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# A Comparison of Force Production in Eccentric Hamstring Exercises

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## ABSTRACT

Eccentric hamstring training has been identified as a factor in reducing the likelihood of hamstring strain injury (HSI) and improving sport performance. Currently the Nordic hamstring exercise (NHE) is one of the most commonly prescribed exercises for this type of training. However, their effectiveness is blunted as a result of poor compliance rates among athletes, due to a multitude of factors. This study aimed to investigate the effectiveness of the eccentric razor curl exercise (RCE) as an alternative to the NHE for eccentric hamstring training. Twelve amateur rugby players took part in this study, testing their peak eccentric force during both the NHE and RCE. Additionally, soreness induced by each exercise was measured in this study. Significance was set at $p \leq 0.05$. The RCE (362.69 ± 45.86 N) resulted in greater force production than the NHE (307.33 ± 67.75 N) ($p < 0.001$). The RCE also showed lower soreness ratings than the NHE (3.83 ± 1.59 vs 5.67 ± 1.30, $p < 0.05$). Large effect sizes were shown between the two exercises for soreness ratings (r = 0.71) and force outputs (g = 1.26). The RCE tested significantly better in terms of force and soreness when compared to the NHE in this study. This suggests that the RCE may provide greater benefit to those seeking to optimise their eccentric hamstring training, with greater force and a potential to improve exercise compliance.

**Keywords:** Razor curl exercise, nordic hamstring exercise, soreness, inter-limb force deficit, hip extension lower

## INTRODUCTION

Eccentric exercises are commonly used to strengthen the hamstrings to improve sports performance and decrease injury (20). One of the most common eccentric hamstring exercises implemented for this purpose is the Nordic Hamstring Exercise (NHE) (6, 20). This high prescription rate is likely due to the high levels of force achieved during the NHE (32). However, the effectiveness of the NHE appears to be dependent on the compliance rate of the program in which it is included and compliance rates of the NHE are observed to be relatively low (1, 3, 6, 9, 10, 15, 21). Cuthbert et al. (15) suggests this is due to the higher volume prescriptions recommended, potentially being enhanced by the acute muscle soreness experienced when NHE is performed (19). It is further shown in a study of professional soccer players that over half of the clubs identified resulting muscle soreness of the NHE as an obstacle to implementation (10). Moreover, the compliance of the exercise is suggested to be related to the NHE being a high intensity exercise with high levels of eccentric force produced and often being performed at a maximal intensity (15). This poses a challenge for eccentric exercises which are characterised by greater force production than concentric muscle contractions and result in increased levels of soreness and muscle damage (8). Alternatively, adherence could be improved through the adjustment of the volume prescribed per session, as it is suggested that the typical high-volume prescription leads to poor adherence (15). Yoshida et al. (42) demonstrated that lower volume prescriptions with higher frequency leads to greater increases in muscular strength than equivocal volume administered less frequently. Presland et al. (34) also displayed low volume NHE training to have greater benefits than high volume training for both strength and hypertrophy. This suggests that the typical high-volume prescriptions can be unnecessary and would show additional benefits to eccentric hamstring training compliance, should practitioners reduce the volume of their eccentric training prescriptions (34, 42). Despite the quantity of research on the NHE, the low compliance rate reduces its effectiveness and suggests an alternative exercise is required to maintain the effectiveness of eccentric hamstring training.

Oliver and Dougherty (29) suggest that hamstring training should be performed in a more functional position and chose the Razor Curl Exercise (RCE) for strengthening the hamstrings. This study found the RCE to be effective at producing supra-maximal contraction forces in the gluteus maximus and hamstrings (29). This shows it allows for effective training of the hamstrings in an eccentric contraction, as greater force outputs are expected in eccentric training when compared to concentric training (29). The prescription of the RCE in this study was due to its biomechanically advantageous position of the hip flexed at 90˚ and the knee mimicking the athletic position seen during many athletic movements (i.e., jumping, landing, decelerating, cycling, Olympic weightlifting), opposed to only the knee flexion occurred in the NHE (11, 16, 29). The biomechanical advantage is suggested to come from increased hamstring contractibility around the knee due to the hip flexion of the RCE (29). A previous study investigating the kinematics of NHE variations, altering the hip and knee angles, displayed a significantly increased peak torque values at the hip and knees with 75˚ of hip flexion, similar to the 90˚ hip angle of the RCE (35). Additionally, significantly greater hip angles and sum of hip and knee angles were reached at the time of peak hip and knee torque at 75˚ of hip flexion (35). This appears to contrast the angle in the NHE at which the athlete begins to sharply increase their downward velocity, indicating a failure to maintain the eccentric contraction and typically occurring shortly after the point of peak torque (17, 35). Achieving a greater hip and knee angle at the point of peak torque and before a sharp increase in downward velocity, suggests that an increased hip angle may result in a significant increase in force output during the RCE. This also reinforces the argument of Oliver and Dougherty (29) that the RCE offers a greater biomechanical advantage than the NHE and allows for the eccentric training of the hamstring at a greater length than that achieved during the NHE (35).

The RCE is also referred to as the Hip Extension Lower when performing the eccentric portion only (28), however this study will continue to refer to it as the RCE, following Pollard et al. (33). Additionally, Whyte et al. (39) found that a hip extension exercise produced similar increases in eccentric hamstring strength compared to NHE. The hip extension exercise used by Whyte et al. (39) is similar to the extension of the hip seen in the eccentric portion of the RCE. This suggests that RCE produces similar benefits to NHE in relation to increased hamstring strength and decreased risk of HSI, along with the potential to decrease ACL injury risk (29). However, there is insufficient evidence directly comparing these exercises, with Pollard et al. (33) being the most recent study to directly compare these exercises. NHE appears to be accepted as the pinnacle exercise for eccentric hamstring training despite the possibility that the RCE may display increased benefit for those looking to strengthen the hamstrings and decrease HSI risk. An investigation into whether the biomechanical advantage of the RCE corresponds in greater force production appears warranted. With the suggestion of the acute soreness following the NHE being linked to decreased adherence, it also appears warranted to investigate and report subjective soreness ratings following the NHE and RCE, independently. If the biomechanical advantage of the RCE remains true, regarding eccentric force production, a greater mean peak force output will be observed from the RCE when compared to the NHE over the course of this research.

## METHODS

### *Participants*

This study recruited twelve (*n*=12) male participants (Mean ± standard deviation, age 23.7 ± 4.7 years, height 179.1 ± 4.6 cm, body mass 94.25 ± 12.86 kg, training age 4.25 ± 1.91 years) from a senior men's amateur rugby team. All participants were aged between 18 and 33 years. The sample was equally distributed between payers in forward (*n*=6) and back (*n*=6) positions. Inclusion criteria for participants consisted of a minimum of 2 years experience playing rugby union with concurrent resistance training. All participants had a minimum of 6 months experience with the NHE but had no experience performing the RCE. Recruited participants were provided with details of all risks they undertook along with how their information would be used and safeguarded for the purposes of this study. Participants provided informed consent to participate in the study. Participants were excluded from the study if they had received an injury within the previous 3 months or if they had received a knee or hamstring injury within the previous 6 months. Ethical approval was granted by the South East Technological University Ethics Committee, following a risk assessment.

