Effects of Different Inter-Set Rest Intervals during the Nordic Hamstring Exercise in Young Male Athletes

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Context: The Nordic hamstring exercise (NHE) is known to reduce hamstrings injury (HIS) risk in athletes. In order to optimise the NHE it is important to understand how acute resistance training variables influence its performance. ***Objective:*** To examine the effects of different inter-set rest intervals (ISRI) on force indices during performance of the NHE. ***Design:*** Crossover Study. ***Setting:*** Laboratory based. ***Patients or Participants*****:** Ten (age = 20.7 ± 2.3 years; height = 179.4 ± 5.5 cm; body mass = 83.9 ± 12.4 kg) well-trained young male team-sport athletes. ***Intervention:*** Participants performed 2 x 6 repetitions of the NHE with either a SHORT (one-minute) or LONG (three-minute) ISRI. All sets were performed on the NordBord. ***Main Outcomes Measure(s):*** Peak force (N), average force (N), percent maintenance (%) and percent decline (%) were recorded for both dominant and non-dominant limbs as well as inter-limb force asymmetries (%) calculated. ***Results:*** Analyses revealed no statistically significant interactions or main effects ($p > 0.05$) between conditions and sets in all variables. However, analysis of individual repetitions showed significant reductions ($p < 0.05$, ES = 0.58-1.28) in peak force from repetition four onwards. ***Conclusions:*** Our findings suggest that a one-minute ISRI is sufficient to maintain force production qualities and inter-limb asymmetries between sets during the NHE in well-trained athletes. However, practitioners should be aware of the potentially high decrements in peak force production that may occur within the set.

Key Words: Youth Sports, Eccentric, Resistance Training, Injury Prevention

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Key Points:

- Minimal reductions in eccentric hamstrings force indices between sets occur when performing the NHE in well-trained individuals.
- A one-minute rest interval between sets during the NHE is adequate to maintain performance although three-minutes may provide modest benefits.
- The structure of the NHE set may potentially be enhanced via the inclusion of fewer repetitions to ensure peak force is maintained throughout the whole set.

In order to maximise an athlete's adaptation to imposed stimuli during resistance training (RT), an athletic trainer can manipulate a number of program-related factors. This includes factors such as the inter-set rest interval (ISRI), muscle action type, loading and volume, order and performance frequency of a given exercise. Of the aforementioned, the ISRI is critical in underpinning both the acute and chronic responses to RT because its duration influences the development of physical qualities such as muscle strength and power.[1] This is because an extended ISRI facilitates the restoration of adenosine triphosphate (ATP) and phosphocreatine (PC) by ~85% within three-minutes of exercise cessation[2] making it reasonable to assume that the longer the ISRI the greater the acute benefit that is derived from RT performance. Results from previous research support this assertion as greater improvements in muscular strength have been reported when using a three-minute (LONG) compared to a one-minute (SHORT) ISRI.[3] Accordingly, when targeting increases in muscular strength, practitioners are encouraged to utilise a longer ISRI. However, whether this approach is applicable to all muscle actions types is unknown.

Despite current recommendations for prescribing the ISRI during RT it should be noted that current guidelines are based on exercises that emphasise a predominant concentric muscle action. Considering the distinctive nature of physiological responses to eccentric muscle actions, the prescription of eccentric RT (ERT) exercises requires a more targeted approach.[4] For example, the energy cost of eccentric muscle actions is lower compared to concentric muscle actions.[5] Furthermore, eccentric muscle actions have been shown to be more fatigue resistant than concentric actions during isokinetic exercises of the knee extensors.[6] Considering the lesser fatigue experienced during eccentric muscle actions it is plausible that during ERT longer ISRI's may not be warranted in the way that they are prescribed for concentric-dominant exercises. This may be of particular importance to practitioners when implementing an injury prevention programme (IPP) considering that time constraints are a perceived barrier.[7] Therefore, information of how the ISRI influences during ERT can provide practitioners with further knowledge of how to optimise its training prescription. This is especially necessary since practitioners place a degree of high importance in developing eccentric strength within an injury prevention programmes (IPP).[7]

An ERT exercise that is known to reduce the risk of hamstring injuries (HSI) in athletes is the Nordic hamstring exercise (NHE) which has been reported to reduce HSI by up to 51% in athletes.[8] This has been attributed to the benefits it conveys in developing eccentric hamstrings strength as well as muscle architectural properties such as increased fascicle length.[9] To date, previous research has shown the NHE to improve both eccentric hamstrings toque and endurance[10] as well as reducing inter-limb asymmetries.[11] This is particularly necessary considering that factors such as low eccentric hamstring strength,[12] high eccentric hamstrings force asymmetries[13] and hamstring fatigue[14] have been cited to increase HSI risk. However, although a number of factors relating to the effective training prescription of the NHE are known, limited information exists concerning how the ISRI may influence its performance. Consequently, knowledge of how acute training prescription variables such as the ISRI may optimise performance of the NHE could provide practitioners with further guidance on its implementation within an IPP. Therefore, the purpose of this study was to examine the effects of a SHORT (one-minute) vs LONG (three-minute) ISRI on such measures during the NHE. Due to the lower levels of fatigue associated with eccentric muscle actions, we hypothesized that the length of the ISRI used for the NHE would not result in significant differences in performance between sets.

