Influence of Muscle Strength on Nordic Hamstring Exercise Performance

By

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Abstract

Hamstring strain injuries (HSI) are one of the most common non-contact injuries in the athlete population. They can be expensive for professional organizations, as rehabilitation can cost upwards of a few hundred thousand dollars. HSIs also have a very high chance of reinjury of about 30-80%, making it important to find injury prevention methods to combat HSIs. The Nordic hamstring exercise (NHE) has been shown to reduce the risk of hamstring strain injury and reinjury in male athlete populations. **Purpose:** The purpose of this study was to determine how the muscle strength of the trunk extensors, hip extensors, and knee flexors predicts the knee breakpoint angle of the Nordic hamstring exercise. **Methods:** 20 recreationally active participants who were familiar with resistance training took part in a series of dynamometer-based strength tests with surface EMGs placed on the hamstrings, gluteus maximus, and the lumbar region of the erector spinae. Knee flexion strength, hip extension strength, and trunk extension strength were measured. Motion sensors were placed after strength testing on the shank, thigh, pelvis, and trunk to calculate joint kinematics and determine the knee breakpoint angle. **Results:** Mean KBPA for the 20 participants was $62.66^0 \pm 9.54^0$ with no significance between strength and NHE performance (Hamstrings -0.294 p=0.208, Erector Spinae -0.281 p=0.231, Gluteus Maximus -0.251 p=0.285) as well as no significance between activation and performance of the NHE (Semitendinosus peak: -0.184 p=.436 mean: -0.221 p=0.350, Biceps Femoris peak: -0.263 p=0.263 mean: -0.344 p=0.137, Gluteus Maximus peak: -0.043 p=0.858

mean: -0.055 p=0.818, Erector Spinae peak: -0.406 p=0.076 mean: -0.418 p=0.066). **Discussion:** This study attempted to find the relationship between muscle strength and NHE performance. EMG data were consistent with previous research, specifically when looking at which muscle groups are most active when performing the NHE. Results may have been affected by the population used in the study, possibly confirming past studies that suggest the exercise may be population dependent. **Conclusion:** With no significant findings, we cannot accept our hypothesis, but future research should be done looking further into the relationship between strength and NHE performance.

Influence of Muscle Strength on Nordic Hamstring Exercise Performance

A Thesis

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Chapter 1

Introduction

Hamstring strain injuries (HSI) are one of the most common injuries in sports and have a high rate of recurrence, about 30-80% (2,3). With upwards of a cost of €250,000 or about $265,000 for the care of athletes who are out due to an HSI for a 2-week period, there is a critical need for a method to reduce hamstring injuries for these professional organizations. The Nordic hamstring exercise (NHE) has been one of the few exercises shown to decrease the rate of hamstring strain injury and reinjury in elite athletes. The NHE is an eccentric hamstring exercise that has the participants kneeling with a partner holding their ankles for support. Participants will then lean forward, extending their knees in an attempt to bring their body parallel to the ground in a slow and controlled manner. However, there is the possibility that the reduction in injuries with the NHE is a population-specific effect, as the current literature shows no injury prevention in the general public despite showing improvements in hamstring strength in both elite athletes and non-athletes (10).

The NHE has been shown to have positive effects in preventing injury and reinjury in elite European athletes, specifically soccer players (6,12), but has had inconsistent results in the recreationally active population (10,11). Other research has found that after 25 sessions over 13 weeks, only 36 of the 579 amateur-level soccer players reported having hamstring injuries, and only 11 of them came from the experimental group (12). Other studies found that out of 461 professional-semiprofessional soccer players in the experimental group with a 91% compliance rate with their intervention, only 15 participants who did the intervention got acute hamstring injuries, which corresponded to a 60% reduction in initial injury and 85% reduction in reinjury

(6). While the NHE has been shown to have positive effects in elite athlete populations, it is also important to ask if these preventative effects are population dependent. Current research showing the injury reduction rates as a result of NHE typically consist of elite or high-level college athletes, and almost all of them are men. In recreationally active individuals, a NHE intervention did not show overall eccentric hamstring strength improvements but there were clear subgroups of responders and non-responders to the NHE (11). With the limited populations who have participated studies investigating the injury reduction potential of the NHE or the biomechanical effects of the NHE, it is hard to determine if this exercise is population dependent and what may be preventing people who are not high-level athletes from being able to perform NHE effectively and thus benefitting from its injury reduction potential. While the Nordic hamstring exercise itself focuses on eccentric hamstring strengthening, other muscle groups such as the trunk and hip extensors likely play a pivotal role in the proper performance of this exercise. For example, it has been shown in previous research that the trunk extensors are the 2nd most active muscle group during the eccentric phase of the NHE (2,4). The hip extensors are likely also instrumental to maintain a neutral hip position throughout the exercise.

Purpose: To determine how muscle strength of the trunk extensors, hip extensors, and knee flexors predicts the knee breakpoint angle of the Nordic hamstring exercise. Knee breakpoint angle is defined as the point at which the participant can no longer go down under control.

Hypothesis:

Second to the hamstring strength, trunk extensor strength will be a major predictor of the knee break point angle. Those with low trunk extensor strength will have a smaller knee breakpoint angle than those with stronger trunk extensors. Athletes may have a stronger core than most recreationally active individuals, so it may be the core muscles, specifically the trunk extensors based on EMG data, that can predict if someone can or cannot complete an effective repetition of the NHE.

Delimitations:

Participants consisted of adults between the ages of 18-30 years who, at a minimum, participated in physical activity at least 3 days a week and were familiar with resistance training. A wide range of individuals was selected so we could possibly see the difference between those who could and could not perform the NHE well. Exclusion criteria consisted of those with a history of documented hamstring injuries, other current lower extremity injuries, and trunk-related injuries.

Operational Definitions:

Nordic Hamstring Exercise (NHE): Exercise where participants are on their knees with knees flexed to 90 ^{o} with torso erect, hands to the side, and ankles are either strapped or held down by a tester. The participant is then instructed to lower their thighs and torso slowly towards the ground by extending their knees in a controlled manner.

Knee Breakpoint Angle (KBPA): The knee flexion angle at which the participant can no longer descend under control during the NHE exercise. This variable was used to determine how well each participant could perform the exercise.

Maximal voluntary isometric contractions (MVIC): A maximum isometric contraction of a muscle performed using a dynamometer as resistance.

Inertial Measurement Unit (IMU): An electronic device that tracks the 3D angular orientation of the body segment it is placed on and allows for range of motion data of joints to be collected when multiple sensors are placed on multiple segments.

Chapter 2

Literature Review

Hamstring strain injuries (HSI) are one of the most common injuries in sports (2) and has a recurrence rate between 30-80% (2,3). In the 2015 summer Olympics, 84% of all acute injuries were HSIs, with 54% being grade 2, requiring approximately 22 days of recovery before the athletes could return to play (3). HSIs are not just significant for the athletes but the organizations these athletes belong to. It is estimated that it costs European soccer clubs approximately €250,000 per 2 weeks a player is unable to train or compete (7). Further consequences in European soccer come from bench players with low chronic workload having to replace starting injured players in the lineup with injury risk increasing two to four times for those bench players (7). With the high risk of hamstring strain injuries and reinjuries as well as the financial burden they carry, identification of exercise interventions aimed to reduce these injury rates and financial burdens is critical.

Effects of Nordic Hamstring Exercise (NHE) on Hamstring Injury Risk

The Nordic hamstring exercise (NHE) has been shown to reduce the rate of hamstring injuries. Van Der Horst et al (2015) took amateur male players from 40 teams (20 in the control and 20 in the experimental group), where the intervention group performed 25 sessions of the NHE over a 13-week period (12). Over the course of the study, 36 of the 579 players reported hamstring injuries (6.2%), with 11(31%) of them being in the intervention group and 25 (69%) in the control with 91% compliance overall (12). What they discovered was that while the NHE decreased HSIs, it did not decrease the severity of the injury. The study was only conducted in male athletes, so these findings may not be generalized to other populations. Petersen et al (2011) recruited 50 Danish professional and amateur soccer teams with 461 players in the intervention (Nordic hamstring exercise) group and 481 players in the control group. After a 10-week mid-season intervention, with a 91% compliance rate they reported 67 acute hamstring injuries in total, with 52 (78% of all injuries) in the control group vs 15 (22%) in the intervention group. They found that through their study, they were able to reduce injury rates by 60% and reduce reinjury by 85%. Overall, while the NHE appears to be an effective exercise that reduces the risk of HSIs, a better understanding on the biomechanical effects of this exercise as an intervention is warranted.

Biomechanical effects of Nordic Hamstring Exercise intervention

While some studies have shown that the NHE is effective in reducing HSIs in male athletes, it is important to understand the biomechanical effects of this exercise as an intervention and whether these effects are population dependent. MjØlsnes et al (2003) used 22 college-level male soccer players who were split into two groups, one that completed just normal hamstring curls and an experimental group that performed the NHE. What they found after the 10-week training intervention was that the NHE was more effective in building eccentric hamstring strength (11% increase) than the regular hamstring curl (No reported increase in strength).

