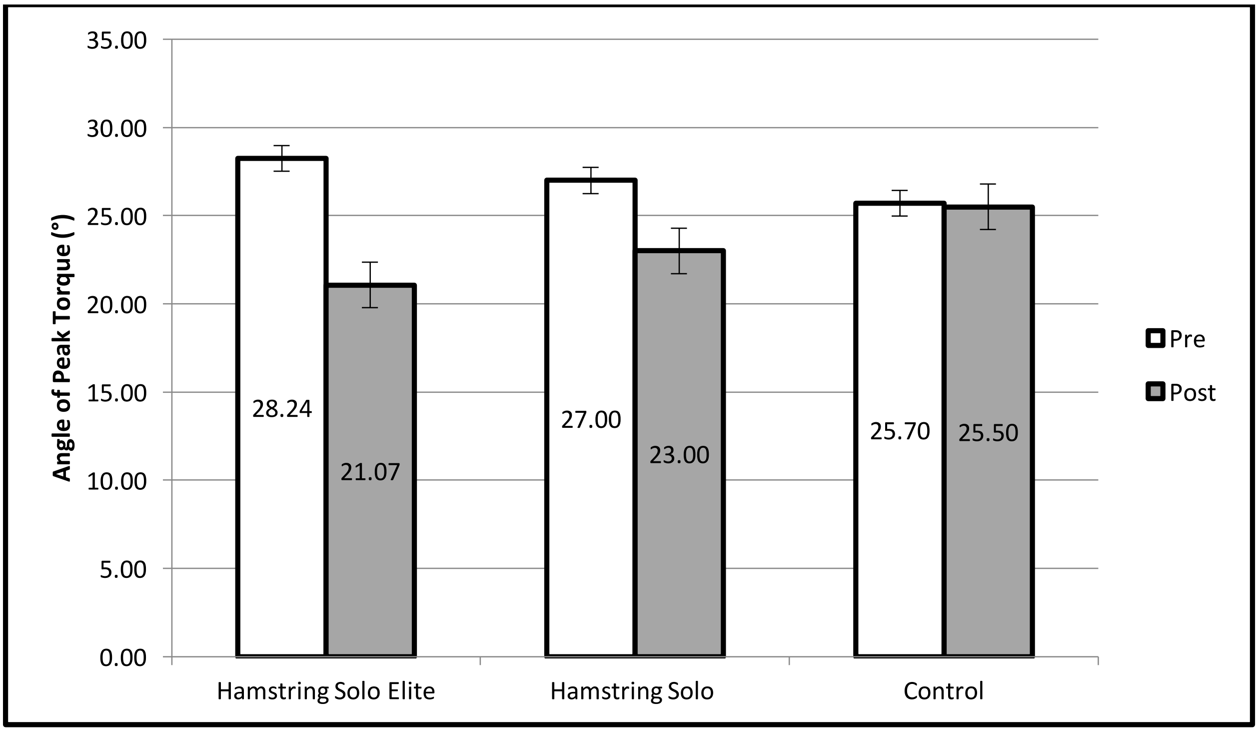

*Figure 13: Pre vs Post intervention isokinetic angle of peak torque measurements at 30°/s (n=60).*

Baseline angle of peak torque values for eccentric knee flexor strength at 120°/s were 30 ±7.7 degrees, 28.6 ±5.7 degrees and 27.7 ±6.5 degrees for the Elite, Solo and Control groups respectively. Changes in angle of peak torque at 120°/s can be seen in Figure 14. There was no observed main effect for time, with angle of peak torque post intervention ($F_{6,108}$ = 1.76; $P > .462$; $\eta^2$ 0.019). There was also no observed main effect for intervention group, with increased hamstring strength between groups ($F_{6,112}$ = 1.84; $P > .260$; $\eta^2$ 0.210). Following Tukey post hoc analysis, no significant differences between groups for increased angle peak torque were observed between the elite and control group (*P*=0.73) while the Solo group also displayed no statistically significant difference in angle of peak torque (*P*=0.96) when compared to the control group. No significant difference was also observed between the Elite and Solo groups (*P*=0.9).

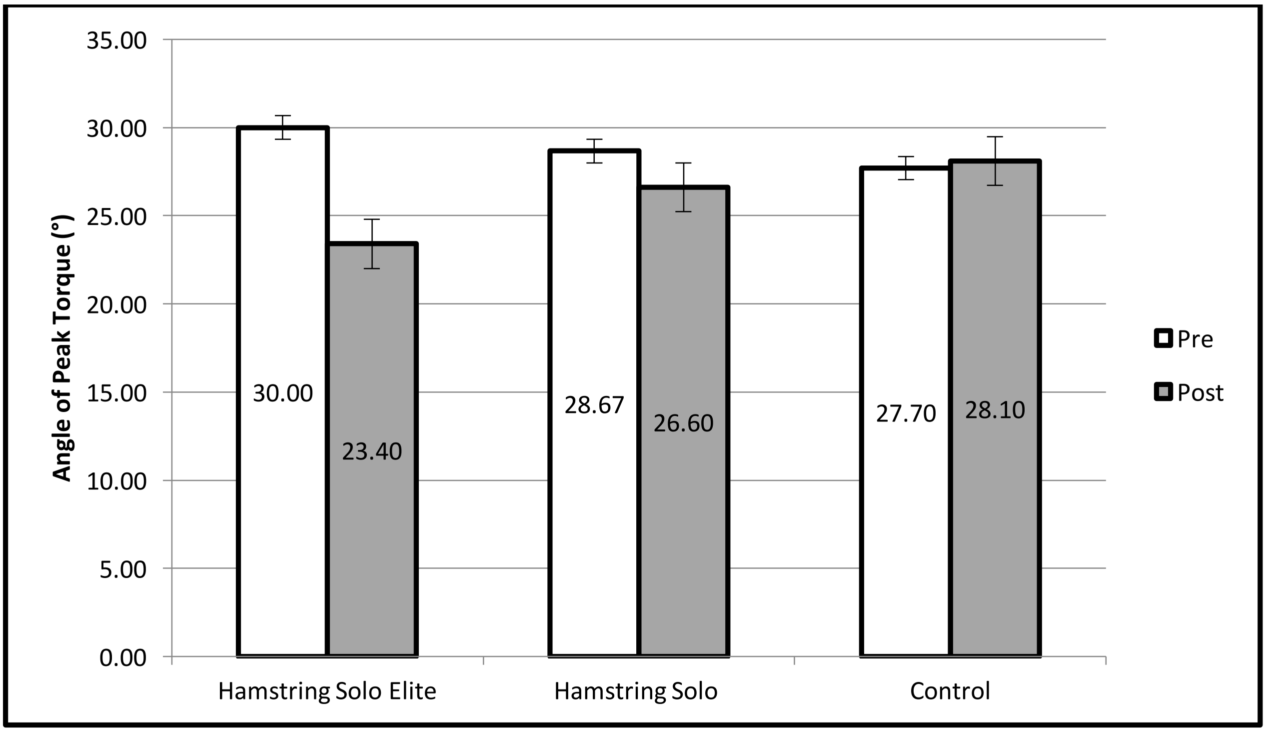

*Figure 14: Pre vs Post intervention isokinetic angle of peak torque measurements at 120°/s (n=60).*

### 2.3.4 Post-Intervention Effects on Peak Torque Between-Limb Imbalances

Peak torque between-limb percent imbalances at 30°/s can be seen in Figure 15 where the HSE demonstrates a considerable post-intervention reduction in between-limb imbalance when compared to the Solo and Control groups. MBIs, as displayed in Table 5, determined that the elite group had a most likely to be beneficial effect on between-limb imbalance when compared to the Solo group and Control group. The Solo group did not have any beneficial effect on between-limb imbalance.