METHODS

Study Design

Our study used a randomised repeated measures crossover design to assess the effect of different ISRI's on selected indices such as force, asymmetries and fatigue during the NHE. The randomisation was performed according to a computer generated sequence (www.randomizer.org). Participants were required to perform two sets of six repetitions of the NHE with either a one-minute (SHORT) or three-minute (LONG) ISRI. We divided pariticpants into two separate groups and performed one of the conditions in their first session before changing to the second condition in the following session (76-96 hours apart). The NHE dosage was chosen in accordance with previous literature that demonstrated positive changes in eccentric hamstring strength within young team-sport athletes when including this prescription.[15]

Although all participants had previous exposure to the NHE, a familiarisation session was required to fully prepare for the execution of the exercise and laboratory procedures and to ensure they met the required inclusion criteria. Prior to SHORT and LONG sessions, the participants completed the same standardized ten-minutes warm-up, including low-intensity jogging, change of direction drills, lower limb dynamic stretching, and jumping-based tasks. All testing sessions occurred at the same time of day (~8am).

Participants

A prior power analysis was conducted (G*Power; University of Düsseldorf, Dusseldorf, Germany) to determine the minimum sample size required to find significance with a desired level of power set at 0.80, an alpha error of 0.05 and an effect size of 0.53 based on previous research investigating the effects of NHE training on young male soccer athletes.[15] Subsequently, the sample included ten young male team-sport athletes (age = 20.7 ± 2.3 years; height = 179.4 ± 5.5 cm; body mass = 83.9 ± 12.4 kg). Participants were physically active and were undertaking two to three sessions of supervised RT and three to five sport specific practices per week. Since previous HSI can influence indices such as force and asymmetries we required participants to meet the following inclusion criteria: i) peak force eccentric hamstring score ≥337 N during the NHE;[12] ii) peak force asymmetry of <15% during the NHE;[13] iii) regular (i.e. once per week) exposure to the NHE within their current training; and iv) clear of any lower-limb injury within the previous six-months as documented by the team's medical department. Participants were instructed to avoid vigorous exercise, caffeine and aclohol consumption for a minimum of 24 hours prior to any of the testing sessions. Additionally, nutritional aids throughout the testing process were prohibited. After explaining the scope of the study, written informed consent was obtained from all players. The University Research Committee provided ethical approval prior to the beginning of testing, and the study was completed in accordance with the Declaration of Helsinki.

Procedures

Anthropometrics

Before testing started, data on age, stature, and body mass was recorded. Participants' standing height was measured using a stadiometer (model 213; seca, Birmingham, England), to the nearest 0.1 cm and body mass was measured, using a calibrated electronic scale (model 813; seca, Birmingham, England), to the nearest 0.1 kg.

Eccentric Hamstrings Strength

The NHE was performed on the NordBord apparatus (Vald Performance, Australia), which has been shown to be a reliable device (CV% = 6.1%–7.4%) to assess eccentric hamstrings strength in young athletes.[16] All testing occurred at the same facility, which was the university's performance gym. For the assessment of eccentric hamstrings strength, participants knelt on the padded part of the NordBord and were positioned with their ankles secured with padded hooks, which were attached to load cells. The participants' position was altered so that ankles would be perpendicular to the lower leg and the hooks were positioned superior to the lateral malleolus. Participants were instructed to gradually lower the upper body trying to resist the movement by contracting the hamstrings and keeping the trunk and hips held in a neutral position throughout. Participants' arms were flexed at the elbow joints such that the palms of the hands were facing forward at the level of the shoulder joints to help buffer the fall as they approached the ground.

For the ascent, participants were assisted back to the starting position. As soon as the participants reached the starting position they were then required to immediately begin the next repetition. Peak force (N), determined as the highest force output from a single repetition and average force (N), calculated as the mean of the peak force outputs from all of the six repetitions, was recorded for each condition and set using LabChart 7.3 (AD Instruments, New South Wales, Australia). All data were subsequently analysed in a predesigned Microsoft Excel spreadsheet, with the scores from each limb calculated.