Ishoi et al (2017) investigated the effect of the NHE on sprint capacity in male amateur soccer players. 35 participants were included in the study, with 11 players in the intervention group and 14 in the control and 10 lost due to injury. After completing a 10-week intervention, they found that the NHE likely influenced a positive change in sprint acceleration time (mean change of -0.045s), meaning the players in the intervention group saw an improvement in their sprint acceleration. With their findings, the authors also speculated that there could be a relationship between lower HSIs rates with the NHE, though they did not measure the occurrence and reoccurrence of HSIs.

Ribeiro-Alverez et al (2018) investigated the biomechanical effects of the NHE in 20 young moderately physically active adults 18-35 years old. The participants were randomized into training and control groups. 10 participants participated in a 4-week NHE training program. They found significant improvements in the eccentric strength of the hamstrings of ~10% in the training group and ~2% in the control group. the hamstring quadriceps functional ratio of ~10% in the training group and ~2% in the control group, and biceps femoris long head fascicle length, which provides some support for findings relating the NHEs to preventative effects.

Seymore et al (2017) investigated the effect of the NHE strength training on muscle architecture and stiffness in 20 adults aged 18-25 who were self-reportedly recreationally active. Participants were randomized into training and control groups, both consisting of 10 participants. All participants in the experimental group participated in every training session. What was found after the 6-week training intervention was that there was no change in the biceps femoris long head fascicle length, but an increase in muscle volume as well as an overall increase in growth. Where the other articles found the NHE experimental groups increasing in eccentric strength, this did not show improvements in terms of peak eccentric strength. There was evidence of a difference in individual responses to the intervention, as they were able to split the intervention group into two groups (responders vs non-responders). The responders had a significant change between pre (1.49±0.68Nm/Kg) and post intervention (1.87±0.93Nm/Kg) in eccentric hamstring torque, Where the non-responder group did not have a significant change pre (1.70±0.14Nm/Kg) and post (1.42±0.24Nm/Kg) intervention in eccentric hamstring strength. These results show the possibility that the NHE could be a population-dependent exercise.

Cadu et al (2022) investigated how a low volume of NHE improved maximum eccentric strength and reduced hamstring injury rate in professional soccer players. Participants consisted of 30 players from a male 1stdivision French soccer club. The experimental group performed weekly training sessions where they completed 3 maximal effort repetitions of the NHE, where the control group just performed their standard training. The participants in the experimental group had a moderate compliance ranking (47.2%), which was then broken into 2 subgroups of high (participated in 12.4±1.4 sessions) and low (7.2±2.1 sessions) compliance. The high-compliance-rate participants displayed a high change in maximal eccentric strength vs the low compliance group. Overall, they found that the NHE did help reduce injury (5 (22%) in the experimental group, 9(39%) in the control group) while improving the eccentric strength, depending on the compliance of the participant. This article showed that the NHE does improve the chances of not getting an HSI but only depending on the compliance of the athlete. Limitations of this study were, once again, they only used males and they also only used high-level athletes, so these results may not be applicable to recreationally active men or women.

Biomechanics of Nordic Hamstring Exercise

The NHE is typically performed while the participant is on both knees, either on the ground or a pad, with their ankles secured by a training partner/coach or straps, with the torso starting upright and knees at 90 degrees of flexion. The participant then tries to resist a fall forward using their hamstrings, only using their arms to buffer the fall (7). Thus, because the exercise utilizes the hamstring muscles to eccentrically lower the thighs, torso, head, and arms toward the ground, it is considered a high-load exercise for the hamstrings. So, what does this exercise look like biomechanically?

In a laboratory-based study, Norikazu Hirose et al used participants that were 14 male amateur athletes (age 21.2±1.5 yrs.) who performed 2 sets of 5 repetitions of the NHE on a custom-made platform that was set at 50º and 40º from horizontal. EMG data was recorded from the time the participant started leaning forward then ended after 5 seconds. What they found was that semitendinosus (ST) had a higher muscle activation than the long head of the biceps femoris (BFlh) by a mean difference of 19.5% meaning that the ST was more active during the exercise vs. the BFlh. Hirose also found that the erector spinae (ES) (~80%) was more active for all the trials performed compared to the gluteus maximus(~15%). Based on their findings, they assumed that the NHE can help reduce hamstring injury when the knee is set at a shallow flexion angle. So the further you are able to go past 90º of knee flexion, the better. This should help activate the BFlh as much as the ST (2). This study's inclusion of only men limits its relevance to female athletes.

Finding the differences in EMG activity during the NHE can possibly help to show how the exercises works at different positions during performance. Soga was interested in determining the differences in EMG activity at different slopes while performing the NHE. The procedure used a sloped platform that ranged from 0º – 50º from horizontal that was randomly set at 0º, 20º, and 40º and the knee angles were set in the range of 0º-50º and set in five phases (0-10, 10-20, 20-30, 30-40, 40-50) (3). What was found was that the slope to get BFlh EMG readings was at 0 slope on the platform, with and in the 40º to 50º of knee flexion range. The highest ST EMG activation was found at 20º of slope and at the 20º to 30º range of knee flexion. Overall, what they found was that using a lower knee flexion angle during hamstring resistance training may be beneficial and performing the exercise at slopes above 0 degrees allows participants to reach the lower knee flexion angles while lowering themselves under control. Compared to the standard NHE (zero slope), if participants cannot lower themselves under control, it will not provide enough elongation stress due to the early knee break point angle (3). This means that the lower knee flexion angle is important for athletes to get the most out of this exercise and potentially reduce their chances of reinjury. This study did only use males so the findings here may not apply to females who are equally as active.

How the hip and trunk interact also needs to be considered when looking at the NHE as weakness in core muscles or how the pelvis is angled can contribute to the effectiveness of the NHE. Narouei et al (2018) investigated the hip and trunk muscle activity during the NHE as it is important to look at how the other muscles contribute to someone being able to perform this exercise well. Ten healthy men (26.1±5.46yrs.) performed the NHE twice in a row by leaning forward as far as possible before returning to upright posture. This study not only measured the long head of the biceps femoris (BFlh) and semitendinosus (ST) activation, but also measured muscle activation of the gluteus maximus (Gmax), erector spinae (ES), and gluteus medias (Gmed). What was found was the ST had the highest EMG activity, which is consistent with previous findings. After the hamstrings, the ES showed that the trunk extensors were the 2^{nd} most active during the NHE, leading the author to recommend that hamstring injury prevention programs start focusing on the core muscles as well.

Both kinematic and EMG data would be helpful when looking at the effects of the NHE on the hamstrings. Ditroilo et al (2013) investigated the kinematics and muscle activation during the NHE. Subjects consisted of 18 male university students who all participated in field sports and were HSI free for 6 months. What they found was that 12 of the 18 participants displayed a higher peak EMG during the NHE for all muscles tested than during a traditional eccentric exercise. This was the first study to conduct a neuro-mechanical analysis of the NHE.

Hamstring muscles adapt during eccentric exercise by first creating protection for the muscles when they are unaccustomed to eccentric exercises to help prevent injury or damage. Brockett et al (2001) investigated hamstring muscle adaptation following the NHE. This study used 10 subjects 8 men and 2 women that were not participating in any regular weight training for the leg muscles. 4 subjects had their strength measured using a Cybex system and a Biodex was used for the other 6 subjects to test the angle-torque relationship of the knee flexors before and after the NHE exercise. Control dynamometry and girth measurements were taken at 3 different times, the week before the exercise. Dynamometer measurements were once again taken immediately following exercise, as well as both girth measurements and soreness ratings for each subject. Immediately following exercise, the 10 subjects showed an average shift in peak torque of $7.7^{o} \pm 2.1^{o}$ favoring longer hamstring muscle lengths. At days 1-4 and 7, all showed significantly longer muscle lengths from the controls while the average torque for the subjects' immediately post exercise was down 80.4% and returned to control values by day 3. The shift in optimum angle persisted to day 10 of the experiment by which time the torque magnitudes had returned to control values, but the optimum angle shift for torque generation remained at longer muscle lengths (13). Some limitations of this study were the fact that they used 2 different systems to take dynamometer data and a small sample size. However, they did use women, so in this case, the results may possibly be applied to women as well as men.

The NHE has been shown to decrease the risk of HSIs in elite athletes while it is still relatively unclear in its effect in amateur and recreational groups (6,12,10,11). Some of the articles that have shown a positive effect with the NHE used some sort of modified version of the exercise (2,3) meaning that maybe it is not just about the population but also how the exercise is being performed. The influence of how muscle strength of the hamstrings in addition to the trunk extensors and gluteus maximus affects the ability to perform the NHE well is currently unknown.

Purpose & Hypothesis:

The purpose of this study was to determine how muscle strength of the trunk extensors, hip extensors, and knee flexors predicts the knee breakpoint angle of the Nordic hamstring exercise. We hypothesized that individuals that have weaker trunk extensors will not be able to perform the NHE, as defined by the knee breakpoint angle, as effectively as individuals with high trunk extensor strength. The results of this study may provide some information to rehab professionals and strength coaches on what muscles to strengthen before prescribing their clients the NHE so they can get as close to the full injury-reducing benefits of the exercise as possible.