### *Experimental Approach to the Problem*

This study was conducted as an AB/BA crossover trial (36) and no blinding was implemented. For this study, participants were asked to perform the testing protocol prior to training in the evening once per week, over the course of 4 weeks total. All familiarisation and testing was conducted in the gym of the participants' sports club. Participants were randomly split into group AB (*n*=6) and group BA (*n*=6), with group BA completing the RCE followed by the NHE and the group AB performing the exercises in the opposite order. Randomisation was accomplished using a random number generator to assign participants to groups. The first session was to perform familiarisation with each of the exercises to be tested and to gather anthropometric data (height and body mass) of the participants. Height was assessed using a portable stadiometer (seca 213, seca GmbH, Hamburg, Germany) and weight was measured using a flat scale (seca 813, seca GmbH, Hamburg, Germany). Familiarisation sessions involved the participants performing 4 sets of 3 repetitions at a self-perceived intensity, increasing each set, in the order 50%, 70%, 85%, 100%. The second week involved a second familiarisation session. Participants' third session took place 7 days after the second visit and during this visit testing of the NHE took place for group AB and group BA performed the RCE. The final attendance was in order to test the opposite exercise for each group and took place 7 days after the third session. Group AB and BA study designs are shown in figures 1a and 1b, below.

### *Procedures*

*Nordic Hamstring Exercise*

Participants completed a standardised warm-up which consisted of performing 2 repetitions of the NHE at a self-perceived intensity of 50%, followed by 1 repetition at 70% and then completing 1 repetition at 80% on the Hamstring Solo Elite (ND Sports Performance, Kilkenny, Ireland). Participants only completed the eccentric portion of the NHE. Participants were set up on the Hamstring Solo device appropriately with their knees on the cushioned surface of the Hamstring Solo device and their ankles positioned beneath the load cells, in accordance with Lodge et al. (26). Intraclass coefficients (ICC) of the Hamstring Solo Elite have shown the device as reliable (ICC = 0.910 and 0.914, for left and right peak forces, respectively) and valid (ICC = 0.823 and 0.840, for left and right peak forces, respectively) for assessing eccentric hamstring strength (26). The knee position of the participant on the Hamstring Solo Elite was recorded. NHE start position and position at ~80° of knee flexion are shown in figures 2a and 2b, respectively. The participants then completed 3 maximal repetitions

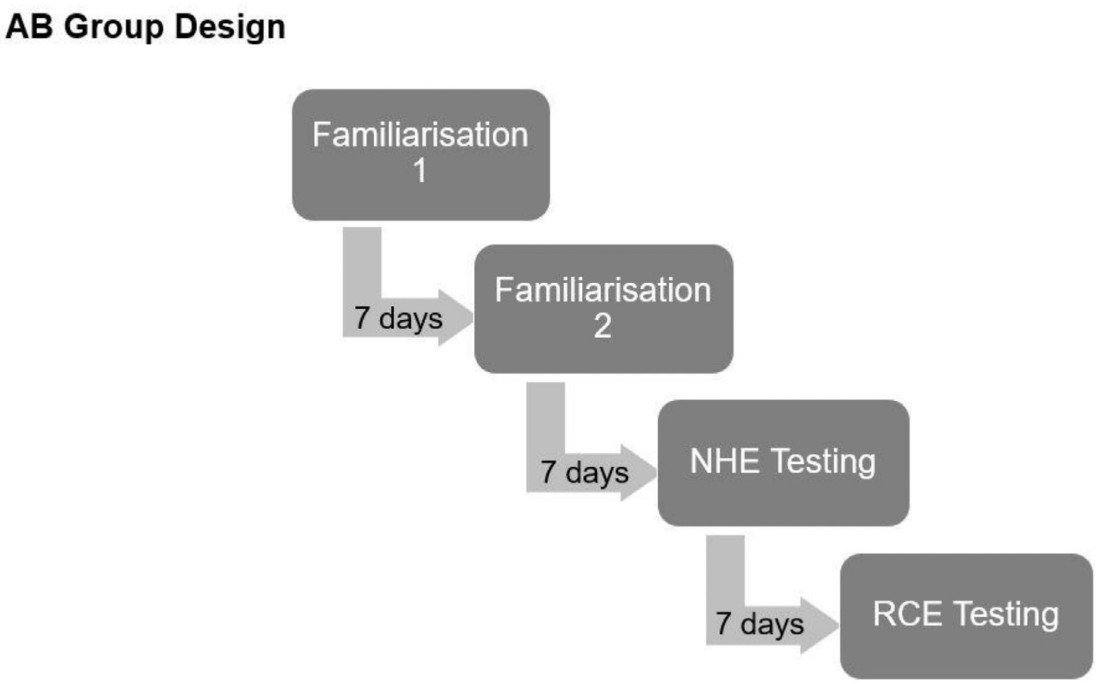


**Figure 1a.** AB Group Study Design. RCE = Razor Curl Exercise. NHE = Nordic Hamstring Exercise.

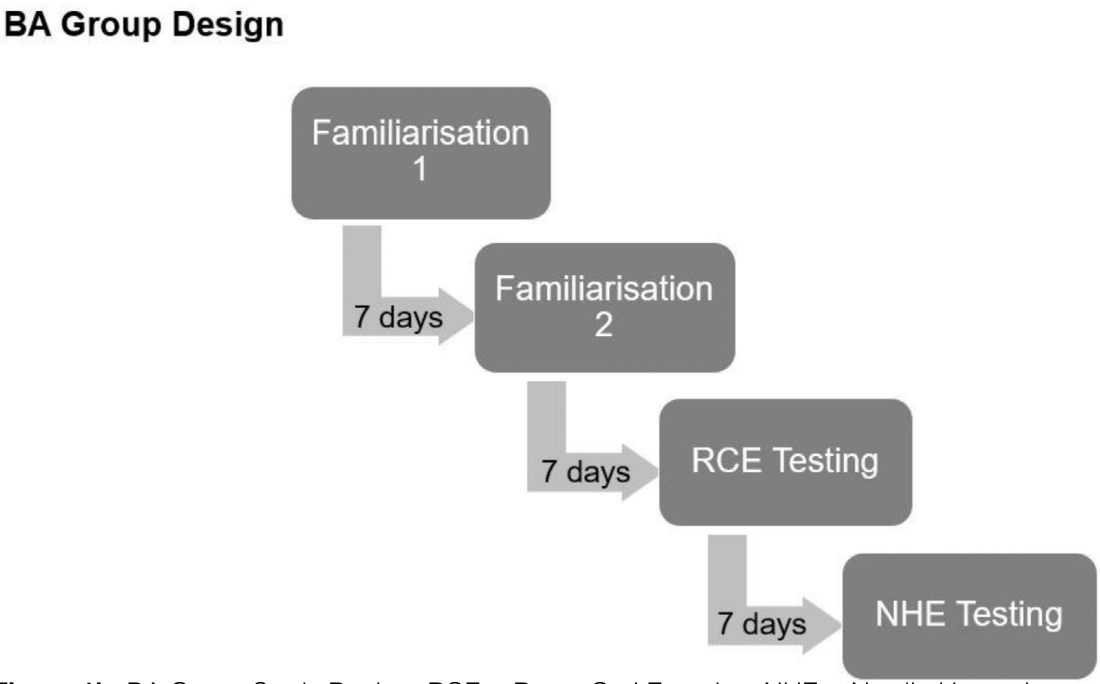


**Figure 1b.** BA Group Study Design. RCE = Razor Curl Exercise. NHE = Nordic Hamstring Exercise.

requiring them to descend into the eccentric lengthening as slowly as possible. The peak force (N) for each repetition was recorded and used to generate average peak force of the 3 repetitions. Following the maximal repetitions, participants were presented with a 10-point Likert scale and asked to grade the soreness of the exercise, used in Freeman et al. (19). Force deficit (%) between each leg, calculated by dividing the lesser force by the greater force to produce a percentage, was also averaged over the three reps.