Calculating Asymmetry and Fatigue

Inter-limb asymmetries for each set were quantified and calculated in accordance with current recommendations.[17] Specifically, the average peak force of each limb across the set was recorded and the magnitude of the inter-limb asymmetries were calculated using the percentage difference method: 100/(maximum value)×(minimum value)×-1+100. The ability to maintain force during all repetitions in each set was assessed using the following equation: percent maintenance = 100 – [(mean set – repetition_1)/repetition_1] × 100.[18] Additionally, the effect of the ISRI length in each condition was determined by a percent decline from the first to 12th repetition using the following equation: percent decline = [(repetition_{12} – repetition_1)/repetition_1] × 100.[18]

Statistical Analyses

All data from each NHE repetition was recorded and entered into Microsoft Excel™ to compute means and standard deviations (SD). Subsequent statistical analysis was performed using Statistical Package for the Social Sciences (SPSS) version 26 (IBM Corp., Armonk, NY, USA) with statistical significance set at $p < 0.05$. Normality was assessed via the Shapiro-Wilk test. A two-way repeated measures ANOVA was performed to assess differences in peak force between conditions (SHORT vs LONG) for individual repetitions (repetitions one to six) in sets one and two. Subsequently, simple planned contrasts were used to assess changes in peak force between repetition one and subsequent repetitions. A two-way repeated measures ANOVA was also performed to assess differences in conditions between sets (set one vs set two) for all force indices measures (peak force, average force, percent maintenance and inter-limb asymmetries). In the event of a significant *F* ratio, post hoc comparisons were made using a Bonferroni correction. The Independent Samples T-Test was used to assess differences between dominant (D) and non-dominant (ND) limbs as well as for percent decline between conditions. Effect sizes (ES) were calculated using Cohen's *d* and defined with the following thresholds: <0.20 = trivial, 0.20 - 0.59 = small, 0.60 - 1.19 = moderate, 1.20 - 1.99 = large, 2.0 - 3.99 = very large, and >4.0 = extremely large.[19]

RESULTS

Force Production

All data were normally distributed ($p > 0.05$). Figure 1 shows the differences between repetitions in Set 1 and Set 2 for peak force. In Set 1 the D Limb showed no significant condition*repetition effect for peak force ($F = 0.570$, $p = 0.723$) but a main repetition effect was observed ($F = 7.636$, $p < 0.001$). Planned contrasts revealed repetitions four ($p = 0.013$, ES = 0.58, -4.86%), five ($p < 0.001$, ES = 0.94, -7.57%) and six ($p < 0.001$, ES = 1.13, -8.25%) were significantly lower compared to repetition one. In Set 2 the D Limb showed no significant condition*repetition effect for peak force ($F = 0.128$, $p = 0.985$) but a main repetition effect was observed ($F = 4.118$,

p <0.004). Planned contrasts revealed repetitions five (p <0.008, ES = 0.82, -4.53%) and six (p <0.001, ES = 0.85, -6.70%) were significantly lower compared to repetition one. Set 1 for the ND Limb showed no significant condition*repetition effect for peak force (F = 0.704, p = 0.624) but a main repetition effect was observed (F = 8.175, p <0.01). Planned contrasts revealed repetitions four (p = 0.002, ES = 0.77, -7.94%), five (p = <0.001, ES = 1.26, -11.49%) and six (p = <0.001, ES = 1.28, -12.61%) were significantly lower compared to repetition one. No significant condition*repetition or main effects were found in the ND limb for Set 2. Table 1 shows the differences between sets in D and ND limbs for peak force, average force and percent maintenance. No significant condition*set interactions or main effects existed for peak force in both D and ND limbs (Figure 2). Independent Samples T-Test results showed no significant differences between SHORT (p = 0.652, ES = 0.21) and LONG (p = 0.560, ES = 0.21) conditions for D and ND limbs. No significant condition*set interactions or main effects existed for average force in both D and ND limbs (Figure 3). Independent Samples T-Test results showing no significant differences between SHORT (p = 0.988, ES = 0.00) and LONG (p = 0.867, ES = 0.07) conditions for D and ND limbs.

Insert Table 1 and Figures 1-3 Near Here

Fatigue

No significant condition*set interactions or main effects were noted for percent maintenance values in both D and ND limbs (Figure 4). Independent Samples T-Test revealed no significant differences between D and ND limbs in both SHORT (p = 0.164, ES = 0.65) and LONG (p = 0.892, ES = -0.06) conditions. Additionally, for percent decline (Figure 5), Independent Samples

T-Test revealed no significant differences between D SHORT vs D LONG (p = 0.882, ES = 0.07), ND SHORT vs ND LONG (p = 0.718, ES = 0.16), D SHORT VS ND SHORT (p = 0.578, ES = 0.25) and D LONG vs ND LONG (p = 0.892, ES = 0.06).

Insert Figures 4-5 Near Here

Inter-Limb Asymmetries

Due to the low variation between sets and small sample size the percentage agreement between sets was calculated to determine the internal consistency for the direction of inter-limb asymmetries. The percentage agreement for tests were 90% and 70% for SHORT and LONG groups, respectively. Inter-limb asymmetries (Figure 6) in the SHORT group were 8.99% (± 8.57%) and 8.85% (± 5.08%) for set one and set two, respectively. In the LONG group, inter-limb asymmetries were 8.06% (± 7.75%) and 8.54% (± 8.16%) for set one and set two, respectively. No significant condition*set interactions or main effects existed. Figure 7 shows the between-group standardised differences for all measures.