Chapter 3

Methods

Twenty people participated in this study between the ages of 18-30 years (Average age: 22.93years, 11 Female, 9 Male), with no documented history of hamstring injuries and no current lower extremity or trunk injuries. Participants were also self-reported recreationally active under the criteria that they were physically active at least 3 times a week. Participants signed a standard informed consent approved (Appendix 1) by the university's IRB before any EMG placements and strength testing. EMGs were placed on the semitendinosus (ST), biceps femoris long head (BFlh), gluteus maximus (Gmax), and the lumbar region of the erector spinae (ES). Strength testing was completed using the HUMAC dynamometer, where the participants performed 3 maximal isometric contractions (MVIC) for each muscle group. Based on previous research conducted by the university, participants then performed 5 reps of the Nordic hamstring exercise, attempting to lean forward with their thighs and trunk under control as far as possible while the knees extended before falling.

Procedure:

NORAXON surface electromyography (EMG) sensors sampling at 2000Hz were placed on the semitendinosus (50% between ischial tuberosity and medial epicondyle of the tibia) (14), biceps femoris (50% between ischial tuberosity and lateral epicondyle of the tibia) the gluteus maximus (50% between the sacral vertebra and the greater trochanter) (14), and the lumbar region of the erector spinae (1 finger length laterally from L2). These sensors read the electrical signals produced by the muscle fibers during a contraction for analysis of muscle activation. The EMG sites were first prepped by shaving the area to remove any hair that could affect the impedance of the EMG signal. Once shaved, the skin was then debrided with lemon prep to further reduce skin impedance. Once fully prepped, the surface EMGs were placed on each site according to standardized placements (Figure 1).

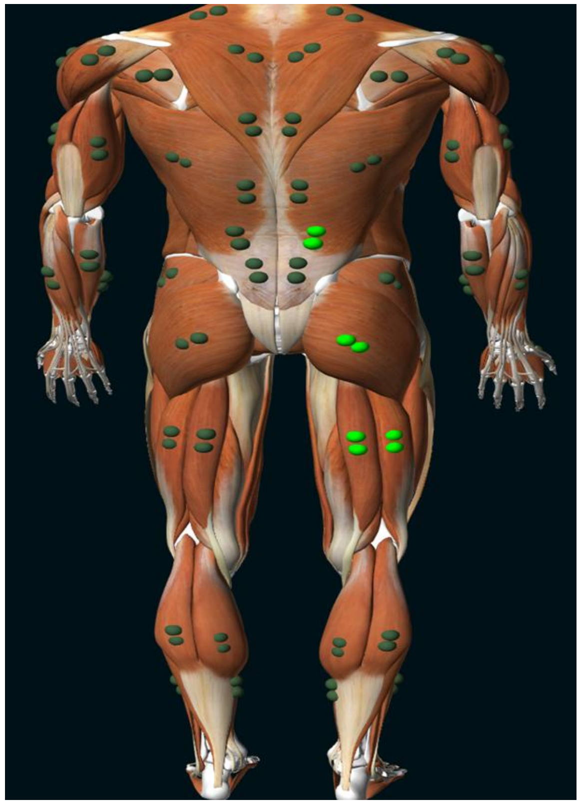

Figure 1: Highlighted are the EMG placements used for the study (22)

Once EMG prep was complete, depending on the muscle, participants were asked to either sit or lie prone on the HUMAC dynamometer for their strength measurements. Muscles tested were the hamstrings (BFlh, ST), Gmax, and trunk extensors. EMG data was collected alongside strength data for the creation of MVICs to normalize the NHE muscle activation data. Trunk Extensors were tested first, as it was the only test done in the seated position (Figure 1). A seated position was chosen for the trunk extensors based on piloting two different methods for trunk extensor strength. Those two methods were sitting vs standing. What was found was that the sitting position allowed for more isolation of trunk extensors as in the standing position participants were able to engage the hips more because the pelvis was not able to be stabilized as well. Participants were seated with their trunk at a 90^0 angle with the arm of the HUMAC placed midway down the scapula. Once the participant and the arm of HUMAC were in place, a strap was placed around the participant's hips to secure them to the chair and to ensure a minimal amount of hip extension occurred. Once fully secured, participants were instructed to push back into the arm of the HUMAC as hard as they could while keeping their hips in the chair.

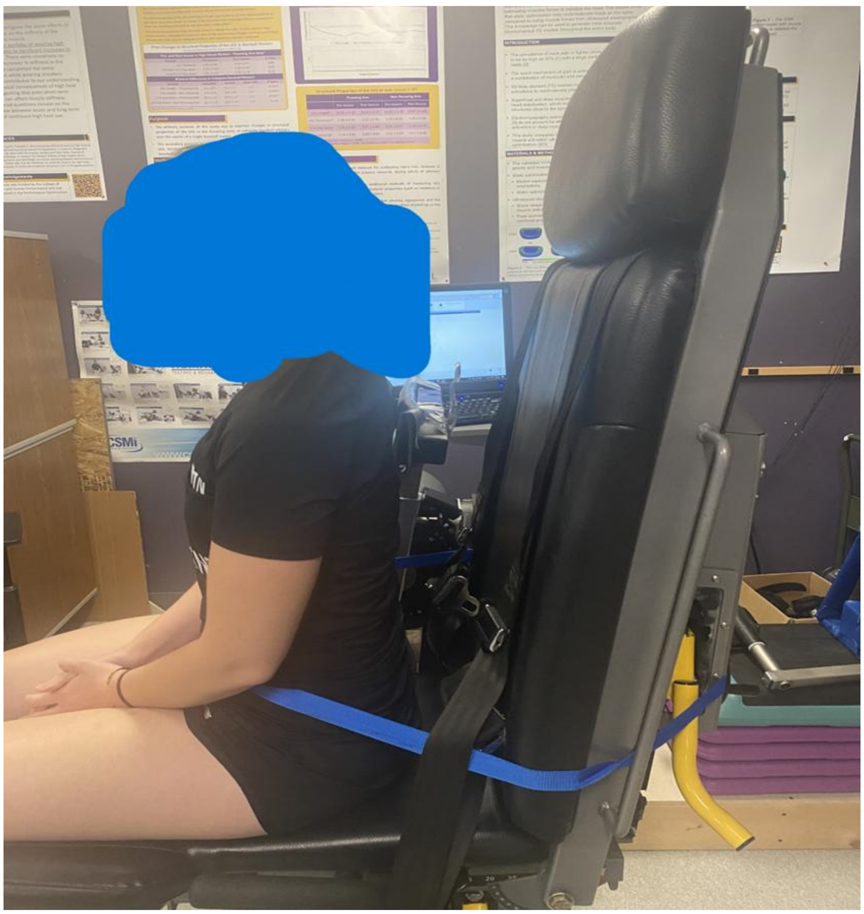

Figure 2: Position for erector spinae strength testing

Once testing of the trunk extensors was complete, participants were instructed to lie prone for the remaining 2 tests. Hamstrings were tested with the arm of the HUMAC placed just below the belly of the gastrocnemius and secured to the leg. Participants were again secured at the hips to minimize the use of the hips during testing. Once in place and the participant was ready, the knee was flexed to 45^0, and the participant was instructed to resist the machine by bringing their foot to their butt as hard as possible (Figure 2).

Figure 3: Position for hamstring strength testing

For the gluteus maximus, the arm of the HUMAC was placed at the thigh just above the knee joint with the knee flexed to 90^0 (15). Participants were instructed to resist the arm by trying to push their foot through the ceiling by extending their hips (Figure 3). 3 MVICs for each muscle at 5 seconds each were taken with the participants being given a 40-second rest in between each repetition. In addition, participants were given 2 warm-up reps to familiarize themselves with how the machine would resist them as well as to get a hang of the movements they would be doing.

Figure 4: Position for gluteus maximus strength testing

After completion of the strength testing, NORAXON IMU motion sensors sampling at 200Hz were placed on the shank (midway between the lateral malleoli and the lateral epicondyle of the distal femur) and thigh (midway between greater trochanter and lateral epicondyle) of both legs, the pelvis, and the trunk (1 on the lower spine at T12 and one on the upper spine at C7). These motion sensors were used to collect kinematic data of the segments and allowed for the calculation of the knee breakpoint angle (KBPA) for each participant. When IMUs are placed on a segment they track the 3D angular orientation of that segment. By adding further sensors to other adjacent segments, you are able to calculate the joint positions. (20). IMU data is collected using a series of accelerometers and gyroscopes to collect data on position and orientation of the sensors based on the segments they are placed on. Data from the IMUs are then transmitted to the NORAXON receiver, where the angular changes of the segments and between segments is quantified (20). Once motion sensors were placed, the orientations were calibrated using NORAXON's forward lean calibration. Participants were instructed to be in a normal standing position before being asked to lean forward at the ankles, placing their hands on a wall, then being asked to return to their original standing position. Special care was taken to minimize magnetic interference with IMUs by calibrating them in an open space with minimal metal to achieve the best possible calibration.

Figure 5: IMU placements used during NHE testing (22)

Once calibration was completed, participants were asked to kneel on a padded platform where they had their legs secured with straps and was supported at the ankle by the tester.

Regardless of previous experience with the NHE, all participants were instructed the same; participants were told to complete the NHE by leaning forward while keeping their trunk and thighs as straight as possible and trying to go parallel to the ground under control. If at any time during the NHE the participant felt that they could no longer go down under control, they were to catch themselves with their arms and lower their body to the platform, marking the end of that trial. Video data was also collected for the use of adding more visual representation of where the knee breakpoint angles were. Video playback paired and synchronized with the EMG and IMU data allowed for easier visualization of the KBPA as you could see better where the participants failed and see if it aligns with where the KBPA should be from the NORAXON analysis. All visual data has the face and any other identifying marks masked.