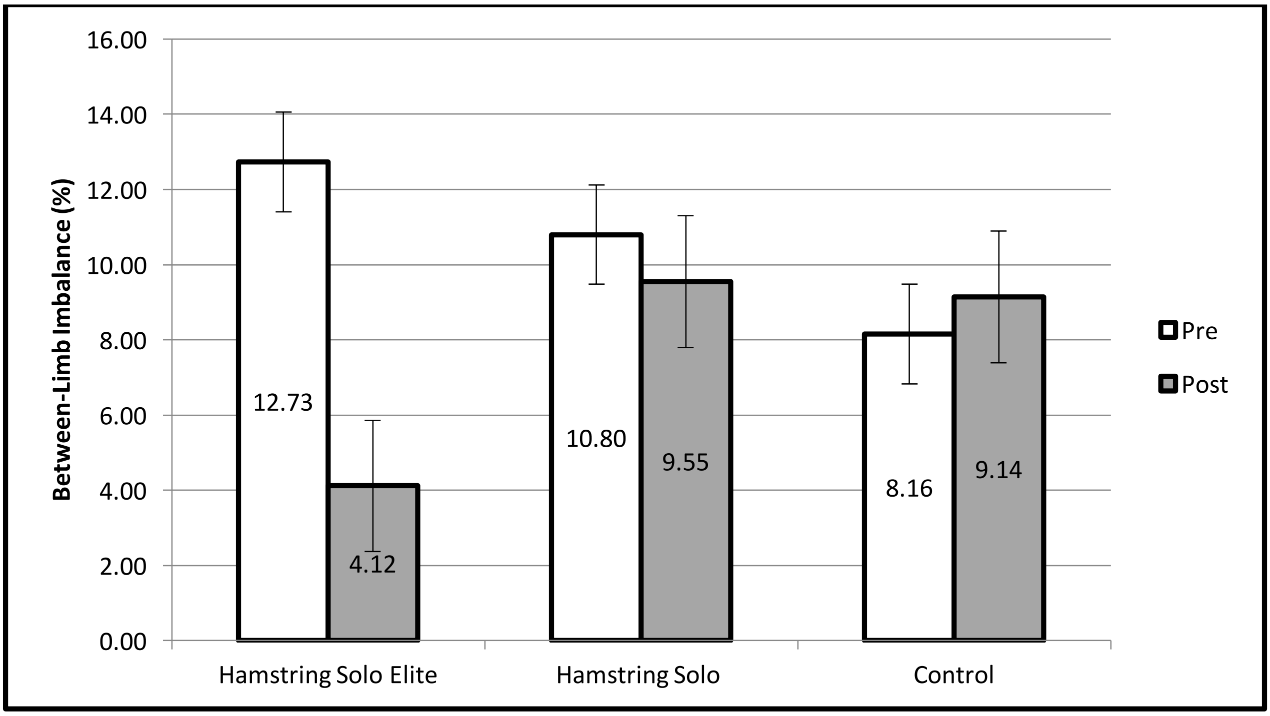

Figure 15: Pre vs Post intervention between-limb peak torque % imbalances at 30°/s (n=60).

*Table 5: Magnitude-Based Inferences for the effect of the respective interventions on between-limb isokinetic peak torque imbalances at 30°/s (n=60).*

| **Variable** | **Time Frame** | **Mean effect ± 90% CI**[a] | **Qualitative Inference**[b] |
|---|---|---|---|
| Elite vs Solo | Pre–Post | 77.9; ±11.8 | Most Likely beneficial |
| Elite vs Control | Pre–Post | 343.6; ±216.0 | Most Likely beneficial |
| Solo vs Control | Pre–Post | 2.2; ±61.1 | Trivial |

[a] *±90% CI: add and subtract this number to the mean effect to obtain the 90% confidence intervals for the true difference*

[b] *Qualitative Inference represents the likelihood that the true value will have the observed magnitude*

Peak torque between-limb percent imbalance at 120°/s can be seen in Figure 16 where the HSE demonstrates a considerable post-intervention reduction in between-limb imbalance when compared to the Solo and Control groups. MBIs, as displayed in Table 6, determined that the elite group had a very likely to be beneficial effect on between-limb imbalance when compared to the Solo group and Control group. The Solo group did not have any beneficial effect on between-limb imbalance.