Insert Figures 6 and 7 Near Here

DISCUSSION

To our knowledge, this is the first study to investigate the effects of the ISRI on NHE force indices. Although previous literature has reported the benefits of utilising a longer ISRI during RT for exercises that are largely concentric in nature, the findings from this study reported no significant differences between conditions and sets during the NHE for all force indices, an exercise that is eccentric in nature. However, although minimal, between-set reductions in measures such as peak and average force production were lower in the LONG ISRI condition. Analysis of the individual repetitions showed that significant decrements in peak force can occur within the a NHE set from repetition four onwards. Overall, the results from this study demonstrate that whilst a one-minute rest interval between sets is sufficient to maintain selected force indices during the NHE, peak force can begin to significantly decrease mid-way through the set in comparison to the first repetition.

The non-significant changes between sets in force production values in our study are in accordance with previous research which also reported no changes in peak maximal eccentric torque of the hamstrings during six sets of five repetitions of the NHE.[20] This finding is somewhat to be expected since peak force is likely to occur at the beginning of the set which is what our results showed too. However, when the changes in peak and average force values in both the D and ND limbs between sets were standardised between conditions (Figure 7) the LONG ISRI was more favourable, although only to a small magnitude. Comparatively, the minimal changes between sets during the NHE in our study is not in accordance with previous research investigating the ISRI during lower-limb resistance training. For example, when performing the leg extension exercise for multiple sets with a ten repetition maximum load, very large and large reductions in performance have been shown by the second set regardless of the duration of the ISRI (one-minute: ES = 6.15; three-minute: ES = 1.54, respectively).[21] The minimal influence of the ISRI during the NHE could be explained by the SHORT IRSI providing adequate time to recover between sets due to the eccentric muscle action that occurs during the exercise. This is because of the lower energy expenditure, reduced carbohydrate utilisation and lesser oxygen consumption observed during eccentric exercise compared to that of concentric exercise.[5] Consequently, it is possible that due to the eccentric nature of the NHE a shorter ISRI between sets is sufficient to restore energy stores and thus maintain force production values between sets.

Our results showed that peak force begun to significantly decrease from repetition four onwards compared to first repetition in set one in the D and ND limb as well as from repetition five in set two for the D limb (Figure 1). Whilst direct comparisons to previous research is difficult due to the differences between exercises, peak force during lower-limb RT training has been shown to decrease from repetition one to all subsequent repetitions' when performing six repetitions of the loaded jump squat.[22] The reductions in peak force occurring later during the NHE set may reflect the lower metabolic costs that occur during eccentric muscle actions compared to concentric muscle actions which consequently reduces mechanical force output.[23] Furthermore, the intermittent nature of the NHE may also help explain our findings. This is because of the time delay that exists between the ending of the descent phase and returning to the start position which inadvertently provides a short rest interval between repetitions. Indeed, the inclusion of an inter-repetition rest has been shown to be beneficial in reducing muscle metabolites and maintaining performance during lower-limb resistance-training.[24] Therefore, based on our findings, it may be permissible to utilise lower repetitions ranges when prescribing the NHE or to include an inter-repetition rest interval after each repetition to try to ensure high levels of eccentric hamstrings force production are achieved throughout the whole set.

Percent maintenance between sets did not differ with participants achieving peak force values above 93% across sets in both conditions. Interestingly, there was a tendency for greater force maintenance values to be observed in the second set compared to the first set. The lower percent maintenance values during the first set compared to the second set are in line with previous research which showed that the greatest declines in eccentric torque occurs during the beginning of the exercise before platueing.[25] However, we believe the percent decline values provide a more accurate insight into the force reductions that occurred during the NHE compared to percent maintenance. This is because the percent maintenance values within the set take into consideration the mean of the peak force values from all six repetitions performed whilst the percent declines calculate the loss of force from the first to the twelve repetition. Consequently, the absolute percentage losses noted between repetitions one to six (>12%) along with the percent decline values in all conditions (7-10%) would suggest that the losses in force production during the NHE may in fact be high. For instance, reported losses in concentric peak force when performing four repetitions of the deadlift at 90% 1-RM and during six repetitions of the jump squat exercise have been 2.3%[26] and ~3%, respectively.[22] Our results somewhat reflect the losses in average eccentric hamstrings torque reported after one set of five repetitions of the NHE reported of up to 17%.[20] Subsequently, although eccentric muscle actions are known to be less fatiguing that concentric actions[7] it may be possible that the specific nature of eccentric hamstrings actions are more susceptible to fatigue. Indeed, it has been recently shown that fatigue was more pronounced during eccentric exercise of the hamstrings compared to eccentric exercise of the quadriceps.[27] Therefore, our results suggest that when prescribing the NHE practitioners should be cognizant of the potentially large decrements in force that can occur within the set and aim to minimise this.