Processing and Analysis:

Once all measurements were completed EMG data for both MVICs and EMG during the NHE was smoothed. MVIC and NHE muscle activation data was smoothed using root mean squared (RMS) in a 100ms window, and EMG during the NHE was then normalized to a percentage of the peak values recorded during the MVIC trials (Figure 6). Strength data were compiled into an Excel document and analyzed to find the peak torque produced by each muscle group. Peak and mean EMG during the NHE were analyzed using NORAXON systems MR4 software. EMG signals came from 500ms before the knee breakpoint angle to the knee breakpoint angle. EMG data was normalized to percent of max activation determined using the MVICs during the strength testing.

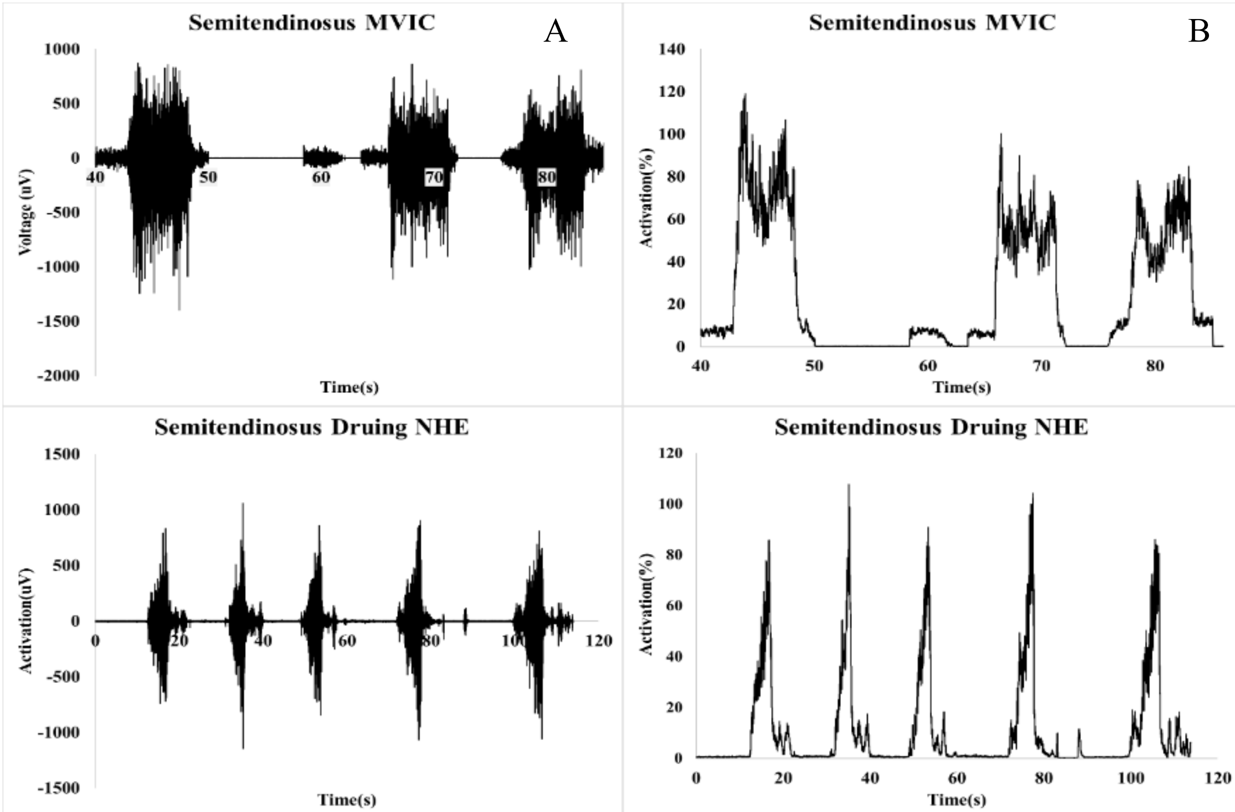

Figure 6: A depicts the EMG of the semitendinosus prior to normalization for both MVIC and during NHE of 5 consecutive trials. B depicts the EMG after RMS smoothing for both MVIC and during NHE performance for the semitendinosus

Motion data collected using the NORAXON system's IMUs were used to determine the angular velocity at the knee joint and to determine the KBPA. Knee angular velocity of both legs was calculated in NORAXON using the equation S[0](t)-(S [0] (t+.0025)/(t-(t+.0025)) where S [0] is the signal for knee flexion angle, t is time, and .0025 is the sampling rate. Simple correlations were taken comparing both the average KBPA to the strength data, as well as the average KBPA to both the mean and peak muscle activations for each muscle. Further analysis was done using an independent variables t-test on 2 groups with a Hedge's correction for effect size within the study of the top 1/3 performers (KBPA ≤60°) and the bottom 1/3 performers (KBPA (≥65°)

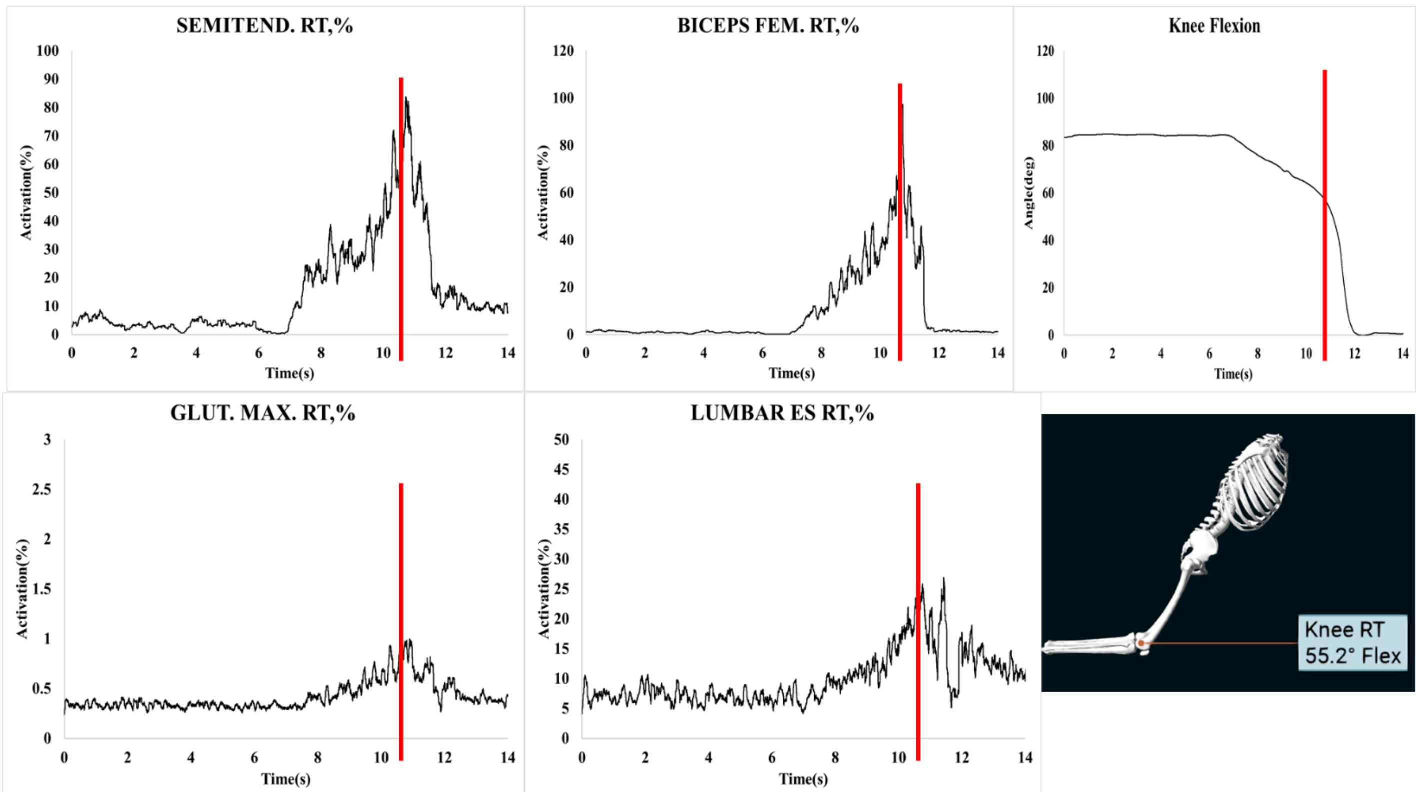

Figure 7: EMG and knee flexion angle during a single trial of the NHE. The blue line represents the KBPA.