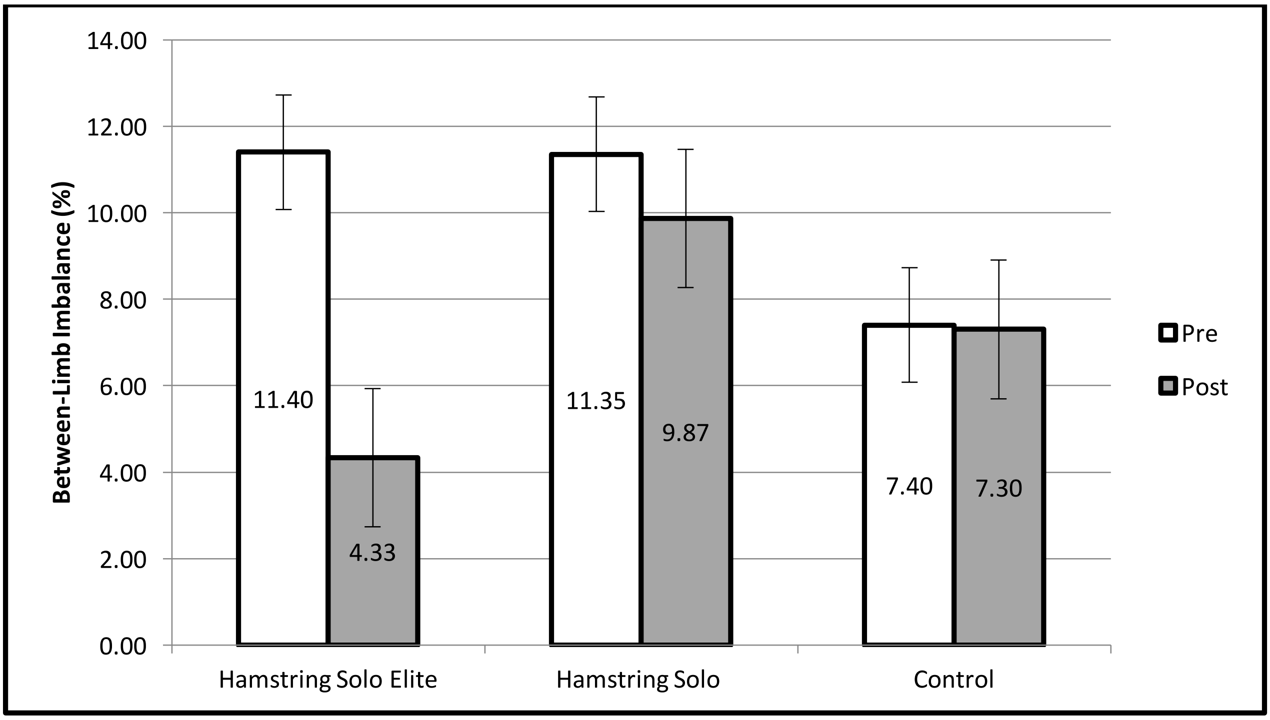

*Figure 16: Pre vs Post intervention between-limb peak torque % imbalances at 120°/s (n=60).*

Table 6: Magnitude-Based Inferences for the effect of the respective interventions on between-limb isokinetic peak torque imbalances at 120°/s (n=60).

| **Variable** | **Time Frame** | **Mean effect; ±90% CI**[a] | **Qualitative Inference**[b] |
|---|---|---|---|
| Elite vs Solo | Pre–Post | 54.0; ±24.0 | Very Likely beneficial |
| Elite vs Control | Pre–Post | 157.2; ±129.9 | Very Likely beneficial |
| Solo vs Control | Pre–Post | 18.4; ±50.2 | Trivial |

[a] *±90% CI: add and subtract this number to the mean effect to obtain the 90% confidence intervals for the true difference*

[b] *Qualitative Inference represents the likelihood that the true value will have the observed magnitude*

### 2.3.5 Post-Intervention Effects on Average Peak Torque Between-Limb Imbalances

Average peak torque between-limb percent imbalances at 30°/s can be seen in Figure 17, where the HSE demonstrates a considerable post-intervention reduction in between-limb imbalance when compared to the Solo and Control groups. MBIs, as displayed in Table 7, determined that the elite group had a very likely to be beneficial effect on between-limb imbalance when compared to the Solo group and a most likely to be beneficial effect compared to the Control group. The Solo group did not have any beneficial effect on between-limb imbalance.

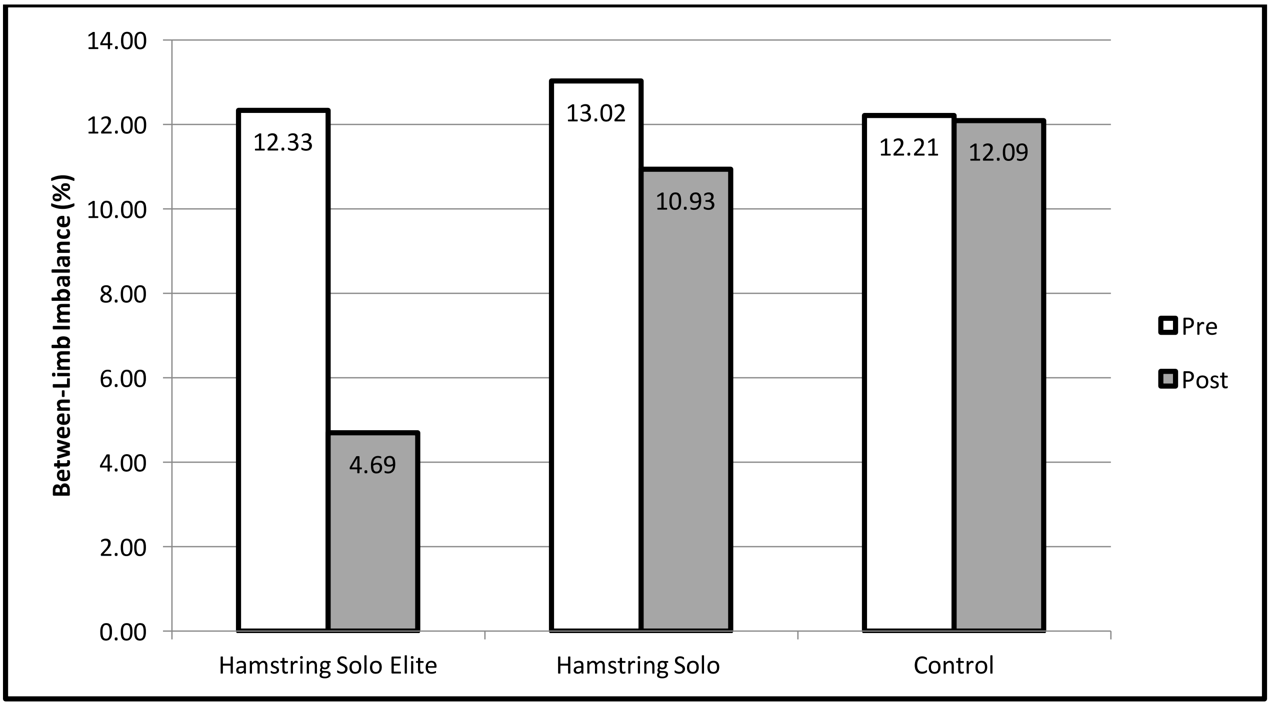

*Figure 17: Pre vs Post intervention between-limb average peak torque % imbalances at 30°/s (n=60).*

Table 7: Magnitude-Based Inferences for the effect of the respective interventions on between-limb isokinetic average peak torque imbalances at 30°/s (n=60).

| **Variable** | **Time Frame** | **Mean effect; ±90% CI**[a] | **Qualitative Inference**[b] |
|---|---|---|---|
| Elite vs Solo | Pre–Post | 61.5; ±18.6 | Very Likely beneficial |
| Elite vs Control | Pre–Post | 116.6; ±60.4 | Most Likely beneficial |
| Solo vs Control | Pre–Post | 16.7; ±34.3 | Trivial |

[a] *±90% CI: add and subtract this number to the mean effect to obtain the 90% confidence intervals for the true difference*

[b] *Qualitative Inference represents the likelihood that the true value will have the observed magnitude*

Average peak torque between-limb percent imbalances at 120°/s can be seen in Figure 18 where the HSE demonstrates a considerable post-intervention reduction in between-limb imbalance when compared to the Solo and Control groups. MBIs, as displayed in Table 8, determined that the elite group had a very likely to be beneficial effect on between-limb imbalance when compared to the Solo and Control groups. The Solo group did not have any beneficial effect on between-limb imbalance.