The inter-limb asymmetry values produced by our participants are in accordance with those recently reported of 8.77% (± 7.92%) in professional male team-sport athletes that had no history of HSI in the prior season.[28] Therefore, it may be advisable that uninjured, well-trained individuals with experience of the NHE should be expected to achieve eccentric hamstrings asymmetry values during the NHE to be <15%. Indeed, individuals above this threshold have been shown to be at higher risk of HSI.[13] Furthermore, the high levels of variability observed in our asymmetry values are also similar to previous research reporting inter-limb asymmetries during the NHE.[28] Therefore, as per current recommendations, it is necessary to undertake an individual approach when interpreting inter-limb asymmetry data.[29] As per our results for other force indices measures, inter-limb asymmetries did not differ between sets or conditions. Whilst our previous explanations for the minimal changes between sets for the other force indices measures may also apply here, our inclusion criteria which required participants to meet a minimum threshold of eccentric hamstrings strength and be injury-free may also provide further reasoning. For example, it has been demonstrated that stronger athletes exhibit less asymmetry than weaker athletes during lower-limb strength tasks.[30] Additionally, individuals with a prior HSI have shown greater declines in knee flexor torque production during an isokinetic endurance test in previously injured than non-injured legs.[14] Consequently, although further research is required to investigate how the ISRI length may influence eccentric hamstring inter-limb asymmetries between injured and non-injured athletes, our findings demonstrate that practitioners can use a one-minute ISRI during the NHE to maintain this quality.

Limitations

This study has some limitations. We utilised one and three-minute ISRI's and therefore considering the minimal differences observed between SHORT and LONG groups, the inclusion of a shorter ISRI may have provided further details with regard to the minimum ISRI required. Additionally, further analysis of changes in force indices across additional sets of the NHE as reported in previous literature[20] may have offered further insight into the fatigue aspects of exercise. However, using low-dosage NHE training is a time efficient strategy from a practitioner's perspective and this approach has been shown to be as effective in developing eccentric hamstrings strength and muscle architecture properties in young male team-sport athletes compared to higher volumes.[9] Additionally, the force indices we measured in this study do not represent angle specific changes in eccentric hamstring force. This is important to acknowledge as reductions in eccentric torque have been found to occur in the final 15° of range of motion following the NHE.[20] Consequently, future research should aim to examine how the length of the ISRI influences angle specific eccentric hamstring forces as well as the longitudinal effects of using a SHORT vs LONG IRSI on eccentric hamstrings strength and muscle architecture properties.

CONCLUSIONS

To the authors knowledge, this is the first study to examine the effects of different ISRIs during the NHE. The findings from this study demonstrate that the use of a one-minute ISRI is adequate to maintain force indices and inter-limb asymmetries during the NHE. Therefore, practitioners can use our findings when prescribing the NHE within an IPP with non-injured players who are accustomed to the exercise. However, practitioners should be aware of the potential for high reductions in eccentric hamstrings strength to occur within a set. Overall, whilst our results provide practitioners with further guidance on the effective prescription of the NHE, current guidelines for its prescription still requires further deliberation.

References

1. de Salles BF, Simão R, Miranda H, et al. Strength increases in upper and lower body are larger with longer inter-set rest intervals in trained men. *J Sci Med Sport*. 2010;13(4):429-433.
2. McMahon S, Jenkins D. Factors affecting the rate of phosphocreatine resynthesis following intense exercise. *Sports Med*. 2002;32(12):761-784.
3. Schoenfeld BJ, Pope ZK, Benik FM, et al. Longer interset rest periods enhance muscle strength and hypertrophy in resistance-trained men. *J Strength Cond Res*. 2016;30(7):1805-1812.
4. Suchomel TJ, Wagle JP, Douglas J, et al. Implementing eccentric resistance training—Part 1: A brief review of existing methods. *J Funct Morphol Kinesiol*. 2019;4(2):38.
5. Penailillo L, Blazevich A, Nosaka K. Energy expenditure and substrate oxidation during and after eccentric cycling. *Eur J Appl Physiol*. 2014;114(4):805-814.
6. Baroni BM, Stocchero CM, do Espirito Santo RC, et al. The effect of contraction type on muscle strength, work and fatigue in maximal isokinetic exercise. *Isokinet Exerc Sci*. 201;19(3):215-220.
7. Read PJ, Jimenez P, Oliver JL, et al. Injury prevention in male youth soccer: current practices and perceptions of practitioners working at elite English academies. *J Sports Sci*. 2018;36(12):1423-1431.
8. Van-Dyk N, Behan FP, Whiteley R. Including the Nordic hamstring exercise in injury prevention programmes halves the rate of hamstring injuries: a systematic review and meta-analysis of 8459 athletes. *Br J Sports Med*. 2019;53(21):1362-1370.

9. Lacome M, Avrillon S, Cholley Y et al. Hamstring eccentric strengthening program: does training volume matter? *Int J Sports Physiol Perform*. 2020;15(1):81-90.