Chapter 4

Results

Descriptive statistics shown in table 1 shows mean KBPA of $62.7^0 \pm 9.5^0$ for the 20 participants. With completion of the study, it was found that there were non-significant weak negative correlations between muscle strength and KBPA. For hamstrings a non-significant weak negative correlation of -0.294 (p= 0.208) was found (Figure 8). Gluteus maximus strength also found a non-significant week negative correlation of -0.251 (p=0.285) (Figure 8). And erector spinae also had a non-significant weak negative correlation of -0.281 (p=0.231) (Figure 8). This data shows that the strength of the muscles taken does not correlate with the average KBPA for participants in this study. Peak and mean muscle activations taken from 500ms prior to KBPA to KBPA were also found to have no significant correlations with weak negative to moderate negative correlations with average KBPA. Erector spinae peak activation had a non-significant but moderate negative correlation of -0.406 (p=0.076) to KBPA (Figure 9). Mean erector spinae activation also had a moderate negative correlation of -0.418 (p=0.066) (Figure 9). Peak Semitendinosus activation had a weak negative correlation of -0.184 (p=0.436) and mean semitendinosus activation had a weak negative correlation of -0.221 (p=0.350). Biceps femoris peak activation had a weak negative correlation of -0.263 (p=0.263) and mean biceps femoris activation had a moderate negative correlation of -0.344 (p=0.137). Gluteus maximus peak activation had a weak negative correlation of -0.043 (p=0.858) and mean gluteus maximus activation had a correlation of -0.055 (p=0.818). With none of muscle strength measurements correlated with knee breakpoint angle (KBPA) a stepwise regression to predict KBPA from the strength measurements was not performed.

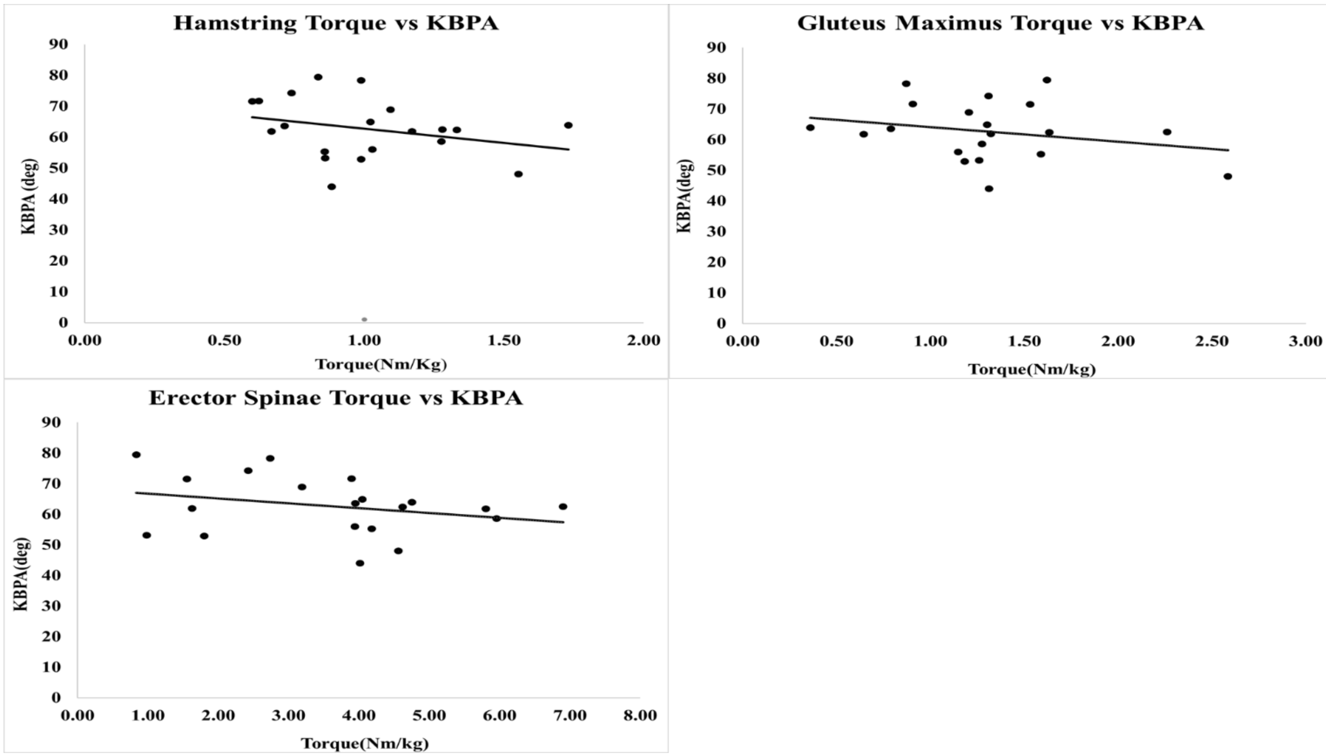

Figure 8: Graphs of normalized torque vs KBPA (Knee breakpoint angle) for each muscle group tested.

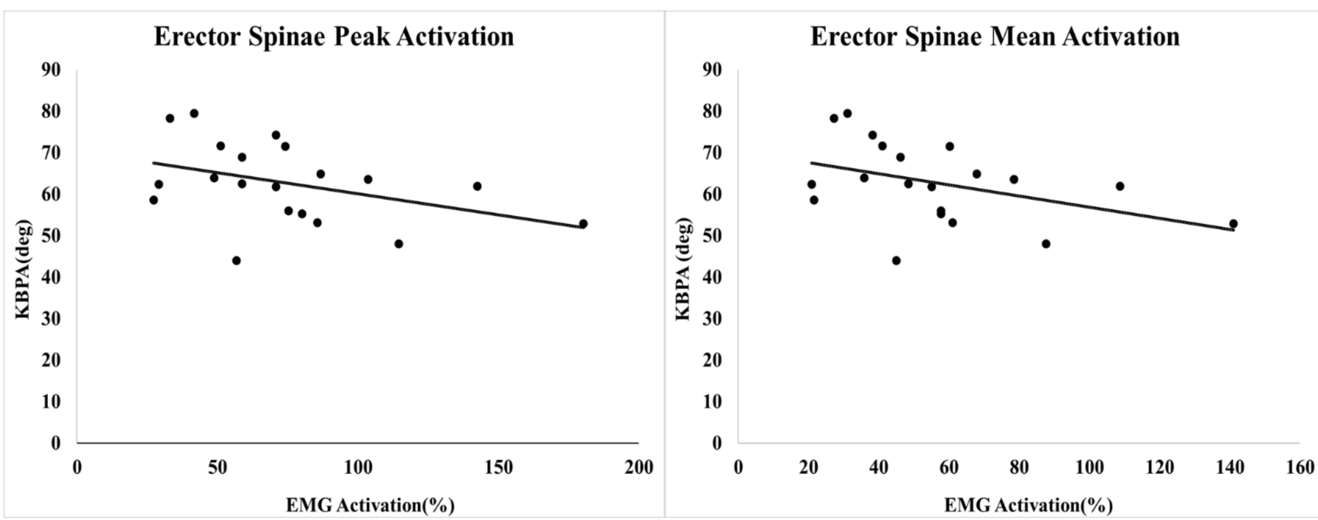

Figure 9: Peak and mean erector spinae muscle activation taken from 500ms before KBPA to KBPA

Due to the strength variables showing no zero order correlations with KBPA, we then determined if there were any differences in muscle strength with the sample partitioned into the top and bottom thirds based on KBPA. Participants were rank ordered by KBPA and split into 2 independent groups: individuals with a KBPA $\leq 60^0$ (n=7) and individuals with a KBPA of $\geq 65^0$ (n=6). An independent samples t-test was then performed. Individuals in group 1 had KBPAs of $52.58^0 \pm 5.01^0$ and individuals in group 2 had KBPAs of $74.03^0 \pm 4.14^0$. Table 2 shows the results of the independent samples t-test with no significant group differences.

	Mean		Std. Deviation
KBPAavg	62.66	±	9.54
Hamstring(Nm/Kg)	1.01	±	0.31
Glute(Nm/Kg)	1.31	±	0.51
ES(Nm/Kg)	3.59	±	1.68
Erector Spinae Mean Activation(%)	56.54	±	29.71
Semitendinosus Mean Activation(%)	76.90	±	53.43
Bicep Femoris Mean Activation(%)	68.06	±	26.84
Gluteus Maximus Mean Activation(%)	19.95	±	29.69
Erector Spinae Peak Activation(%)	74.46	±	38.16
Semitendinosus Peak Activation(%)	99.62	±	65.48
Bicep Femoris Peak Activation(%)	88.87	±	31.74
Gluteus Maximus Peak Activation(%)	28.21	±	38.56

Table 1: Mean and standard deviations for entire study population showing the average knee breakpoint angle (KBPA), average normalized torque, and average of both mean and peak muscle activations.

	$\leq 60^{0}$(n=7)			$\geq 65^{0}$(n=6)				
	Mean			Mean			P value	Effect Size
KBPAavg	52.58	±	5.01	74.03	±	4.14	4.48E-06	-4.31
Hamstrings(Nm/Kg)	1.06	±	0.26	0.81	±	0.20	0.08	0.99
Gluteus Maximus(Nm/Kg)	1.48	±	0.51	1.24	±	0.31	0.34	0.52
Erector Spinae(Nm/Kg)	3.63	±	1.69	2.44	±	1.11	0.17	0.76
Erector Spinae Mean Activation(%)	67.36	±	37.98	40.68	±	11.78	0.13	0.85
Semitendinosus Mean Activation(%)	103.84	±	86.62	64.73	±	12.60	0.30	0.56
Bicep Femoris Mean Activation(%)	82.08	±	35.19	54.92	±	13.12	0.10	0.92
Gluteus Maximus Mean Activation(%)	27.79	±	49.92	17.74	±	7.05	0.64	0.25
Erector Spinae Peak Activation(%)	88.51	±	48.46	54.91	±	16.17	0.13	0.84
Semitendinosus Peak Activation(%)	130.29	±	107.25	88.07	±	14.16	0.36	0.49
Bicep Femoris Peak Activation(%)	103.81	±	40.11	77.54	±	22.32	0.18	0.74
Gluteus Maximus Peak Activation(%)	38.07	±	64.15	26.42	±	12.31	0.67	0.23

Table 2: Group statistics and results of the independent variables t-test for averages of KBPA, torques, and muscle activations. Cohen's d with a Hedges correction used for effect size.