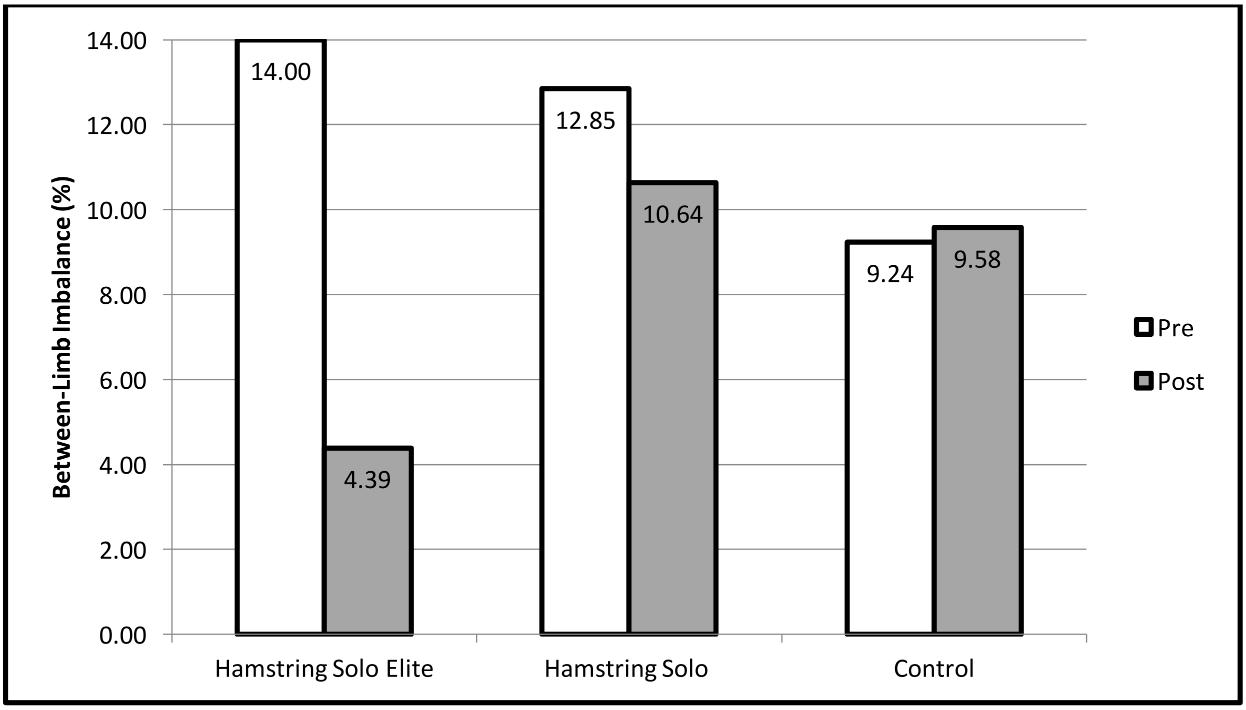

*Figure 18: Pre vs Post intervention between-limb average peak torque % imbalances at 120°/s (n=60).*

Table 8: Magnitude-Based Inferences for the effect of the respective interventions on between-limb isokinetic average peak torque imbalances at 120°/s (n=60).

| **Variable** | **Time Frame** | **Mean effect; ±90% CI**[a] | **Qualitative Inference**[b] |
|---|---|---|---|
| Elite vs Solo | Pre–Post | 56.3; ±18.0 | Most Likely beneficial |
| Elite vs Control | Pre–Post | 241.4; ±144.6 | Most Likely beneficial |
| Solo vs Control | Pre–Post | 49.2; ±58.6 | Possibly Harmful |

[a] *±90% CI: add and subtract this number to the mean effect to obtain the 90% confidence intervals for the true difference*
[b] *Qualitative Inference represents the likelihood that the true value will have the observed magnitude*

### 2.3.6 Post-Intervention Effects on Angle of Torque Between-Limb Imbalances

Angle of peak torque between-limb percent imbalances at 30°/s can be seen in Figure 19 where the HSE demonstrates a considerable post-intervention reduction in between-limb imbalance when compared to the Solo and Control groups. MBIs, as displayed in Table 9, determined that the elite group had a most likely to be beneficial effect on between-limb imbalance when compared to the Solo and Control groups. The Solo group did not have any beneficial effect on between-limb imbalance.