*Razor Curl Exercise*

An identical warm-up protocol was carried out prior to the RCE, however the NHE was replaced with performing the RCE. Similar to the NHE, participants only completed the eccentric portion of the RCE, starting at 90˚ of hip and knee flexion before extending at the knees and hips. This method was shown to be a reliable assessment (ICC = 0.91 and 0.90, for left and right peak forces, respectively) of eccentric hamstring strength (28). Hip flexion prior to execution was assessed by the present researcher using a goniometer. The body of the goniometer was centred on the greater trochanter of the femur while the stationary arm was aligned with the lateral epicondyle of the femur and the moving arm was aligned with the trunk. Participants were set up so that their knee position is the same as in the NHE test. RCE start position and position at ~75˚ of knee flexion is displayed in figures 3a and 3b, respectively. This test also consisted of 3 maximal repetitions performed on a Hamstring Solo Elite board with the peak force (N) also recorded for each rep and used to generate average peak force. Participants were asked to grade their soreness in the same manner used following the NHE. Force deficit (%) between each leg was also averaged over the three reps.

*Statistical Analyses*

All results were reported as mean ± standard deviation, along with 95% confidence intervals (CI). Mean peak forces (N) for each exercise were analysed as the primary dependent variable of this study and the exercise (NHE or RCE) it was achieved on was to act as the independent variable. Mean peak force figures were reported as an average of the left leg force and right leg force. Inter-limb force deficits (%) and soreness ratings (19) were also analysed as dependent variables. Dependent variables were tested for normality using a Shapiro-Wilk test. Significance testing was then performed to determine if there was an observable difference between force production during each exercise using a dependent t-test. Force deficits and soreness ratings were analysed for significance using Wilcoxon Signed-Rank test, as these variables were found to be non-parametric. Hedges' correction (g) was used to calculate the effect size of the mean peak force variable, as $n < 20$ (22). Effect size for force values were interpreted according to Cohen (13), with ≥ 0.2 being classified as small, ≥ 0.5 as medium and ≥ 0.8 as large. Wilcoxon effect sizes (r) were calculated for the soreness ratings and


**Figure 2a.** NHE Start Position including Hip Angle

**Figure 2b.** NHE at ~80˚ of Knee Flexion


**Figure 3a.** RCE Start Position including Hip Angle

**Figure 3b.** RCE at ~75˚ of Knee Flexion

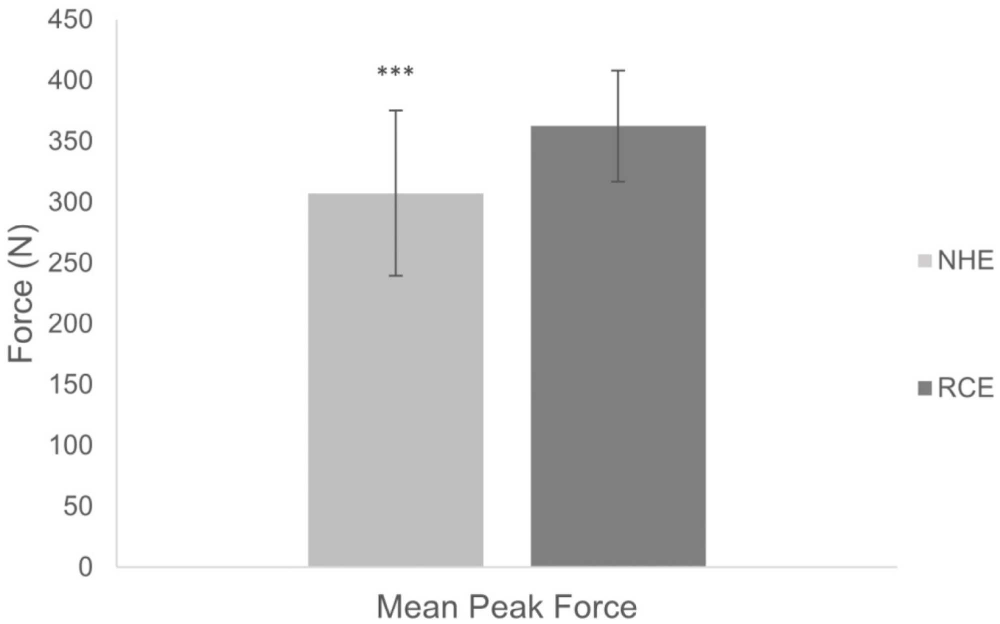


**Figure 4. Mean peak force of NHE vs RCE.** RCE = Razor Curl Exercise. NHE = Nordic Hamstring Exercise. *** = significant difference to RCE ($p < 0.001$).

force deficits, due to these being nonparametric variables, and effect sizes were interpreted as ≥ 0.1 being small, ≥ 0.3 being medium and ≥ 0.5 as large (38). Statistical significance was set at $p \leq 0.05$. All statistical analysis was conducted using Statistical Package for Social Sciences software (Version 28, SPSS Inc., Illinoi, USA).

## RESULTS

All twelve recruited participants were included in results, as none dropped out or had to be excluded. All testing sessions, including familiarisation, were conducted between 14/02/2023 and 07/03/2023. A significant difference was observed between the mean peak force ($p < 0.001$, t (11) = -4.679) of the RCE (362.69 ± 45.86 N, 95% CI [333.55, 391.83]) and NHE (307.33 ± 67.75 N, 95% CI [264.29, 350.38), with a large effect size (g = 1.26). Mean force values are represented in figure 4, below. Average peak forces between exercises across all participants are displayed in figure 5.

No significant difference was noted for inter-limb force deficits ($p = 0.182$, Z = -1.334) during RCE vs NHE (10.57 ± 5.17% vs 15.43 ± 11.69%, 95% CI [7.28, 13.86] vs [8.00, 22.85]), with a medium effect size (r = 0.39). Soreness ratings displayed significance ($p < 0.05$, Z = 2.448) in the RCE (3.83 ± 1.59, 95% CI [2.83, 4.84]) vs the NHE (5.67 ± 1.30, 95% CI [4.84, 6.49]), and showed a large effect size (r = 0.71). Mean soreness ratings for each exercise are shown in figure 6 below. Individual soreness ratings of each exercise are shown in figure 7.