Chapter 5

Discussion

This study attempted to identify how muscle strength relates to someone's ability to effectively perform the NHE. The major findings of this study were that there was no significant correlation between muscle strength and knee breakpoint angle, as well as no significant correlation between muscle activation and KBPA. With all findings being non-significant, we cannot accept our hypothesis, as there was no relationship between muscle strength and Nordic hamstring performance as defined by the knee breakpoint angle. There was also no difference in strength between groups when separated by knee breakpoint angle.

One of the potential reasons why muscle strength did not correlate with NHE performance was based on the positions we tested hamstring and gluteus maximus strength. Hamstring strength was measured in the prone position with the hip at 0^0 and the knee flexed to 45^0 putting the hamstring muscles in a relatively shortened position, making it sub-optimal for the hamstrings to produce large torques than if we had the participants perform the strength test in a seated position with the hamstrings in a more lengthened state. Our muscle strength numbers, specifically the hamstrings and gluteus maximus, were thus lower compared to the literature. In the hamstrings, the literature has reported mean hamstring strength to body mass ratio values of 3.29±0.74 Nm/Kg for males and 2.62±0.46 Nm/Kg for females tested in a seated position with knee and hip a 90º (16), where we had a mean of 1.16 Nm/Kg for males and 0.89 Nm/Kg for females. The gluteus maximus was also in a relatively shortened position with the hip at neutral 0 degrees of flexion. The literature has shown a mean of 1.57±0.38Nm/Kg with participants with trunk lying flat on a table with the legs hanging off putting the hip at 90º (15), where we found an average of 1.31±0.51. Both of these show that we collected lower values than the literature. The positions to test for hamstring and gluteus maximus strength were chosen in the current study specifically to replicate the positions the hamstrings and gluteus maximus would be in during the actual performance of the NHE. Thus, the positions the hamstrings and gluteal muscles tested should be considered more relevant to the NHE but do not represent the idealized positions to elicit the greatest muscle torques.

Our trunk extensor strength was a little higher compared to the literature, where a mean of 158.9 Nm for a seated position (21) was reported in older adults, and a study in untrained males found a range between 121-360 Nm of torque for trunk extension (22). A third study also using the seated position found a mean of 367±80 Nm/Kg for men and 212±56 Nm/Kg with the hip totally stabilized (24) We found a mean of 252.6 ±130.4Nm also in a seated position with an attempt to completely stabilize the hip. It is also important to note that while the erector spinae muscle group is primarily responsible for trunk extension, the deeper abdominal muscles (transversus abdominis and lower fibers of the internal oblique) also function to increase intra-abdominal pressure which assist in generating trunk extensor moments. With this in consideration, it is reasonable how the trunk extensor moments are high compared to the other muscle groups tested in the current study.

Is NHE Influenced More by Composite Muscle Strength Index?

While individual muscle strength was not correlated with NHE performance as defined by the knee break point angle, it is possible that a composite strength score may provide a more realistic picture on how muscle strength relates to NHE performance. A supplemental composite analysis was therefore run. Normalized torque values were rank-ordered for each muscle strength test across the current study sample to convert the strength values to percentile ranks. After torque values were rank ordered for each of the three muscle strength tests, two categories were created: average percent rank, which was the average rank of the muscle groups, and minimum percent rank, which took the minimum of the three individual strength values. What was found was a non-significant weak negative correlation between the average percent rank composite to KBPA of -0.22 (p=0.34) and a non-significant weak negative correlation between the minimum percent rank to KBPA of -0.23 (p=0.31). With this supplemental analysis, it appears that a composite strength score does not correlate with KBPA. Future studies could aim to create composite scores based on a population percentile rank rather than the sample percentile rank.

Factors Other Than Muscle Strength Influencing NHE Performance?

While muscle strength, especially of the hamstrings, is likely influencing the ability of individuals to properly perform the NHE, other factors may also play a pivotal role in this exercise, such as the subject's anthropometrics. In order to demonstrate this, we created a free-body diagram to illustrate the required torque the hamstrings must produce to complete the NHE (Appendix 2).

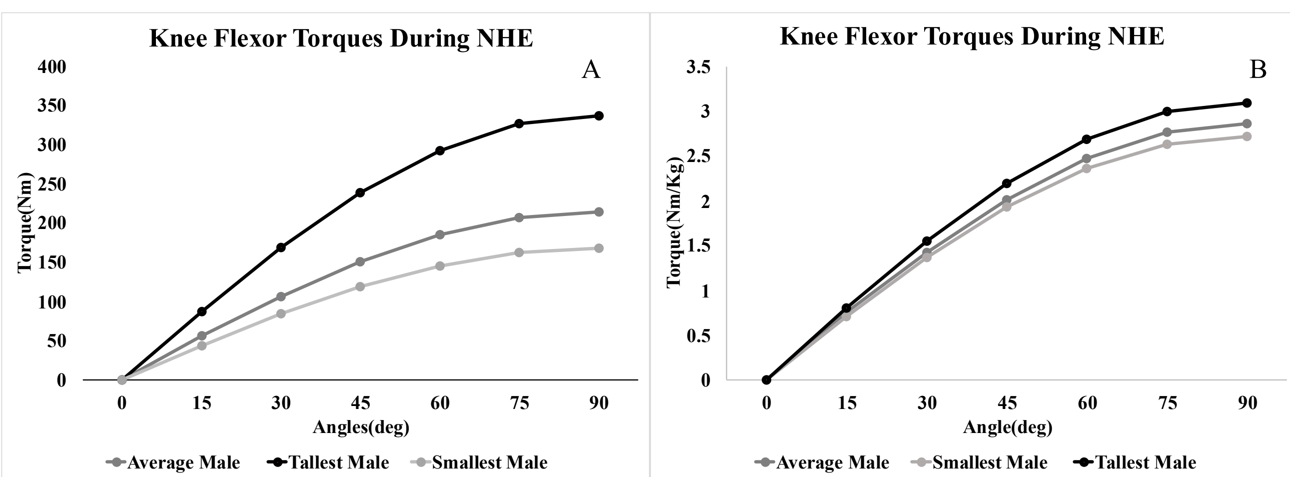

Figure 10: A: Shows the theoretical required torques based on a free-body diagram for 3 different 3-segment models not normalized to mass. B: Same people but torques are normalized to mass

Figure 10 shows the theoretical torque requirements of the knee flexors (primarily hamstring) from one limb to achieve each angle during NHE performance for 3 different 3-segment models. Angles are based on where they are relative to the vertical axis, so 0^{o} on the graph is representative of 90^{o} of knee flexion where the model is upright and about to start the exercise while 90^{o} is representative of the model being horizontal (0^{o} of knee flexion). These models were created using: 1) the average of all our male participants, 2) the tallest male, and 3) the shortest male to show the different torque requirements required by our study population. For out tallest male to reach 45^{o} of knee flexion they would have had to have each hamstring produce 239.27 Nm of torque which corresponds to 2.20 Nm/Kg, where the max hamstring torque this participant was able to produce during the isometric strength testing at 45 degrees of knee flexion was only 1.03 Nm/Kg. Our supplemental analysis of these models shows that for our male population; they had to have fallen in the range of 119.08Nm – 239.27Nm of torque which corresponded to a normalized torque in the range of 1.93Nm/Kg – 2.20Nm/Kg to achieve 45^{o} of knee flexion. All but one male from our study sample was able to achieve the 45-degree breakpoint angle, possibly suggesting our population just did not have strong enough hamstrings to perform the NHE adequately. The full explanation of how this analysis was completed can be found in Appendix B.

While the analysis of the model to determine theoretical knee flexor torque requirements during the NHE is useful and provides insight into how anthropometrics affects the range of torque requirements, direct comparison of the NHE to the muscle strength tests should be interpreted with caution because of the differences in contraction type. While strength testing was performed isometrically, eccentric hamstring contractions are required during the NHE. Why this is an issue is because the human body can produce more torque during an eccentric contraction than during an isometric contraction based on the muscle force-velocity relationship. During an eccentric contraction, a person will produce more muscle force due to the muscle force generated by both the active and passive (tendon) components of muscle. EMG only reads the neural signal that is sent to the muscle to allow the active portion of the muscle to contract. But EMG does not reflect the passive components muscle during contraction. Since we tested the hamstring strength in an isometric contraction, it is assumed that during eccentric contractions during the NHE, the passive tension developed was more than during the isometric strength test (17). Regardless our EMG data in the current study was consistent with the literature as it showed hamstrings as the primary muscle group active during the NHE, followed by the trunk extensors and then the hip flexors (2,4). Future studies should aim to test for muscle strength eccentrically rather than isometrically to better match the type of hamstring contraction required of the NHE.

Limitations

There are several limitations in the current study that may have impacted the overall results. The results of the current study investigating the influence of muscle strength on NHE performance could have been limited by the majority of the sample overall not being able to perform the NHE well. In this sample, one participant was able to, on average, go below 45^0. A knee breakpoint angle of between $40\text{-}50^0$ has been suggested as the minimum position to be achieved in order for the NHE to be beneficial (3). Having a more balanced sample of subjects who can perform the exercise well, in addition to subjects who could not perform well, would have allowed for a more diverse population and potentially offer more insight into the influence of muscle strength on NHE performance.