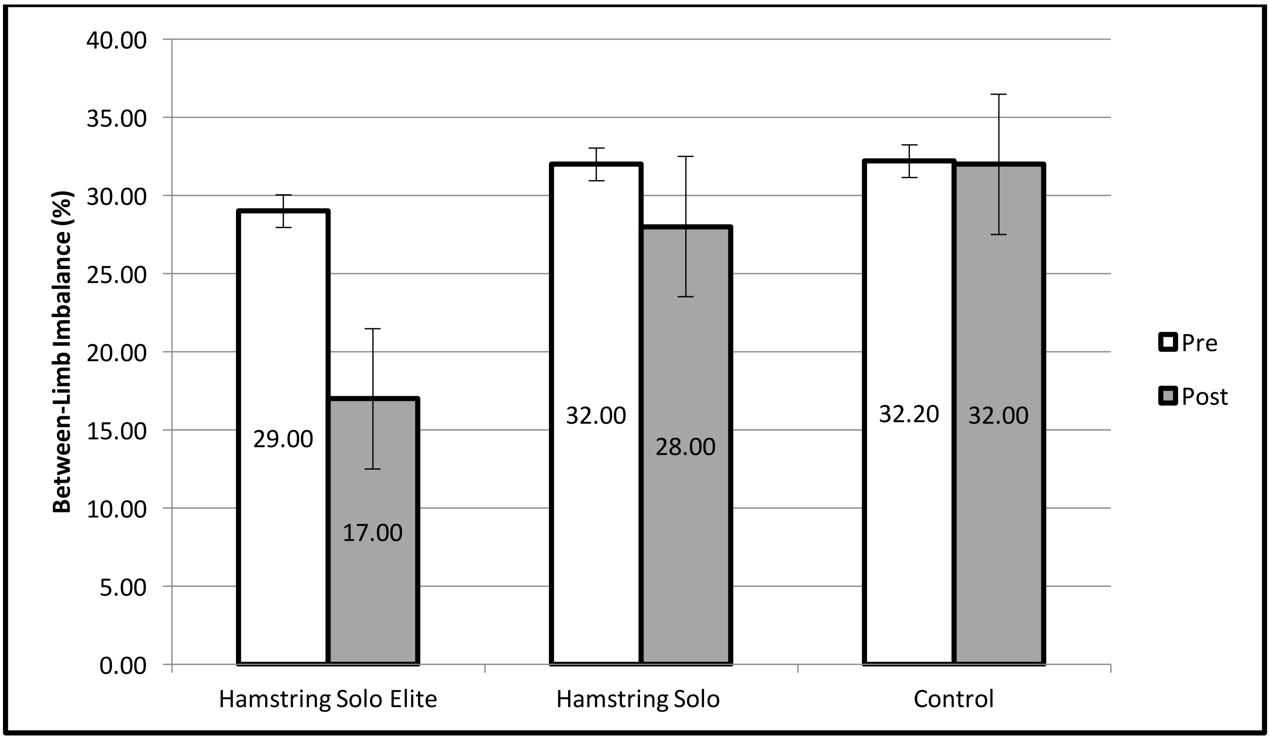

*Figure 19: Pre vs Post intervention between-limb angle of peak torque % imbalances at 30°/s (n=60).*

Table 9: Magnitude-Based Inferences for the effect of the respective interventions on between-limb isokinetic angle of peak torque imbalances at 30°/s (n=60).

| Variable | Time Frame | Mean effect; ±90% CI[a] | Qualitative Inference[b] |
|---|---|---|---|
| Elite vs Solo | Pre–Post | 75.1; ±12.7 | Most Likely beneficial |
| Elite vs Control | Pre–Post | 255.5; ±153.5 | Most Likely beneficial |
| Solo vs Control | Pre–Post | 11.5; ±26.9 | Trivial |

[a] *±90% CI: add and subtract this number to the mean effect to obtain the 90% confidence intervals for the true difference*

[b] *Qualitative Inference represents the likelihood that the true value will have the observed magnitude*

Angle of peak torque between-limb percent imbalances at 120°/s can be seen in Figure 20 where the HSE demonstrates a considerable post-intervention reduction in between-limb imbalance when compared to the Solo and Control groups. MBIs, as displayed in Table 8, determined that the elite group had a most likely to be beneficial effect on between-limb imbalance when compared to the Solo group and a very likely to be beneficial effect when compared to the Control group. The Solo group did not have any beneficial effect on between-limb imbalance.

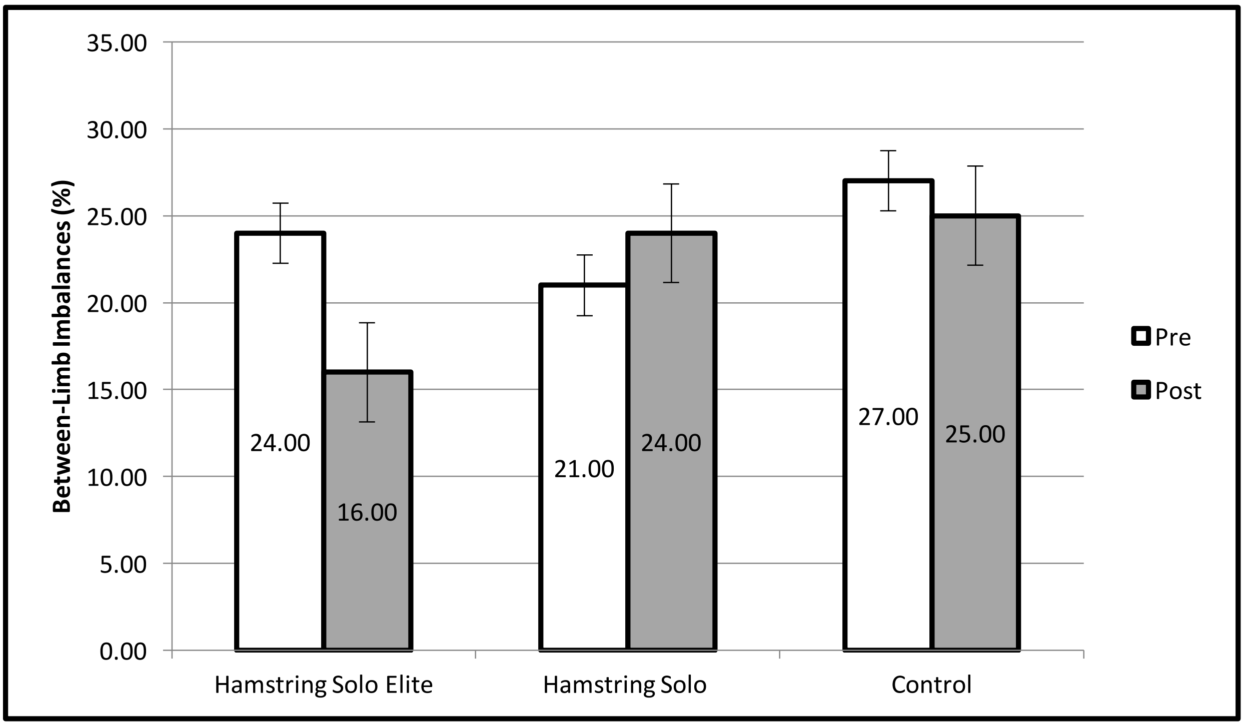

*Figure 20: Pre vs Post intervention between-limb angle of peak torque % imbalances at 120°/s (n=60).*

Table 10: Magnitude-Based Inferences for the effect of the respective interventions on between-limb isokinetic angle of peak torque imbalances at 120°/s (n=60).

| **Variable** | **Time Frame** | **Mean effect; ±90% CI**[a] | **Qualitative Inference**[b] |
|---|---|---|---|
| Elite vs Solo | Pre–Post | 52.2; ±15.0 | Most Likely beneficial |
| Elite vs Control | Pre–Post | 98.8; ±70.6 | Very Likely beneficial |
| Solo vs Control | Pre–Post | 12.1; ±12.2 | Trivial |

[a] *±90% CI: add and subtract this number to the mean effect to obtain the 90% confidence intervals for the true difference*

[b] *Qualitative Inference represents the likelihood that the true value will have the observed magnitude*

# 2.4 Discussion

The present research study examined the effects of the NHE, with and without pressure feedback, on eccentric hamstring peak torque, average peak torque and angle of peak torque including the potential effects each had on between-limb imbalances following a 5 week intervention. The results of the study show that performing the NHE for 5 weeks led to significant (16.2% and 18.2%) increases in eccentric hamstring peak torque, at speeds of 30°/s and 120°/s respectively, when the Elite group was compared with the Control group. Significant increases (13.8% and 8.4%) were also observed when the Solo group was compared to the Control group at both respective speeds. There was no significant difference between the peak torque increases observed in the Elite and Solo groups at either of the isokinetic speeds.