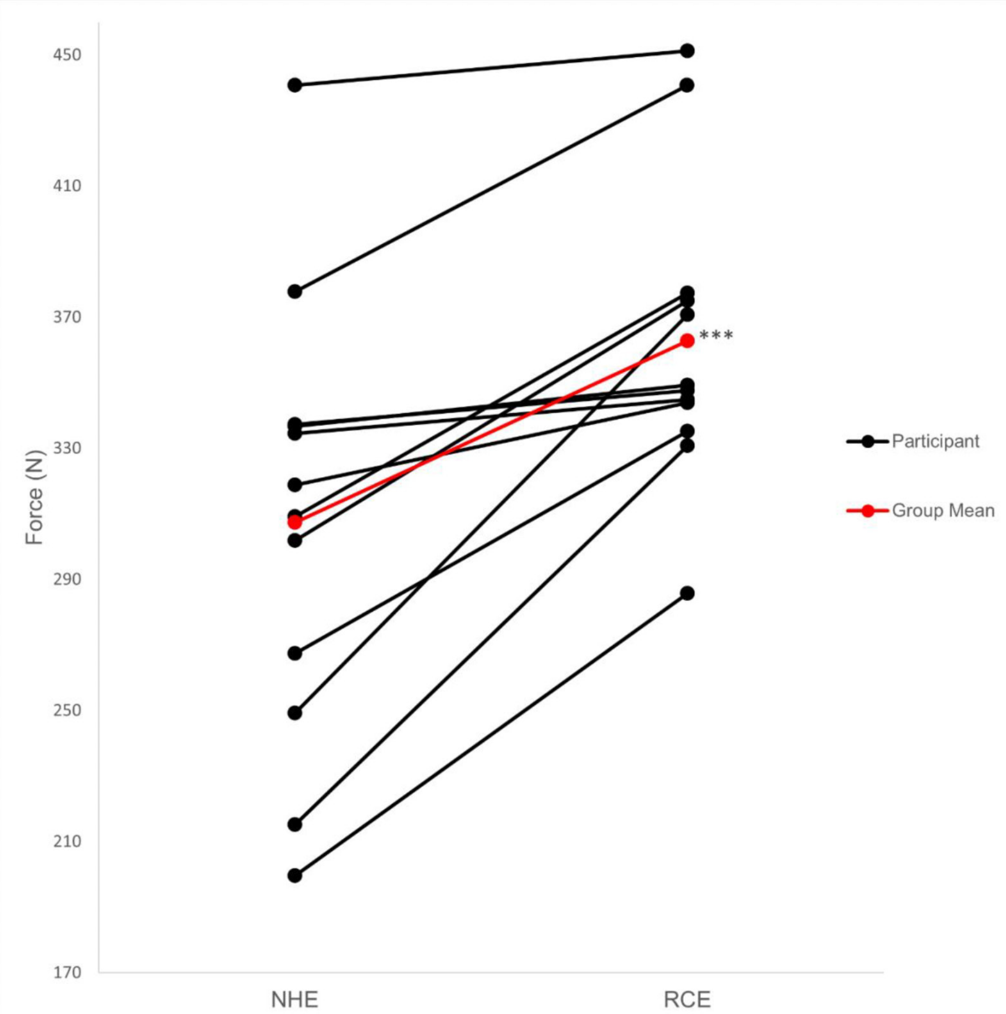


**Figure 5.** Individual Responses NHE Force vs RCE Force. RCE Force = Razor Curl Exercise Average Peak Force. NHE Force = Nordic Hamstring Exercise Average Peak Force. *** = significant difference in group mean to NHE ($p < 0.001$).

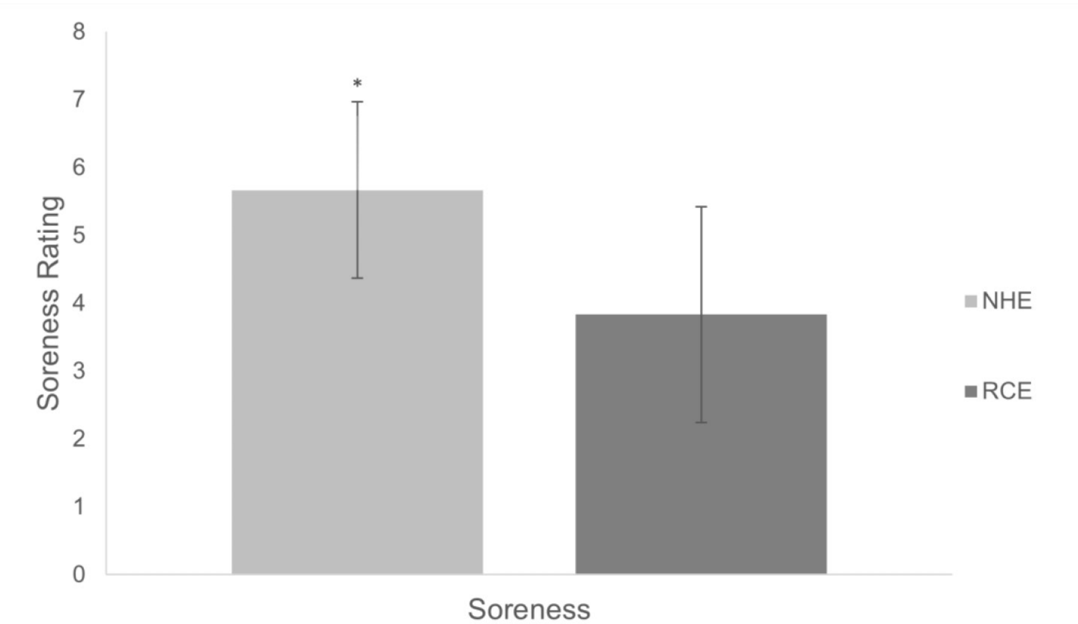


**Figure 6.** Soreness ratings for NHE and RCE. RCE = Razor Curl Exercise. NHE = Nordic Hamstring Exercise. * = significant difference to RCE ($p < 0.05$).