The decision not to include the role of the abdominal muscles could have negatively impacted the results, as there is a chance that it is the abdominals stabilizing the trunk during the NHE that limits performance. As noted earlier, the abdominals contribute to increasing the intra-abdominal pressure to stabilize the trunk. The choice not to include the abdominals came from wanting to make the pool of possible participants wider, as getting a good signal with surface EMG is difficult to get on non-lean individuals, and we wanted a wide range of body types to possibly apply the results to a wider range of recreationally active individuals. With a wider range of participants, we hoped to be able to understand how the recreationally active population performed the NHE to see if there were any suggestions to be made by either a personal trainer or a rehab professional prior to suggesting the NHE as an exercise to strengthen the hamstrings.

Another limitation could be the possibility that the exercise is population-dependent, as suggested in previous research (11). Seymore et al 2017 looked at the differences in eccentric hamstring muscle strength pre- and post a 6-week intervention, which showed that while no significant change in eccentric strength was seen overall when split into groups, it was discovered that there were responders and non-responders. With this information that not everyone who participated in this NHE intervention showed strength gains, it suggests that a person must be at a greater fitness level than recreationally active to perform the exercise well, regardless of initial strength measurements. As our sample was only recreationally active, there is a chance that results were not found do to the activity level of the sample as a whole.

How one performs the NHE could have also affected the results of the study it has been shown in previous research that pelvic tilt may possibly play a role in female performance of the NHE (16). Women generally have more of an anterior tilt to their pelvis, possibly placing the hamstrings in a more lengthened state than the male participants possibly allowing for an easier time completing the NHE. Outside of just the pelvic tilt, female anatomy also tends to have more femoral anteversion, so the femur is rotated anteriorly (16). This could affect NHE performance because if the femur is rotated anteriorly, it's going to change how the femur articulates with the tibia where the hamstrings insert, possibly altering how the hamstrings activate during the NHE.

Future studies

Future studies should be conducted to better determine the limiting factors of the NHE. From the analysis of the biomechanical model, anthropometrics should be considered more in-depth. If segment lengths are measured, you can calculate required torques at each joint and the torques produced more accurately. It is likely that the combination of both muscle strength and an individual's anthropometrics are both important in the successful performance of the NHE. A change in how hamstring strength testing is done should also be considered, specifically an eccentric isokinetic test. Because the NHE is an eccentric exercise, performing an eccentric isokinetic test on the HUMAC might better correlate with the torque the hamstrings can produce during the NHE and the knee breakpoint angle as well. Another way this research could be continued is with the use of an intervention study, as you would be able to have baseline data to compare to, as well as be able to see if performance improves over time with increases in muscle strength for the given muscle groups. Future studies should also include the stabilization role of the abdominal muscles in their evaluation, as it could help to create a better understanding of the exercise requirements as a whole. Due to the anterior pelvic tilt and differences in how the femur is rotated in females it is suggested that there needs to be an emphasis on proper trunk control (16). While this study did not see a significant correlation between trunk extensor strength and NHE performance, future studies including both trunk flexors and extensors, or a flexor to extensor ratio is warranted.

Conclusion:

This study investigated possible limiting factors of the NHE, specifically how muscle strength relates to performance. What was found in this study was a non-significant weak correlation between hamstring, gluteus maximus, and erector spinae strength and the average knee breakpoint angle. A non-significant moderate negative correlation between erector spinae activation and average knee breakpoint angle was also found. With these findings, we cannot accept our hypothesis that individuals with higher erector spinae strength would perform the NHE better than those with weaker erector spinae strength as defined by the knee breakpoint angle.

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Appendix A

East Carolina University

Informed Consent to Participate in Research

Information to consider before taking part in research that has no more than minimal risk.

Title of Research Study: Limiting Factors of The Nordic Hamstring Exercise

Principal Investigator: Anthony S. Kulas

Institution, Department or Division: East Carolina University Department of Kinesiology

Address: Minges Coliseum 177

Telephone #: 252-737-2884

Researchers at East Carolina University (ECU) study issues related to society, health problems, environmental problems, behavior problems and the human condition. To do this, we need the help of volunteers who are willing to take part in research.

Why am I being invited to take part in this research?

The purpose of this research is to determine factors that could be limiting individuals from being able to complete the Nordic Hamstring Exercise effectively. You are being invited to take part in this research because 1) You are a recreationally active individual with familiarity in resistance training and 2) have no known history of hamstring injuries and do not have any current trunk or lower extremity injuries. The decision to take part in this research is yours to make. By doing this research, we hope to learn factors that may be limiting a person's ability to effectively complete the Nordic Hamstring Exercise.

If you volunteer to take part in this research, you will be one of about 30 people to do so.

Are there reasons I should not take part in this research?

I understand that I should not participate in this study if I am under the age of 18 and over the age of 30, if I have any history of hamstring injuries or any current trunk or lower extremity injuries.

What other choices do I have if I do not take part in this research?

Because participation is completely voluntary, you can choose not to participate.

Where is the research going to take place and how long will it last?

The research will be conducted at East Carolina University in the Ward Sports Medicine building You will need to come to the Biomechanics Lab which is located on the third floor in room 332 of the Ward Sports Medicine building one time during the study. The total amount of time you will be asked to volunteer for this study approximately 2 hours.

What will I be asked to do?

You will be asked to do the:

- A simple questionnaire to determine your eligibility for the study, perform 3 isometric strength tests on the dynamometer to determine knee flexion strength by having you lay prone on the dynamometer table, hip extension strength also while lying prone, and trunk extension strength which will be done in a seated position, as well as 5 repetitions of the Nordic hamstring exercise.
- You will also be asked to have noninvasive electromyography sensor placed on your skin to record muscle activation as well as motion sensors placed on your person which will record the movement of your legs and trunk. As well as have basic anthropometric measurements be taken i.e. height and weight. For the EMG sensors to be placed on your skin you will need to have the EMG sites shaved of any hair and debrided of any dead skin with an abrasive cream known as lemon prep.
- All repetitions of the Nordic hamstring exercise will be recorded to help with the motion analysis with all videos using video editing software to obscure the face and any other identifying features. Further all the data will be further anonymized by use of a pre-determined alphanumeric code to name all files. Only study staff will have access to recorded data. All data will be kept on a secure server for 3 years after which all data will be deleted. You have the right to not have video recording be taken during the study

Participant agrees to be videotaped ___________YES ___________NO

What might I experience if I take part in the research?

We do not know of any risks (the chance of harm) associated with this research. Any risks that may occur with this research are no more than what you would experience in everyday life. We don't know if you will benefit from taking part in this study. There may not be any personal benefit to you but the information gained by doing this research may help others in the future.

Will I be paid for taking part in this research?

We will not be able to pay you for the time you volunteer while being in this study

Will it cost me to take part in this research?

It will not cost you any money to be part of the research.

Who will know that I took part in this research and learn personal information about me?

ECU and the people and organizations listed below may know that you took part in this research and may see information about you that is normally kept private. With your permission, these people may use your private information to do this research:

- The University & Medical Center Institutional Review Board (UMCIRB) and its staff have responsibility for overseeing your welfare during this research and may need to see research records that identify you.

How will you keep the information you collect about me secure? How long will you keep it?

If you elect to participate in this study by signing the informed consent document, you will be assigned an alphanumeric code. Only this code will be used on all electronically saved data measurements and will be backed up onto a secure server in the lab. The only persons with access to the master list that link you to your alphanumeric code will be the above researchers Mr. J.W. Barrett and Dr. Anthony S. Kulas. All paperwork forms linking you to the study will be kept int the P.I.s office (Minges 177) which is locked except when in use.

What if I decide I don't want to continue in this research?

You can stop at any time after it has already started. There will be no consequences if you stop and you will not be criticized. You will not lose any benefits that you normally receive.

Who should I contact if I have questions?

The people conducting this study will be able to answer any questions concerning this research, now or in the future. You may contact the Principal Investigator at (252) 737-2884 (Monday-Friday 8am-5pm)

If you have questions about your rights as someone taking part in research, you may call the ECU University and Medical Center Institutional Review Board (UMCIRB) at phone number 252-744-2914 (Monday-Friday 8am-5pm). If you would like to report a complaint or concern about this research study, you may call the Director for Human Research Protections, at 252-744-2914

Is there anything else I should know?

Motion sensors will only be used to record position of the knee and hip during movement but all sessions will be video recorded and all videos will be edited to obscure the face and all other identifying features.

Your information will not be distributed or used for future studies.

This research is overseen by the University and Medical Center Institutional Review Board (UMCIRB) at ECU. Therefore, some of the UMCIRB members or the UMCIRB staff may need to review your research data. Your identity will be evident to those individuals who see this information. However, I will take precautions to ensure that anyone not authorized to see your identity will not be given that information.

Identifiers might be removed from the identifiable private information and, after such removal, the information could be used for future research studies or distributed to another investigator for future research studies without additional informed consent from you or your Legally Authorized Representative (LAR). However, there still may be a chance that someone could figure out the information is about you.

I have decided I want to take part in this research. What should I do now?