Similar findings were present with average peak torque increasing at both speeds. Average percentage strength gains of both limbs combined displays significant respective increases of 20.2% and 23.7% were observed between the Elite group and the Control group. Significant increases between the Solo group and Control group were observed as 15.1% and 11.5% respectively. Again, there was no significant difference between the average peak torque increases observed between the Elite and Solo groups.

The above results support the hypothesis that a pressure feedback system such as the HSE is effective at reducing between-limb imbalances following a 5 week NHE intervention. Between-limb peak torque imbalances reduced by 8.6% and 7% at isokinetic speeds of 30°/s and 120°/s respectively. Similar results were found for average peak torque with observed reductions in between-limb imbalance of 7.6% and 9.6% at both respective isokinetic speeds. Between-limb imbalances for the angle of peak torque were also reduced following the NHE intervention and were reduced by 12% and 8% at 30°/s and 120°/s respectively.

It was hypothesised that the NHE would significantly increase peak and average peak torque which may be due to several mechanisms such as neuromuscular adaptations, increased cortical activity and increased motor unit recruitment. The eccentric muscle contractions performed during the NHE may also have resulted in increased muscle fibre size through muscle hypertrophy increases associated with eccentric training (Maroto-Izquierdo et al., 2017, Hedayatpour and Falla, 2015). Physiological adaptations within the muscle units themselves such as an increased number of sarcomeres in parallel and in series which lead to an increase in fascicle length and more efficient pennation angle of the muscle fibres are associated with the NHE as proposed by Timmins et al. (2016) and Guex et al. (2016a). Therefore it is likely that these adaptations to the progressive overload of the muscle tissue during the NHE are the mechanisms by which the strength increases in this study were observed. The strength increases observed may also be as a result of the NHE isolating the hamstrings in an optimal knee joint position, as previously discussed, thus facilitating greater proprioception which may have led to strength increases but this cannot be conclusive for the current study.

These findings support research by Breno de et al. (2017) and McHugh et al. (2014) who respectively observed 13% and 17.6% increases in eccentric peak torque at speeds of 60°/s and 30°/s following 4 week NHE interventions. These studies, however, did not attempt to investigate or address between-limb imbalances. These studies looked at field sport athletes as did the current study, however, the sample size tested by McHugh et al. (2014) was 10 participants (8 Male & 2 Female) and did not include a control group which differs from the 60 Male participants in the current study. The sample size tested by Breno de et al. (2017) was 20 physically active young adults but only 10 received the intervention as the remaining 10 were used as a control group. The main difference in the sample used in the current study compared to that of Breno de et al. (2017) is that their subjects had not performed any resistance training before or during the intervention.

The current study used a session frequency of twice per week as did Breno de et al. (2017) while McHugh et al. (2014) included 3 sessions in the final two weeks of their intervention. With significant increases in eccentric hamstring peak torque observed in the Breno de et al. (2017) study and the current study it suggests that a session frequency of twice per week may facilitate neuromuscular and/or structural adaptations to increase eccentric hamstring strength. The subjects in the current study had a sufficient resistance training age allowing them to adapt to and recover adequately from eccentric loading. The greater training age of the current subjects and their existing between-limb strength deficits also suggest that while their strength training motor patterns were well established, the introduction of a new pressure feedback stimulus allowed significant changes in their muscle recruitment strategies to occur ultimately reducing the pre-existing deficits. The greater sample set (n=60) in the current study means allows for stronger results that are applicable to the general male athletic population.

As a strength training exercise, the NHE is a time efficient conditioning strategy as time is not consumed with the loading or unloading of barbells and also does not require a spotter in order for the exercise to be performed safely under high load. Another advantage of the NHE is that it does not have to be programmed as a percentage of an athlete's one rep max and the progression of loading is self-controlled by the athlete. The average duration of the NHE intervention sessions in the current study was 15 minutes (including rest periods) which supports the NHE as being an effective and time-efficient method of increasing eccentric hamstring strength. The time efficiency of the NHE, with a lower volume of repetitions, is evident by the inclusion of the exercise in the FIFA 11+ warm up (1 set of 3 -15 repetitions depending on ability).

The pressure feedback group in the current study achieved the greatest increases in peak torque (16.2% and 18.2%) when compared to the Solo group (13.8% and 8.4%) in the current study. While there was no statistical difference in strength between the two groups, the greater percentage increases observed in the HSE group may well be considered clinically relevant when plied in an injury prevention or rehabilitation program. The superior improvements in peak torque observed in the HSE may have been elicited through the improved proprioceptive feedback provided through visual feedback from the HSE. As previously discussed, the inclusion of visual proprioceptive feedback can lead to the stimulation of alpha-motor neurons within the muscle spindles which then illicit an increase in force production (Lephart et al., 1997). This finding is supported by Kellis and Baltzopoulos (1996) who observed greater eccentric strength increases in groups with visual feedback than groups with no visual feedback when eccentric hamstring strength training was carried out on an isokinetic dynamometer. There are several potential mechanisms (as discussed below) that may explain the response to the pressure feedback stimulus. The increases observed in the comparable studies mentioned above, suggests that the inclusion of visual feedback alone during the NHE may have resulted in greater proprioception contributing to an improved peak torque.

The results of the current study show that any improvements in the angle of peak torque observed were not statistically significant. This means that we must reject the hypothesis that that a 5 week NHE intervention can significantly increase the eccentric hamstrings' angle of peak torque. It was hypothesised that by eccentrically loading the hamstring muscle group at longer lengths it would result in a reduced angle of peak torque. This hypothesis was based on current literature proposing that eccentric training leads to a shift in optimum muscle length as proposed by Brockett et al. (2001). This theory is further supported through research by Brughelli et al. (2009) who observed significant changes in the angle of peak torque of the hamstring muscle group following eccentric training. The eccentric NHE program adopted by Brockett et al. (2001) resulted in significant changes in optimum muscle length was a heavily loaded one day treatment of 12 sets of 6 repetitions which, for the purpose of current study, was not a practical loading strategy for field-sport athletes due to the significant delayed onset muscular soreness (DOMS) associated with such a heavily loaded NHE program.

The findings of the current study are similar to those reported by Iga et al. (2012) who did not observe a significant difference in the angle of peak torque following a 4 week NHE intervention carried out on 18 professional soccer players. The study by Iga et al. (2012) failed to observe any significant changes in angle of peak torque at speeds of 60°/s, 120°/s or 240°/s following their NHE intervention adopted from Mjolsnes et al. (2004). The non-significant findings of the current study may be as a result of the intervention duration lasting only 5 weeks as opposed to the 9 week intervention applied in the study by Brughelli et al. (2009) which led to significant changes in the angle of peak torque. A possible explanation for this is that any changes in angle of peak torque resulting from eccentric training may be an adaptation that is experienced through long term eccentric conditioning only or that the trained subjects in the current study required a longer duration intervention in order to adapt their movement patterns and experience these changes in optimal muscle length as a result. While there was no statistical difference in the angle of peak torque observed in the current study, clinically, there was a notable improvement in angle of peak torque with a 25% and 22% improvement from baseline measurements observed at speeds of 30°/s and 120°/s respectively for the elite and solo groups respectively.