10. Matthews MJ, Heron K, Todd S, et al. Strength and endurance training reduces the loss of eccentric hamstring torque observed after soccer specific fatigue. *Phys Ther Sport.* 2017;25:39-46.

11. Anastasi SM, Hamzeh MA. Does the eccentric Nordic Hamstring exercise have an effect on isokinetic muscle strength imbalance and dynamic jumping performance in female rugby union players? *Isokinet Exerc Sci.* 2011;19(4):251-260.

12. Timmins RG, Bourne MN, Shield AJ, et al. Short biceps femoris fascicles and eccentric knee flexor weakness increase the risk of hamstring injury in elite football (soccer): a prospective cohort study. *Br J Sports Med*. 2016;50(24):1524-1535.

13. Bourne MN, Opar DA, Williams MD, et al. Eccentric knee flexor strength and risk of hamstring injuries in rugby union: a prospective study. *Am J Sports* Med. 2015;43(11):2663-2270.

14. Lord C, Ma'ayah F, Blazevich AJ. Change in knee flexor torque after fatiguing exercise identifies previous hamstring injury in football players. *Scand J Med Sci Sports*. 2018;28(3):1235-1243.

15. Drury B, Green T, Ramirez-Campillo R, et al. Influence of Maturation Status on Eccentric Hamstring Strength Improvements in Youth Male Soccer Players After the Nordic Hamstring Exercise. *Int J Sports Physiol Perform*. 2020;18(1):1-7.

16. Fernandes JF, Moran J, Clarke H, et al. The influence of maturation on the reliability of the Nordic hamstring exercise in male youth footballers. *Transl. Sports Med*. 2020;3(2):148-153.

17. Bishop C, Read P, Chavda S, et al. Using unilateral strength, power and reactive strength tests to detect the magnitude and direction of asymmetry: a test-retest design. *Sports*. 2019;7(3):58.

18. Tufano JJ, Conlon JA, Nimphius S, et al. Maintenance of velocity and power with cluster sets during high-volume back squats. *Int J Sports Physiol Perform*. 1;11(7):885-892.

19. Hopkins WG, Marshall SW, Batterham AM, et al. *Progressive statistics for studies in sports medicine and exercise science*. 2009:3-12.

20. Marshall PW, Lovell R, Knox MF, et al. Hamstring fatigue and muscle activation changes during six sets of Nordic hamstring exercise in amateur soccer players. *J Strength Cond Res*. 2015;29(11):3124-3133.

21. Senna G, Willardson JM, de Salles BF, et al. The effect of rest interval length on multi and single-joint exercise performance and perceived exertion. *J Strength Cond Res*. 2011;25(11):3157-3162.

22. Hansen KT, Cronin JB, Newton MJ. The effect of cluster loading on force, velocity, and power during ballistic jump squat training. *Int J Sports Physiol Perform*. 2011;6(4):455-468.

23. Gonzalez-Izal M, Cadore EL, Izquierdo M. Muscle conduction velocity, surface electromyography variables, and echo intensity during concentric and eccentric fatigue. *Muscle & nerve*. 2014;49(3):389-397.

24. Girman JC, Jones MT, Matthews TD, et al. Acute effects of a cluster-set protocol on hormonal, metabolic and performance measures in resistance-trained males. *Eur J Sport Sci*. 2014;14(2):151-159.

25. McNeil CJ, Allman BL, Symons TB, et al. Torque loss induced by repetitive maximal eccentric contractions is marginally influenced by work-to-rest ratio. *Eur J Appl Physiol.* 2004;91(5-6):579-585.

26. Moir GL, Graham BW, Davis SE, et al. Effect of cluster set configurations on mechanical variables during the deadlift exercise. *J Hum Kinet.* 2013;18(39):15.

27. Paulus J, Croisier JL, Kaux JF, et al. Eccentric versus Concentric—Which Is the Most Stressful Cardiovascularly and Metabolically? *Current Sports Medicine Reports*. 2019;18(12):477-489.

28. Ribeiro-Alvares JB, Oliveira GD, De Lima-E-Silva FX, et al. Eccentric knee flexor strength of professional football players with and without hamstring injury in the prior season. *Eur J Sport Sci*. 2020;27:1-9.

29. Bishop C, Lake J, Loturco I, et al. Interlimb asymmetries: The need for an individual approach to data analysis. *J Strength Cond Res*. 2018;27.