The person obtaining informed consent will ask you to read the following and if you agree, you should sign this form:

- I have read (or had read to me) all of the above information.
- I have had an opportunity to ask questions about things in this research I did not understand and have received satisfactory answers.
- I know that I can stop taking part in this study at any time.
- By signing this informed consent form, I am not giving up any of my rights.
- I have been given a copy of this consent document, and it is mine to keep.

____

Participant's Name (PRINT) **Signature** **Date**

Person Obtaining Informed Consent: I have conducted the initial informed consent process. I have orally reviewed the contents of the consent document with the person who has signed above, and answered all of the person's questions about the research.

____

Person Obtaining Consent (PRINT) **Signature** **Date**

EAST CAROLINA UNIVERSITY
University & Medical Center Institutional Review Board
Willis Building · Mail Stop 682
600 Moye Boulevard · Greenville, NC 27834
Office **252-744-2914** · Fax **252-744-2284** · **rede.ecu.edu/umcirb/**

Notification of Initial Approval: Expedited

From: Biomedical IRB

To: Anthony Kulas

Date: 1/3/2025

Re: UMCIRB 24-000698
Limiting Factors Of The Nordic Hamstring Exercise

I am pleased to inform you that your Expedited Application was approved. Approval of the study and any consent form(s) occurred on 1/2/2025. The research study is eligible for review under expedited category # 4,6,7. The Chairperson (or designee) deemed this study no more than minimal risk.

As the Principal Investigator you are explicitly responsible for the conduct of all aspects of this study and must adhere to all reporting requirements for the study. Your responsibilities include but are not limited to:

1. Ensuring changes to the approved research (including the UMCIRB approved consent document) are initiated only after UMCIRB review and approval except when necessary to eliminate an apparent immediate hazard to the participant. All changes (e.g. a change in procedure, number of participants, personnel, study locations, new recruitment materials, study instruments, etc.) must be prospectively reviewed and approved by the UMCIRB before they are implemented;

2. Where informed consent has not been waived by the UMCIRB, ensuring that only valid versions of the UMCIRB approved, date-stamped informed consent document(s) are used for obtaining informed consent (consent documents with the IRB approval date stamp are found under the Documents tab in the ePIRATE study workspace);

3. Promptly reporting to the UMCIRB all unanticipated problems involving risks to participants and others;

4. Submission of a final report application to the UMICRB prior to the expected end date provided in the IRB application in order to document human research activity has ended and to provide a timepoint in which to base document retention; and

5. Submission of an amendment to extend the expected end date if the study is not expected to be completed by that date. The amendment should be submitted 30 days prior to the UMCIRB approved expected end date or as soon as the Investigator is aware that the study will not be completed by that date.
The approval includes the following items:

Name	Description
IRB Flyer (1).docx	Recruitment Documents/Scripts
IRB Informed Consent .docx	Consent Forms
IRB Protocol.docx	Study Protocol or Grant Application
Screening Questionnaire.docx	Surveys and Questionnaires

For research studies where a waiver or alteration of HIPAA Authorization has been approved, the IRB states that each of the waiver criteria in 45 CFR 164.512(i)(1)(i)(A) and (2)(i) through (v) have been met. Additionally, the elements of PHI to be collected as described in items 1 and 2 of the Application for Waiver of Authorization have been determined to be the minimal necessary for the specified research.

The Chairperson (or designee) does not have a potential for conflict of interest on this study.

IRB00000705 East Carolina U IRB #1 (Biomedical) IORG0000418
IRB00003781 East Carolina U IRB #2 (Behavioral/SS) IORG0000418

Appendix B

To theorize how much hamstring torque must be produced at the knee joint for someone to perform the NHE, we created 3 free-body diagrams to give us the hamstring torque at 15° increments from the starting position to the ending position. The starting position is in kneeling with knees at 90 degrees of flexion, and the ending position shows the knee at full extension and the thighs, torso, and head aligned with the horizontal plane. All three of our models used were based on the study population. Model 1 was based on the average male in the current study. Height and mass were taken from the averages of both for the male population of the study. Model 2 was based on our tallest male participant, and model 3 was based on the shortest male participant. The models were chosen this way because we wanted to see what the hamstring torque requirements would look like for the average as well as the extremes, as they would have differing anthropometrics. To create these free-body diagrams, we first had to find the mass and lengths of each segment of the body. To find these values, we used a mix of data by Dempster and Clauser (18,19). For the lengths of each segment in meters, Dempster's data shows that the head and neck is 15% the total body length, trunk length is 33% total body length (from the hip to the base of the neck), and the thigh is 24% total body length. The masses of each of the segments in the model used Clauser's data where the mass of the head and neck is 8% of body mass and trunk mass is 42.1% of body mass. But for this model, since the arms are at the sides and stationary during the NHE, we added the mass of the arms to the trunk, so trunk mass was calculated using 52.4% total body mass. The mass of the thigh was 12.6% of total body weight, but since this is a bilateral exercise, we combined both legs, so 25.2% of total body mass for the thighs. The center of mass for each of the three model segments was as follows based on

Dempster's and Clauser's work: center of mass of the head was placed at 56.7% from the neck base, center of mass of the trunk was placed 66.1% from the hip, and center of mass of the thigh was placed at 57% from the knee. The following equations were then used for determining the center of mass location for each of the model segments relative to the knee joint: $Thigh_{loc} = Thigh_L \times 0.57$; $Trunk_{loc} = (Trunk_L \times 0.661) + Thigh_L$; $Head_{Loc} = (Head_L \times 0.567) + Thigh_L + Trunk_L$. Once locations were found, we then calculated the center of mass location of the total model relative to the knee joint. This was found by using the equation $\sum T = \sum(W \times r) = (\sum W) \times r_{cm}$ (r_{cm} = center of mass). When the model is positioned horizontally, the model's center of mass location relative to the knee joint is equivalent to the moment arm relative to the knee. For NHE positions where the knee is flexed, the moment arm relative to the knee is shorter.

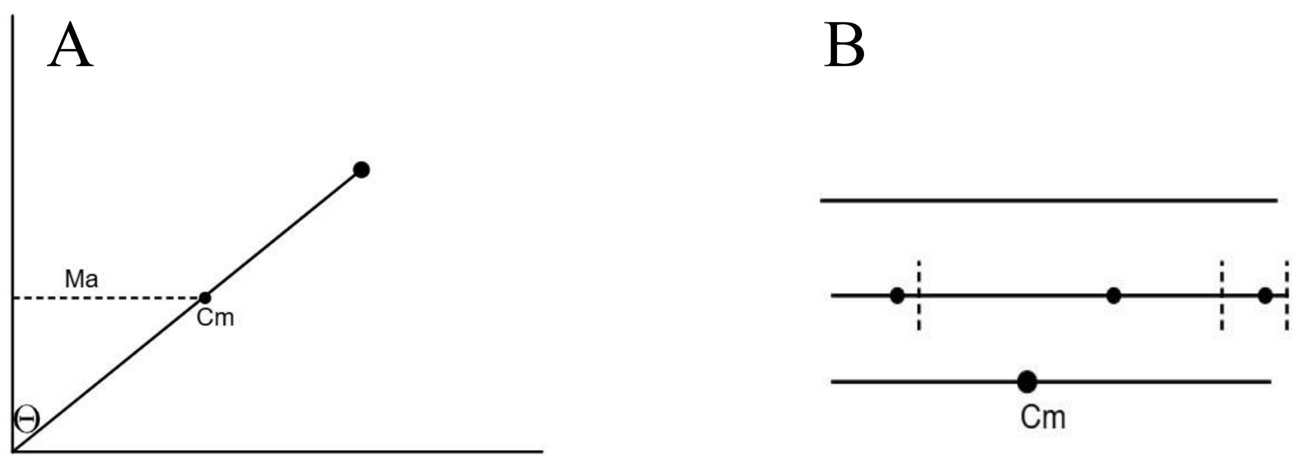

Figure 11: Figure A shows how each torque was calculated for each angle, where Cm is the center of mass for the whole model and remained constant for each, Ma is the moment arm, and Θ represents the angle we manipulated. Figure B shows the total length of the model, each segment of the model with the Center of mass represented by the dots, and the center of mass for the whole model, which was calculated after each segment's center of mass was calculated.

The torques of each segment were calculated by multiplying the segment's center of mass location by the weight of the segment, so each mass first had to be converted from kilograms

(Kg) to Newtons(N). This would give us the torques at 90^0 from the vertical for each segment. From there, you calculate the total weight of the model and the total torque produced by the model, and then find the center of mass location for the model by using this equation: $r_{cm} = \sum(W \times r)/ \sum W$. The total torque from the model is equal to the torque produced by both hamstring groups during performance of the NHE. So to find torque of just a single limb hamstring group you divide the torque by 2 ($\sum T/2$). This gives us the torque of one hamstring at 90° relative to the vertical. To find the torques at a different knee flexion angles less than 90 degrees, you must first find the length of the moment arm (Figure 11a). To find the length of the moment arm, you you trigonometry functions to solve for the moment arm shown in Figure 11a. The angle is known, and the center of mass location of the model is always constant. So, to solve for the moment arm, you use: sinϴ x Cm location (ϴ is converted into radians). Once the moment arm is solved for each angle, you then use the equation: T = moment arm x the total model weight and then divide by 2 to get the torque produced by 1 hamstring at each angle.