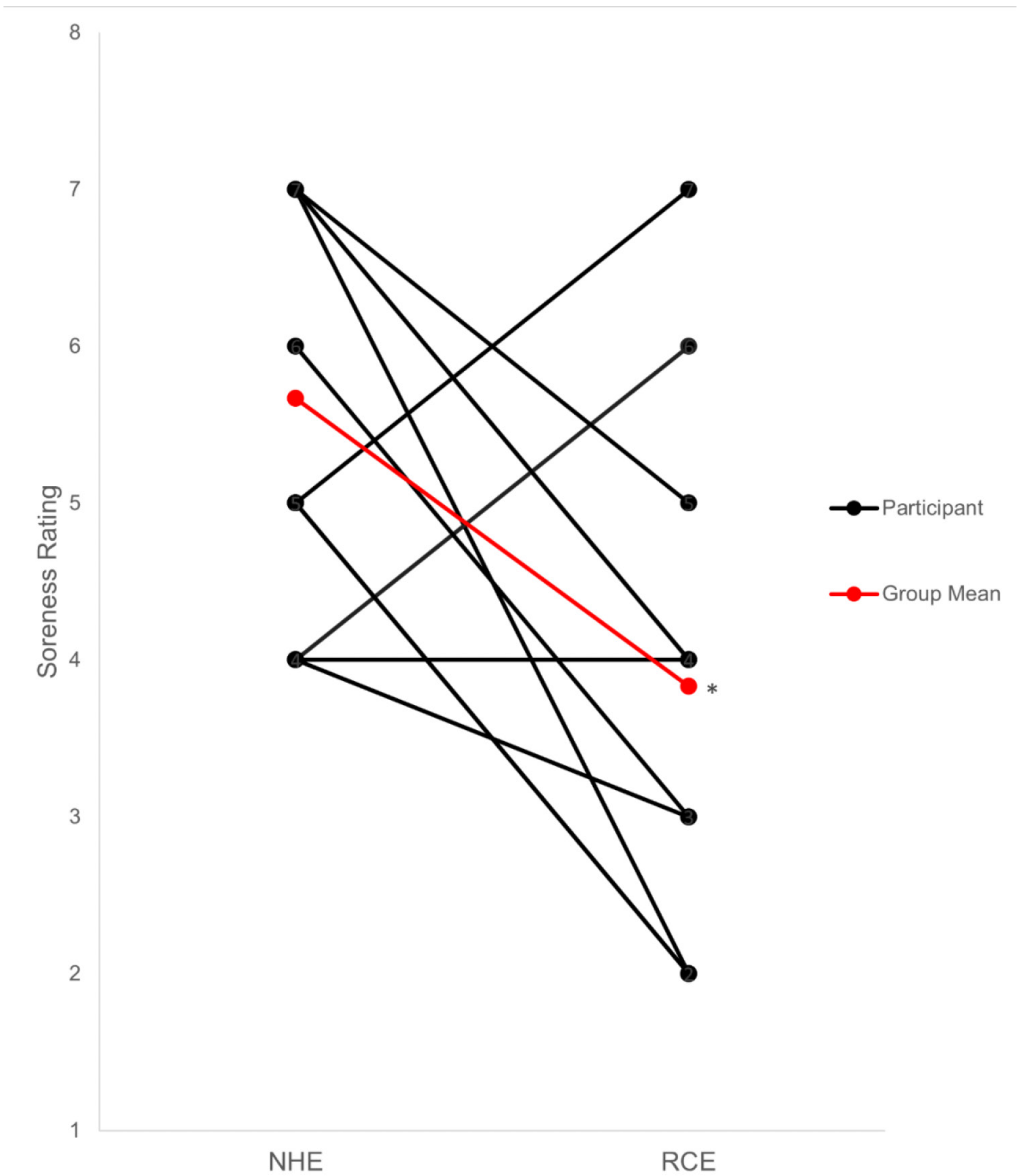


**Figure 7.** Individual Responses NHE Soreness vs RCE Soreness. RCE Soreness = Razor Curl Exercise Soreness Rating. NHE Soreness = Nordic Hamstring Exercise Soreness Rating. * = significant difference in group mean to NHE ($p < 0.05$).

## DISCUSSION

The present study aimed to investigate the differences in force production between the commonly used NHE and the RCE for the purpose of improving training recommendations surrounding eccentric hamstring strengthening. This study has affirmed the initial hypothesis stated through the RCE showing significantly greater force output ($p < 0.001$) when compared to the NHE (362.69 ± 45.86 N vs 307.33 ± 67.75 N, respectively), along with a large effect size (g = 1.26), demonstrating a large magnitude of difference. This finding is in line with arguments extracted from other research (29, 35, 39). A suggestion for the increased force output of the RCE may be linked to an increased contribution of the non-contractile elements of the hamstrings as they are trained at a greater length (35). Furthermore, increased levels of electrical activity, reported as a percentage of maximal voluntary isometric contraction (MVIC), have been detected in the biceps femoris (BF) when in the start position of the RCE (140 ± 33.87% MVIC), when compared to electromyography (EMG) activity in the BF during the NHE (128.1% MVIC) (25, 29). Additionally, peak medial hamstring activity in the RCE has been shown at 220 ± 66.08% MVIC (29), while Sarabon et al. (35) found semitendinosus activity at the time of peak torque to be only 106.7 ± 15.5% MVIC during the NHE. This suggests an increase in force production at the beginning of the movement accredited to greater muscle activity. Although Pollard et al. (33) found strength adaptations of a weighted RCE and NHE to be movement specific in a recreationally trained sample. However, if this is true and the adaptations are specific, it may encourage athletes regularly performing movements with hip and knee flexion to train using the RCE. Additionally, this study's findings lend significance to the suggestion within Oliver and Dougherty (29) of the RCE offering a more biomechanically advantageous position, due to greater force outputs achieved during this movement. As hypothesised, the flexed hip and knee position led to greater force production and potentially demonstrates further applicability of the athletic position witnessed during many sporting movements (11, 16, 29). This familiarity with the athletic position may be another explanation for the increased force. As it appears that RCE strength adaptations are movement specific (33), the fact that athletes commonly perform movements in this position may have led to increased force production during the RCE (11, 16, 29). This finding also agrees with Sarabon et al. (35) and shows that greater forces can be produced while training the BF long head at a greater muscle length. However, the present study did not measure the EMG of the hamstrings and cannot be confident that the reason for the increase in force output was due to greater contractibility of the hamstring at the knee (29).

Additional discoveries of this study include a significantly lower soreness rating ($p < 0.05$) of the RCE (3.83 ± 1.59) vs the NHE (5.67 ± 1.30), paired with a large effect size (r = 0.71). This shows a substantial decrease in the acute muscle soreness experienced following the performance of the RCE. A potential reason for the decreased soreness observed during the RCE may be associated with less muscle damage caused by the RCE. Pollard et al. (33) showed a greater effect on muscle thickness and fascicle length of the BF long head with weighted NHE compared to weighted RCE. Weighted NHE showed a small effect size ($d$ = 0.27) on muscle thickness, while weighted RCE resulted in almost no change ($d$ = -0.03) (33). Additionally, weighted NHE showed a large effect size ($d$ = 1.41) on fascicle length while no change was observed from the RCE ($d$ = 0.00) (33). It is suggested that the differing effects on muscle thickness and fascicle length between the weighted NHE and RCE is associated with decreased involvement of the BF long head during the RCE (33), however it may also be associated with decreased muscle damage resulting from the RCE (8). Furthermore, Sarabon et al. (35), in alignment with suggestions in Pollard et al. (33), demonstrated significantly reduced EMG activity of the BF muscle below 100% MVIC while performing NHE variations involving hip flexion ($p < 0.001$). BF activity reduced as hip flexion increased with the difference in activity between 0° and 75° of hip flexion resulting in a medium effect size ($d$ = 0.74) (35). Contrary to this, Oliver and Dougherty (29) showed increased BF activity in the RCE start position, compared to the NHE. Peak EMG activity of the BF was found to be 140.00 ± 33.87% MVIC in the RCE start position (29), meanwhile peak BF activity during the NHE was recorded at 99.72 ± 22.17% MVIC (35). However, an inverse relationship has previously been determined between EMG activity and hamstring muscle length during eccentric movements (23, 27). This implies that the mean EMG activity of BF is increased during the NHE, despite peak activity being lower than in the RCE (25, 29). This increase in mean activity level of the BF could lead to greater levels of muscle damage causing increased hypertrophy resulting from the NHE, while also increasing the soreness experienced from the exercise (33). Similar to the explanation for greater force during the RCE, a reason for less soreness during the RCE may also be linked to increased familiarity with the position (29).