The primary hypothesis of this trial was to determine if the incorporation of a pressure feedback system such as the HSE could encourage equal force distribution of both limbs during the NHE. Magnitude based inferences (MBIs) as reported in the current study show that the pressure feedback system had a 'most likely to be beneficial' effect on peak torque imbalances at 30°/s and a 'very likely to be beneficial' effect at 120°/s when compared to the Solo group that performed the NHE with no pressure feedback. The results also show that the pressure feedback system had a 'very likely to be beneficial' and a 'most likely to be beneficial' effect on average peak torque between-limb imbalances at speeds of 30°/s and 120°/s respectively when compared to the Solo group. Again the pressure feedback system had a 'most likely to be beneficial' effect on angle of peak torque between-limb imbalances at both speeds when compared to group with no pressure feedback. The results of the current study suggest that we can accept the hypothesis that incorporating a pressure feedback system such as the HSE into a NHE program reduces between-limb imbalances for peak torque, average peak torque and angle of peak torque at speeds of 30°/s and 120°/s.

The results of the current study support the effectiveness of the HSE in facilitating even force distribution by both limbs which allowed the participants to experience the adaptations, such as increased eccentric peak and average peak torque evenly in both limbs. As proposed by Bourne et al. (2015), between-limb eccentric strength imbalances significantly increase the likelihood of an athlete incurring a HSI and this risk is exponentially higher in athletes who have had a previous HSI. The observed reduction in between-limb imbalance in the HSE group is likely to be as a result of the proprioceptive responses to the visual feedback supplied by the HSE.

With live feedback regarding force distribution in each limb supplied by the HSE, it is possible that the visual centres in the brain stem received the afferent information from the device resulting in altered muscle force distribution in response to the feedback provided. It is postulated that force distribution by each individual limb is altered through proprioceptive monitoring of force exertion by the co-activation of alpha-motor neurons and gamma motor neurons. This process constantly monitors muscle length and tension allowing the brain stem to cognitively address any uneven force distribution between both limbs that is visually observed through the feedback provided by the HSE. To date there is no known comparative research that has investigated the use of a pressure feedback system to enhance the effectiveness of a NHE protocol. However, the possible causes of a between-limb imbalance in eccentric hamstring strength vary from a limb dominant preferential distribution force during eccentric exercise as proposed by Croisier et al. (2008) to neuromuscular inhibition following a HSI as suggested by Fyfe et al. (2013). A residual strength deficit following inadequate rehabilitation of a previous HSI is suggested by Opar et al. (2015) to be a cause of between-limb imbalances. The normalization of between-limb isokinetic strength deficits through individualised strength profiling has been effective in significantly reducing the risk of further HSIs (Croisier et al., 2008).

### *Limitations*

The participants of the study are collegiate athletes meaning regular access for long term interventions was restricted by college term duration. While the 5 week intervention applied to the current study resulted in significant findings, the investigation of a more long term intervention, such as the 13 week intervention applied by van der Horst et al. (2015) or the 10 week intervention applied by Petersen et al. (2011), is desirable to determine the mechanisms behind the proven effectiveness of these long term interventions in significantly reducing HSIs. Effects such as improvements in the angle of peak torque may be better tested following interventions of a similar duration to those discussed. Other external confounding factors that were difficult to control included the subjects' individual training and competition load as the intervention was carried out prior to the commencement of the competitive college sports season. Demands of the subjects' playing schedules meant that the subjects in the current study were unable to refrain from all training during the intervention. As a result of this, it is possible that different volumes and/or intensities of training between subjects may have influenced the contractile capabilities of their hamstrings during strengthening and/or testing sessions. A further limitation of the current study is that while the groups were normalised for peak strength, between-limb imbalances were not normalised between groups prior to testing, this may have resulted .

### *Practical Applications*

By providing live pressure feedback to an athlete during the NHE, a more balanced force output can be achieved leading to even eccentric strength adaptations being elicited by both limbs. The practical applications of a device such as the HSE include daily athlete screening where any undetected reduction in force production by either limb could increase injury risk during training or competition. The strength increases observed in this study and physiological adaptations associated with the NHE may explain the effectiveness of the NHE in reducing HSIs that has been widely reported in studies incorporating amateur and professional athletes (Al Attar et al., 2016, van der Horst et al., 2015, Petersen et al., 2011). A further potential application of a pressure feedback system is it's utilisation in the rehabilitation of HSIs where the progress of a program to increase eccentric hamstring strength can be conveniently assessed on a regular basis. The use of such a pressure feedback system as the HSE as a monitoring tool for responses to training interventions is yet another practical application due to its proven reliability when compared to an isokinetic dynamometer where ICCs>0.7 were observed .

### *Future directions*

Future research into the integration of pressure feedback systems with NHE interventions may target a NHE intervention of longer duration such as those applied by van der Horst et al. (2015) or Petersen et al. (2011) to determine their effects on physiological adaptations that support the significant preventative effects each intervention had on HSI risk while also observing the long term effects that the integration of a pressure feedback system can have on between-limb imbalances. A more longitudinal investigation better represents the effect of HSI prevention strategies that typically span over an entire season in team sports.

# 2.5 Conclusion

The aims of this study were to establish the test-retest reliability of the HSE pressure feedback device and its validity when compared to an isokinetic dynamometer. The aims of the second part of this study were to investigate the effects of the NHE, with and without pressure feedback, on eccentric hamstring peak torque, average peak torque and angle of peak torque including the potential effects each had on between-limb imbalances following a 5 week NHE intervention. The results obtained in the first part of this study support the hypothesis that the HSE is a valid device for measuring eccentric hamstring strength when compared to the Biodex isokinetic dynamometer and that the HSE displays acceptable test-retest reliability when compared over two consecutive tests.

The high validity and test-retest reliability results mean that the device shows a good level of consistency when assessing eccentric hamstring strength during the performance of the NHE. Reliability is essential for a device such as this with any changes in strength observed being attributed to an intervention rather than an associated error with the device. This has significant implications in a clinical setting where accuracy is essential to prevent a misrepresentation of clinical findings. The accuracy displayed by the HSE in this study supports the use of such a pressure feedback system as reliable assessment of hamstring strength that has the potential to regularly monitor eccentric hamstring strength to identify any unexplained drops that may put the athlete at risk of incurring a HSI. A device such as the HSE may also monitor the progression of a rehabilitation program and may be a useful indicator of when to progress a patient’s hamstring rehab.