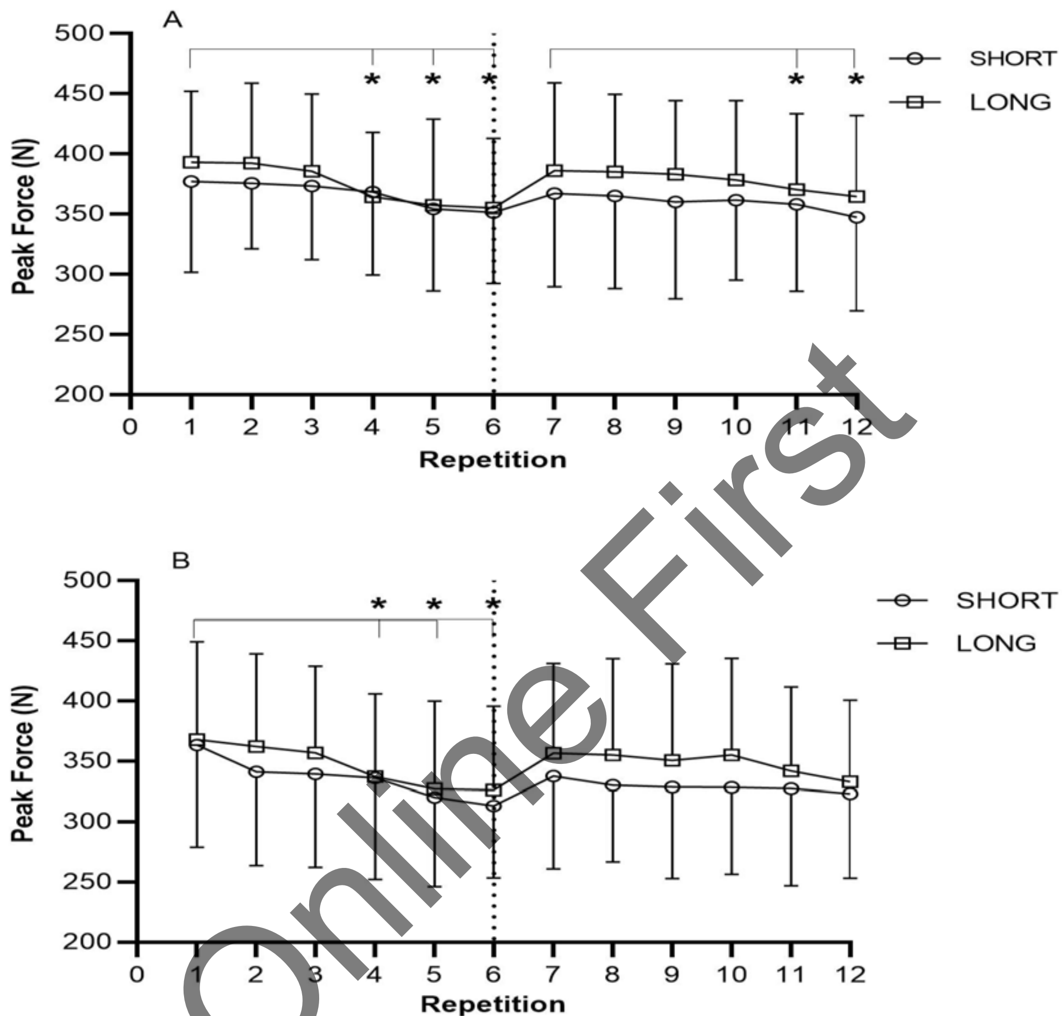
30. Bailey CA, Sato K, Burnett A, et al. Force-production asymmetry in male and female athletes of differing strength levels. *Int J Sports Physiol Perform*. 2015;10(4):504-508.

Table 1. Changes in Eccentric Hamstrings Force Indices Measures Between Sets for SHORT and LONG Conditions.

Variable	Group	Set 1	Set 2	ES (90% CI)	ANOVA Condition	ANOVA Set	ANOVA Condition x Set
Peak force (N)	Short-D	398.60 ± 58.64	388.60 ± 69.35	-0.16 (-0.89, 0.59)	$F = 1.079$	$F = 1.228$	$F = 0.571$
	Long-D	405.70 ± 62.88	406.30 ± 59.89	0.01 (-0.73, 0.74)	$p = 0.326$	$p = 0.296$	$p = 0.469$
	Short-ND	371.00 ± 81.42	354.60 ± 73.50	-0.21 (-0.94, 0.53)	$F = 1.641$	$F = 2.452$	$F = 0.623$
	Long-ND	380.80 ± 80.94	374.70 ± 73.37	-0.08 (-0.81, 0.66)	$p = 0.232$	$p = 0.152$	$p = 0.450$
Average force (N)	Short-D	366.63 ± 61.17	360.40 ± 70.90	-0.09 (-0.83. 0.65)	$F = 0.998$	$F = 0.103$	$F = 0.771$
	Long-D	374.63 ± 58.63	377.93 ± 62.29	0.05 (-0.68, 0.79)	$p = 0.334$	$p = 0.756$	$p = 0.403$
	Short-ND	335.55 ± 73.38	329.18 ± 71.04	-0.09 (-0.82, 0.65)	$F = 1.851$	$F = 0.402$	$F = 0.376$
	Long-ND	346.18 ± 70.28	347.48 ± 73.62	0.02 (-0.72, 0.75)	$p = 0.207$	$p = 0.542$	$p = 0.555$
Maintenance (%)	Short-D	98.14 ± 8.15	96.35 ± 8.26	-0.22 (-0.95, 0.53)	$F = 0.046$	$F = 0.148$	$F = 1.164$
	Long-D	95.31 ± 3.18	98.53 ± 5.57	0.71 (-0.08, 1.44)	$p = 0.835$	$p = 0.709$	$p = 0.397$
	Short-ND	93.04 ± 7.00	98.00 ± 7.53	0.68 (-0.10, 1.41)	$F = 0.136$	$F = 3.492$	$F = 1.017$
	Long-ND	94.81 ± 6.23	97.43 ± 3.56	0.52 (-0.25, 1.24)	$p = 0.721$	$p = 0.094$	$p = 0.340$