Moreover, despite no significance being detected for between-leg force deficits (p = 0.182) in the RCE vs NHE (10.57 ± 5.17% vs 15.43 ± 11.69%, respectively), a medium effect size (r = 0.39), favouring RCE, indicates the potential for training with improved symmetry between legs. Observed in conjunction with overall greater force outputs, the lesser deficit shown in the RCE is not at the loss of total force output. This study suggests that the reduced force deficit may be linked to an increased neural drive associated with greater force outputs and marked by increased EMG values (24). Claudino et al. (12) identifies inter-limb force deficit reliability is linked to a maximal contraction occurring, possibly indicating that the decreased RCE deficit is caused by the more forceful contraction. An alternative cause for the lower RCE deficit may be linked to the suggestion of a greater reliance on non-contractile elements proffered within Sarabon et al. (35). This greater reliance could lead to a lesser representation of hamstring muscular strength in RCE deficits. Lower deficits may be especially favourable for those training to reduce force deficits between hamstrings. This appears to be highly critical for athletes performing high-speed running as part of competition, as greater force deficits have been associated with a higher likelihood of HSI (5, 14, 31). The risk of HSI in high level rugby union players has been shown to increase by 2.4 times for those with a deficit of 15-20% and up to 3.4 times for those with a >20% deficit (5). This risk has been shown to be greater within other field sports involving high speed running, with injury risk increasing 4-fold among professional soccer players (14). Despite this, the research is not definitive on the use of muscle strength testing to predict HSI likelihood (4, 41). Previous research has shown that the NHE has a positive effect on between-leg hamstring force deficits (2). Due to its similar function of training and assessing eccentric hamstring strength (28, 29), it may be reasoned that the RCE could result in positive effects on between-leg hamstring deficits and potentially to a greater magnitude.

Meanwhile, the use of NHE for reducing HSI incidence is well-documented across various sports (6, 20), including rugby union (5, 7, 18), and with force outputs < 337 N in the NHE acting as an additional sign of injury risk in elite soccer (37). Although, absolute figures likely need to be investigated in the specific sport and/or exercise to which it is being applied and therefore, force outputs < 337 N in the NHE may not be an applicable indicator of injury risk outside of elite soccer. Following similar suggestions within the present study, the RCE could serve the purpose of injury prevention more effectively than the NHE, due to the increased force output associated with it and similar hip extension movements (35, 39). As previously stated, research is inconclusive on the association of eccentric strength with HSI risk (4, 30, 40, 41). However, research highlighting a link between eccentric force production and HSI suggests that the production of greater eccentric force in training could assist in decreasing HSI rates and therefore the use of the RCE in training may be warranted.

## CONCLUSION

The primary practical recommendation following the findings of this study involves implementing the RCE as an alternative to the NHE, as the findings show it is superior to the NHE in relation to force output. This study found no contradictions to implementing the RCE and the sole modification to its prescription being lower volume exposures performed more frequently. The present study shows that the RCE shows strong potential to act as a more effective exercise for eccentric hamstring training than the NHE, due to its greater force output, decreased soreness and potential to train between-leg asymmetries more effectively.

## FUTURE RECOMMENDATIONS

Recommendations for future research includes larger sample sizes, along with assessing athletes from various sports. Larger and a greater total number of cohorts would strengthen the evidence base surrounding the implementation of the RCE as a more beneficial exercise for training eccentric hamstring strength. Moreover, research into the performance of each exercise following a training intervention, as a randomised control trial, would be recommended as a topic for further research.

A limitation in the design of this study was the time of the year during which testing was conducted. As participants were presently in their competitive season, a greater number of potential participants were excluded due to recent injury than otherwise would have been excluded, were testing conducted in the competitive off-season. This ultimately limited the number of players available to participate in the study. Furthermore, it appears that eccentric hamstring strength fluctuates throughout the competitive calendar (32). This implies that the force values achieved by the present study's participants were blunted due to fatigue, detraining or both due to being in-season. It should also be noted, due to the nature of the study, the participants could not be blinded, along with this they had previous experience with the NHE but not the RCE. Ultimately, this may have led to participant bias influencing the subjective soreness ratings.

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## REFERENCES

1. Al Attar, W., Soomro, N., Sinclair, P., Pappas, E. and Sanders, R. (2016). Effect of Injury Prevention Programs that Include the Nordic Hamstring Exercise on Hamstring Injury Rates in Soccer Players: A Systematic Review and Meta-Analysis. Sports Medicine, [online], 47 (5), available: https://link.springer.com/article/10.1007/s40279-016-0638-2 [accessed 10 July, 2023].
2. Anastasi, S. and Hamzeh, M. (2011). Does the eccentric Nordic Hamstring exercise have an effect on isokinetic muscle strength imbalance and dynamic jumping performance in female rugby union players?. Isokinetics and Exercise Science, [online], 19 (4),

available: https://content.iospress.com/articles/isokinetics-and-exercise-science/ies00420 [accessed 10 July, 2023].