With the reliability of the device supported by the first part of the study, it meant that the device could then be utilised in a trial to investigate its potential benefits in ensuring equal force distribution during a 5 week NHE intervention. The results of the second part of this study investigated these potential benefits. The findings support the hypothesis that a 5 week NHE intervention can significantly increase eccentric hamstring peak and average peak torque. The findings also support the hypothesis that utilising a pressure feedback system to ensure equal limb force distribution during a NHE intervention can have a beneficial effect on between-limb strength imbalances. This is the first study to investigate the effects of including a pressure feedback system such as the HSE in a NHE intervention.

While the above results support previous literature that has investigated the benefits of the NHE, the results that are unique to this study are the beneficial reductions in between-limb imbalance when the NHE is augmented with a pressure feedback device such as the NHE and the greater strength increases observed in the elite group compared to the Solo group. The current study is the only known study to explore the application of such a device in a NHE intervention. The possible mechanisms by which a pressure feedback system can facilitate even force distribution of both limbs are likely to result from enhanced proprioceptive feedback through afferent visual input provided by the HSE. The control of individual force distribution is achieved through proprioceptive monitoring of force exertion allowing the athlete to adjust muscle force distribution. This may allow the athlete to address any imbalances that are visually observed through the feedback provided by the HSE by constantly monitoring muscle length and tension in the individual muscle fibres.

In conclusion, based on the results observed in the current study, the HSE is a valid and reliable device that can accurately measure eccentric hamstring strength. By utilising the HSE device in conjunction with the progressively loaded NHE intervention in this study, it can be concluded that a pressure feedback system such as the HSE can have beneficial effects on between-limb eccentric strength imbalances.

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# Appendices

*Appendix A:*

Institiúid Teicneolaíochta Cheatharlach
INSTITUTE *of* TECHNOLOGY
CARLOW
At the heart of South Leinster

CONSENT FORM: **Human Participants**

RESEARCH - INFORMED CONSENT FORM

I. Project Title:

A comparison of conditioning methods to determine the optimal method of eccentric training for the Hamstring muscle group: and to determine their efficiency in ensuring bilateral force distribution through the use of a pressure feedback system.

II. Introduction to the study:

Hamstring strain is one of the most common injuries in sports, and causes significant loss of training and competition time and significantly affects the quality of life of injured athletes. This indicates a need to prevent this injury. Hamstring strains (HSI) are reported to account for 12-16% of all injuries in athletes, with a reoccurrence rate as high as 22-34% . HIS commonly occurs in the athletes of many popular sport events in which high speed sprinting and kicking are frequently performed. In particular, a large proportion of HSI's are sustained during the terminal swing phase of high speed running, this is when a forceful eccentric contraction of the hamstring unit is required to prepare the limb for deceleration. Lower eccentric knee flexor strength has also been reported as a risk factor for HSI indicating the importance of eccentric strength for HSI avoidance. It is well established in the literature that eccentric training is an effective method in the prevention of HSI. Given the importance of eccentric hamstring strength as a risk factor to HSI's, the aim of the proposed project it to investigate the efficiency in strengthening of a new portable eccentric hamstring training device (The Hamster), as compared to traditional eccentric strengthening exercises.

I am being asked to take part in this research study. The purpose of the study is to investigate the various eccentric hamstring conditioning methods and determine the most effective/efficient method.

This research study will take place at IT Carlow and will require me to attend the Institute for 2 sessions per week for 6 weeks.

This is what will happen during the research day:

On the test day you will be required to perform maximal eccentric muscle contractions against the biodex device where your eccentric strength will be measured. You will then be required to perform a strengthening program 2 days per week for 6 weeks after which your eccentric strength will be measured again using the biodex device.

VI. Sometimes there are problems associated with this type of study. These are:

You may experience some temporary muscle soreness following the sessions.

If there are any adverse effects during your visit you will be monitored until the effects pass.

VII. Their maybe benefits to me from this treatment. These are: Eccentric hamstring strength will increase and as a result, will reduce the likelihood of you experiencing a hamstring strain injury.

VIII. My confidentiality will be guarded. IT Carlow will make reasonable efforts to protect the

information about me and my part in this study and no identifying data will be published. This will be achieved by assigning me an ID number against which all data will be stored. Details linking my ID number and name will not be stored with the data. The results of the study maybe published and used in further studies.

IX. If I have any questions about the study, the tester is free to call on 087 0560607.

Taking part in this study is my decision. If I do agree to take part, I may withdraw at any point including during the exercise test. There will be no penalty if I withdraw before I have completed all stages of the study. I also confirm that I will not be taking part in any other research of this nature at the same time.

XI. Signature: ____________________________________________________________

I have read and understood the information in this form. My questions and concerns have been answered by the researchers, and I have a copy of this consent form. Therefore, I consent to take part in this research project entitled:

*A comparison of conditioning methods to determine the optimal method of eccentric training for the Hamstring muscle group: and to determine their efficiency in ensuring bilateral force distribution through the use of a pressure feedback system.*

Signature: __________________________ Date: __________________________

Witness: ___________________________ Witness: _________________________

Signature Printed name

*Appendix B:*

## Health Screening Form

Institiúid Teicneolaíochta Cheatharlach
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For Your Safety:

- Please answer the following questions. All information will be treated in the strictest confidence.
- Please check with your doctor or specialist before exercising:

Name: _________________________ Date of birth: _______________________

Address: ___________________________________________________________________

____________________________________________________________________

(Mobile)__________________________________ (e-mail)___________________

Local GP________________________ Number_______________________

Next of Kin_____________________ Number_______________________

- Do you now or have you had in the past 12 months (Please tick)?

History of heart problems: ( )

History of heart problems in immediate family ( )

History of lung problems: ( )

High/Low Blood Pressure: ( )

Diabetes: ( )

Asthma / respiratory issues ( )

Arthritis ( )

Hernia ( )

Dizziness ( )

Chronic Illness ( )

Back Issues ( )

Epilepsy: ( )

- Have you had a recent operation / injury / chronic illness?

If yes please state:

- Do you have a history of joint, ligament or muscle damage, limited movements in any joints?

If yes please state:

- Are you taking any drugs or medication?

If yes please state:

- Are you accustomed to physical exercise?

If yes please state: (Types of exercise, duration and times per week/ month)

(Past)

______________________________________________________________

(Present)

______________________________________________________________

- Do you smoke?

If yes how many per day?

- Have you previously been asked not to partake in physical exercise by a physician?

If yes please state:

- Please state any illness/injury you have suffered or presently suffering, if not asked above:

__________________________________________________________________

Signed: __________________________________ Date: _________________________________