3. Bahr, R., Thorborg, K. and Ekstrand, J. (2015). Evidence-based hamstring injury prevention is not adopted by the majority of Champions League or Norwegian Premier League football teams: the Nordic Hamstring survey. British Journal of Sports Medicine, [online], 49 (22), available: https://bjsm.bmj.com/content/49/22/1466.short [accessed 10 July, 2023].
4. Bennell, K., Wajswelner, H., Lew, P., Schall-Riaucour, A., Leslie, S., Plant, D. and Cirone, J. (1998). Isokinetic strength testing does not predict hamstring injury in Australian Rules footballers. British Journal of Sports Medicine, [online], 32 (4), available: https://bjsm.bmj.com/content/32/4/309.short [accessed 10 July, 2023].
5. Bourne, M., Opar, D., Williams, M. and Shield, A. (2015). Eccentric knee flexor strength and risk of hamstring injuries in rugby union: a prospective study. The American Journal of Sports Medicine, [online], 43 (11), available: https://journals.sagepub.com/doi/full/10.1177/0363546515599633?casa_token=lAdcAZE8JogAAAAA%3Abebi09ZbmzItIRcjrupYCqf6BJWUpK3LRTGVofdoJ35AiIGIUj4nI7ULAIr8mX9SZ6n8U7h9qWks [accessed 10 July, 2023].
6. Bourne, M., Timmins, R., Opar, D., Pizzari, T., Ruddy, J., Sims, C., Williams, M. and Shield, A. (2018). An Evidence-Based Framework for Strengthening Exercises to Prevent Hamstring Injury. Sports Medicine, [online], 48 (2), available: https://link.springer.com/article/10.1007/s40279-017-0796-x [accessed 10 July, 2023].
7. Brooks, J., Fuller, C., Kemp, S. and Reddin, D. (2006). Incidence, risk, and prevention of hamstring muscle injuries in professional rugby union. The American Journal of Sports Medicine, [online], 34 (8), available: https://journals.sagepub.com/doi/full/10.1177/0363546505286022?casa_token=jkaBopdN66YAAAAA%3AiMboFSRlyPbd_5MaQnatlTBoUZeh4VZ8TcApdjseJ-niN4HsoN2frppMfNvm0TOk44LaJ2bhB5k9 [accessed 10 July, 2023].
8. Cadore, E., Gonzalez-Izal, M., Grazioli, R., Setuain, I., Pinto, R. and Izquierdo, M. (2018). Effects of Concentric and Eccentric Strength Training on Fatigue Induced by Concentric and Eccentric Exercise. International Journal of Sports Physiology and Performance, [online], 11 September 2018, available: https://pubmed.ncbi.nlm.nih.gov/30204507/ [accessed 14 January, 2023].
9. Chebbi, S., Chamari, K., Van Dyk, N., Gabbett, T. and Tabben, M. (2022). Hamstring injury prevention for elite soccer players: a real-world prevention program showing the effect of players' compliance on the outcome. Journal of Strength and Conditioning Research, [online], 36 (5), available: https://www.ingentaconnect.com/content/wk/jsc/2022/00000036/00000005/art00030 [accessed 10 July, 2023].
10. Chesterton, P., Tears, C., Wright, M. and Portas, M. (2021). Hamstring injury prevention practices and compliance of the Nordic hamstring program in English professional football. Translational Sports Medicine, [online], 4 (2), available: https://onlinelibrary.wiley.com/doi/full/10.1002/tsm2.209?casa_token=btdSGTY5rJkAAAAA%3A2oKprvFPgEEQsI-mjrr7IssVhjemstYsPWMETXU5yAdHcCDng2ESnfgE2YebLa3qmoBfcrbyo5rxVlc [accessed 10 July, 2023].
11. Clarke, R., Hughes, J., Aspe, R., Sargent, D. and Mundy, P. (2018). Plyometric technical models: biomechanical principles. Professional Strength & Conditioning, [online], 49, available: https://www.researchgate.net/profile/Richard-Clarke-11/publication/328561170_Plyometric_Technical_Models_Biomechanical_Principles/links/5c548c19a6fdccd6b5da6258/Plyometric-Technical-Models-Biomechanical-Principles.pdf [accessed 10 July, 2023].
12. Claudino, J., Filho, C., Bittencourt, N., Goncalves, L., Couto, C., Quintao, R., Reis, G., Junior, O., Amadio, A., Boullosa, D. and Serrao, J. (2021). Eccentric Strength Assessment of Hamstring Muscles with New Technologies: A Systematic Review of Current Methods and Clinical Implications. Sports Medicine – Open, [online], 7 (1), available: https://sportsmedicine-open.springeropen.com/articles/10.1186/s40798-021-00298-7 [accessed 10 July, 2023].
13. Cohen, J. (1988). Statistical power analysis for the behavioral sciences (2nd ed.). Hillsdale, NJ: Lawrence Earlbaum Associates.
14. Croisier, J., Ganteaume, S., Binet, J., Genty, M. and Ferret, J. (2008). Strength imbalances and prevention of hamstring injury in professional soccer players: a prospective study. The American Journal of Sports Medicine, [online], 36 (8), available: https://journals.sagepub.com/doi/full/10.1177/0363546508316764?casa_token=ybJJwkIVABUAAAAA%3AVpX3yiHCwlNdG9EWcL4g0JfChQOSaGGhcXFLLDLJxP80X9ALCCualZ9R7EN3wtBQrnzNBmaBK0yh [accessed 10 July, 2023].
15. Cuthbert, M., Ripley, N., McMahon, J., Evans, M., Haff, G. and Comfort, P. (2020). The Effect of Nordic Hamstring Exercise Intervention Volume on Eccentric Strength and Muscle Architecture Adaptations: A Systematic Review and Meta-analyses. Sports Medicine, [online], 50 (1), available: https://link.springer.com/article/10.1007/s40279-019-01178-7 [accessed 10 July, 2023].
16. DeWeese, B., Serrano, A., Scruggs, S. and Sams, M. (2012). The Clean Pull and Snatch Pull Proper Technique for Weightlifting Movement Derivatives. Strength and Conditioning Journal, [online], 34 (6), available: https://journals.lww.com/nsca-scj/fulltext/2012/12000/the_clean_pull_and_snatch_pull__proper_technique.14.aspx?casa_token=QywOzaaiiiYAAAAA:_Yio4hqIsd3Mf1GQ2Pv5XHE1_ucXigjOz09pAYj9way0VGNgjis0NTT4hIW3bt5imC7vDDZTulLQK_WOf8W_sB2K [accessed 10 July, 2023].
17. Ditroilo, M., Vito, G. and Delahunt, E. (2013). Kinematic and electromyographic analysis of the

Nordic Hamstring Exercise. Journal of Electromyography and Kinesiology, [online] 23 (5), available: https://www.sciencedirect.com/science/article/pii/S1050641113001223?casa_token=savB_yzUIacAAAAA:wwh58dPM2juang9_qz0J5k5YX-Z_y_6v6FOaQ0q5BwBbHzAI7yrg636XxeiNf910MIte-fYzu8tw [accessed 10 July, 2023].
18. Evans, K. and Williams, M. (2017). The effect of Nordic hamstring exercise on hamstring injury in professional rugby union. British Journal of Sports Medicine, [online], 51 (4), available: https://bjsm.bmj.com/content/51/4/316.3?int_source=trendmd&int_medium=trendmd&int_campaign=trendmd [accessed 10 July, 2023].
19. Freeman, B., Young, W., Talpey, S., Smyth, A., Pane, C. and Carlon, T. (2019). The effects of sprint training and the Nordic hamstring exercise on eccentric hamstring strength and sprint performance in adolescent athletes. The Journal of Sports Medicine and Physical Fitness, [online], 59 (7), available: https://www.researchgate.net/profile/Brock-Freeman/publication/327410656_The_effects_of_sprint_training_and_the_Nordic_hamstring_exercise_on_eccentric_hamstring_strength_and_sprint_performance_in_adolescent_athletes/links/5fd7dbcb299bf140880f56d4/The-effects-of-sprint-training-and-the-Nordic-hamstring-exercise-on-eccentric-hamstring-strength-and-sprint-performance-in-adolescent-athletes.pdf [accessed 10 July, 2023].
20. Gerard, R., Gojon, L., Decleve, P. and Van Cant, J. (2020). The Effects of Eccentric Training on Biceps Femoris Architecture and Strength: A Systematic Review With Meta-Analysis. Journal of Athletic Training, [online], 55 (5), available: https://meridian.allenpress.com/jat/article/55/5/501/436800/The-Effects-of-Eccentric-Training-on-Biceps [accessed 10 July, 2023].
21. Goode, A., Reiman, M., Harris, L., DeLisa, L., Kauffman, A., Beltramo, D., Poole, C., Ledbetter, L. and Taylor, A. (2015). Eccentric training for prevention of hamstring injuries may depend on intervention compliance: a systematic review and meta-analysis. British Journal of Sports Medicine, [online], 49 (6), available: https://bjsm.bmj.com/content/49/6/349.short [accessed 10 July, 2023].
22. Goulet-Pelletier, J. and Cousineau, D. (2018). A review of effect sizes and their confidence intervals, Part I: The Cohen'sd family. The Quantitative Methods for Psychology, [online], 14 (4), available: https://www.tqmp.org/RegularArticles/vol14-4/p242/p242.pdf [accessed 10 July, 2023].
23. Higashihara, A., Ono, T., Kubota, J. and Fukubayashi, T. (2010). Differences in the electromyographic activity of the hamstring muscles during maximal eccentric knee flexion. European Journal of Applied Physiology, [online], 108, available: https://link.springer.com/article/10.1007/s00421-009-1242-z [accessed 10 July, 2023].
24. Hug, F., Goupille, C., Baum, D., Raiteri, B., Hodges, P. and Tucker, K. (2015). Nature of the coupling between neural drive and force-generating capacity in the human quadriceps muscle. Proceedings of the Royal Society B: Biological Sciences, [online], 282 (1819), available: https://royalsocietypublishing.org/doi/full/10.1098/rspb.2015.1908 [accessed 10 July, 2023].
25. Llurda-Almuzara, L., Labata-Lezaun, N., López-de-Celis, C., Aiguadé-Aiguadé, R., Romaní-Sánchez, S., Rodríguez-Sanz, J., Fernández-de-Las-Peñas, C. and Pérez-Bellmunt, A. (2021). Biceps femoris activation during hamstring strength exercises: a systematic review. International Journal of Environmental Research and Public Health, [online], 18 (16), available: https://www.mdpi.com/1660-4601/18/16/8733 [accessed 10 July, 2023].
26. Lodge, C., Tobin, D., O'Rourke, B. and Thorborg, K. (2020). Reliability and Validity of a New Eccentric Hamstring Strength Measurement Device. Archives of Rehabilitation Research and Clinical Translation, [online], 2 (1), available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7853328/ [accessed 11 November, 2022].
27. Lunnen, J., Yack, J. and LeVeau, B. (1981). Relationship between muscle length, muscle activity, and torque of the hamstring muscles. Physical Therapy, [online], 61 (2), available: https://academic.oup.com/ptj/article-abstract/61/2/190/2727294 [accessed 10 July, 2023].
28. O'Brien, J., Browne, D., Earls, D. and Lodge, C. (2021). Reliability of the Hip Extension Lower Exercise as a Measure of Eccentric Hamstring Strength. Biomechanics, [online], 2 (1), available: https://www.mdpi.com/2673-7078/2/1/1 [accessed 10 July, 2023].
29. Oliver, G. and Dougherty, C. (2009). The razor curl: a functional approach to hamstring training. Journal of Strength and Conditioning Research, [online], 23 (2), available: https://journals.lww.com/nsca-jscr/Fulltext/2009/03000/Effect_of_Neuromuscular_Training_on.00009.aspx?casa_token=0jgiOa1NwnwAAAAA:bWzW4fASSW9ATxkxctwaD7DPesbSmU9ETqSzFLZZPKMgZALhJw4q_mAmB2aHG2V6c6IqFlwnOI3Qi8V5nLhWFXtI [accessed 10 July, 2023].
30. Opar, D., Timmins, R., Behan, F., Hickey, T., van Dyk, N., Price, K. and Maniar, N. (2021). Is Pre-season Eccentric Strength Testing During the Nordic Hamstring Exercise Associated with Future Hamstring Strain Injury? A Systematic Review and Meta-analysis. Sports Medicine, [online], 51 (9), available: https://link.springer.com/article/10.1007/s40279-021-01474-1 [accessed 10 July, 2023].
31. Opar, D., Williams, M. and Shield, A. (2012). Hamstring strain injuries: factors that lead to injury and re-injury. Sports Medicine (Auckland, NZ), [online], 42 (3), available: https://link.springer.com/article/10.2165/11594800-000000000-00000 [accessed 10 July, 2023].
32. Opar, D., Williams, M., Timmins, R., Hickey, J., Duhig, S. and Shield, A. (2015). Eccentric Hamstring Strength and Hamstring Injury Risk in Australian Footballers. Medicine and Science in Sports and Ex-

ercise, [online], 47 (4), available: https://eprints.qut.edu.au/75526/ [accessed 10 July, 2023].

33. Pollard, C., Opar, D., Williams, M., Bourne, M. and Timmins, R. (2019). Razor hamstring curl and Nordic hamstring exercise architectural adaptations: impact of exercise selection and intensity. Scandinavian Journal of Medicine & Science in Sports, [online], 29 (5), available: https://onlinelibrary.wiley.com/doi/full/10.1111/sms.13381?casa_token=BE_C1PYJDE-QAAAAA%3AbdqfcVQppFmJowGtRbCrVbSPU4A8I-TLquMPgHb5MC8D-rVm6JaalmkYXuNDSCi03mHW-Dyi81vAME9GY [accessed 10 July, 2023].
34. Presland, J., Timmins, R., Bourne, M., Williams, M. and Opar, D. (2018). The effect of Nordic hamstring exercise training volume on biceps femoris long head architectural adaptation. Scandinavian Journal of Medicine & Science in Sports, [online], 28 (7), available: https://onlinelibrary.wiley.com/doi/full/10.1111/sms.13085?casa_token=z8RQQ3WZD-1kAAAAA%3ArLIxgzVudouWUPDLDtaf2vWyPS8jD-ppTj16A1v9PwvOq0rMUZthR1fWEZLVIOizZNC7B-kQ07L1hjo8A [accessed 10 July, 2023].
35. Sarabon, N., Marusic, J., Markovic, G. and Kozinc, Z. (2019). Kinematic and electromyographic analysis of variations in Nordic hamstring exercise. PloS One, [online], 14 (10), available: https://pubmed.ncbi.nlm.nih.gov/31644582/ [accessed 14 January, 2023].
36. Sibbald, B. and Roberts, C. (1998). Understanding controlled trials. Crossover trials. BMJ (Clinical Research Ed.), [online], 316 (7146), available: https://www.bmj.com/content/316/7146/1719.short [accessed 10 July, 2023].
37. Timmins, R., Bourne, M., Shield, A., Williams, M., Lorenzen, C. and Opar, D. (2016). Short biceps femoris fascicles and eccentric knee flexor weakness increase the risk of hamstring injury in elite football (soccer): a prospective cohort study. British Journal of Sports Medicine, [online], 50 (24), available: https://bjsm.bmj.com/content/50/24/1524.short [accessed 10 July, 2023].
38. Tomczak, M. and Tomczak, E. (2014). The need to report effect size estimates revisited. An overview of some recommended measures of effect size. Trends in Sport Sciences, [online], 1 (21), available: https://www.wbc.poznan.pl/dlibra/publication/413565?language=en [accessed 10 July, 2023].
39. Whyte, E., Heneghan, B., Feely, K., Moran, K. and O'Connor, S. (2021). The Effect of Hip Extension and Nordic Hamstring Exercise Protocols on Hamstring Strength: A Randomized Controlled Trial. Journal of Strength and Conditioning Research, [online], 35 (10), available: https://www.ingentaconnect.com/content/wk/jsc/2021/00000035/00000010/art00004 [accessed 10 July, 2023].
40. Wille, C., Stiffler-Joachim, M., Kliethermes, S., Sanfilippo, J., Tanaka, C. and Heiderscheit, B. (2022). Preseason Eccentric Strength Is Not Associated with Hamstring Strain Injury: A Prospective Study in Collegiate Athletes. Medicine and Science in Sports and Exercise, [online], 54 (8), available: https://europepmc.org/article/med/35420594 [accessed 10 July, 2023].
41. Yeung, S., Suen, A. and Yeung, E. (2009). A prospective cohort study of hamstring injuries in competitive sprinters: preseason muscle imbalance as a possible risk factor. British Journal of Sports Medicine, [online], 43 (8), available: https://bjsm.bmj.com/content/43/8/589.short [accessed 10 July, 2023].
42. Yoshida, R., Sato, S., Kasahara, K., Murakami, Y., Murakoshi, F., Aizawa, K., Koizumi, R., Nosaka, K. and Nakamura, M. (2022). Greater effects by performing a small number of eccentric contractions daily than a larger number of them once a week. Scandinavian Journal of Medicine & Science in Sports, [online], 32 (11), available: https://onlinelibrary.wiley.com/doi/full/10.1111/sms.14220 [accessed 10 July, 2023].