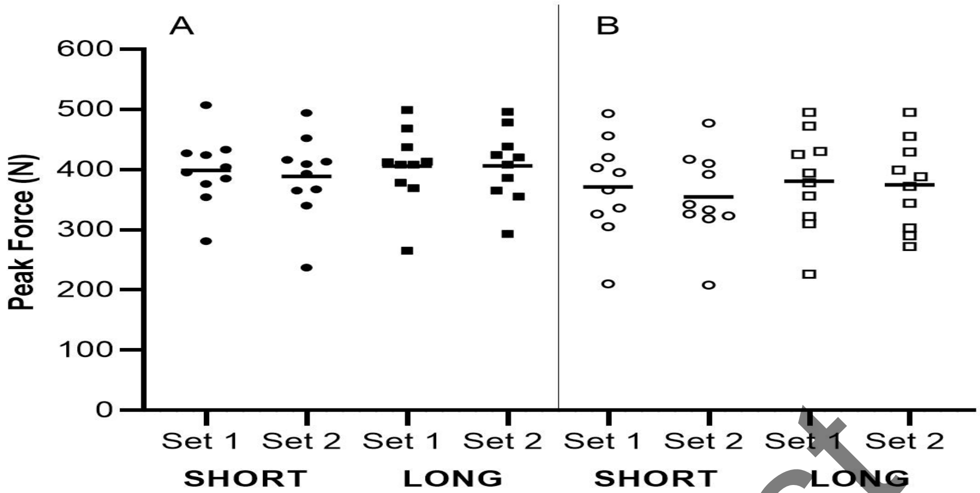
Abbreviations: Short-D, one-minute inter-set rest interval dominant limb; Long-D, three-minute inter-set rest interval dominant limb; Short-ND, one-minute inter-set rest interval non-dominant limb; Long-ND, three-minute inter-set rest interval non dominant limb; ES (90%), effect size with 90% confidence intervals; ANOVA, analysis of variance.

Figures 1. Mean and SD of all Individual Repetitions for Eccentric Hamstrings Peak Force during SHORT and LONG ISRI Conditions.



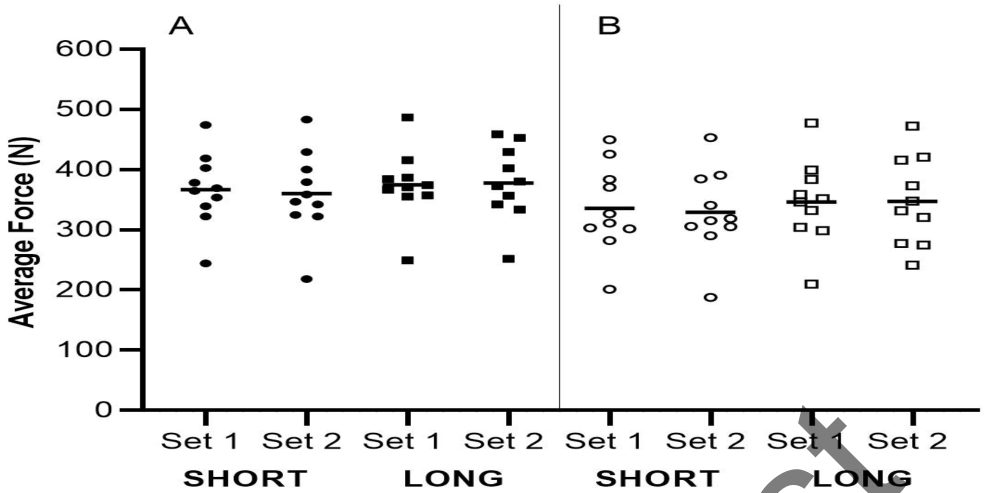
Abbreviations: SHORT, one-minute inter-set rest interval; LONG, three-minute inter-set rest interval; A) Dominant Limb B) Non-Dominant Limb. *Significant main effect for time (p < 0.05) between repetitions. The dashed line represents the end of set one and the beginning of set two.

Figure 2. Mean and Individual Changes in Eccentric Hamstrings Peak Force for SHORT and LONG ISRI Conditions.



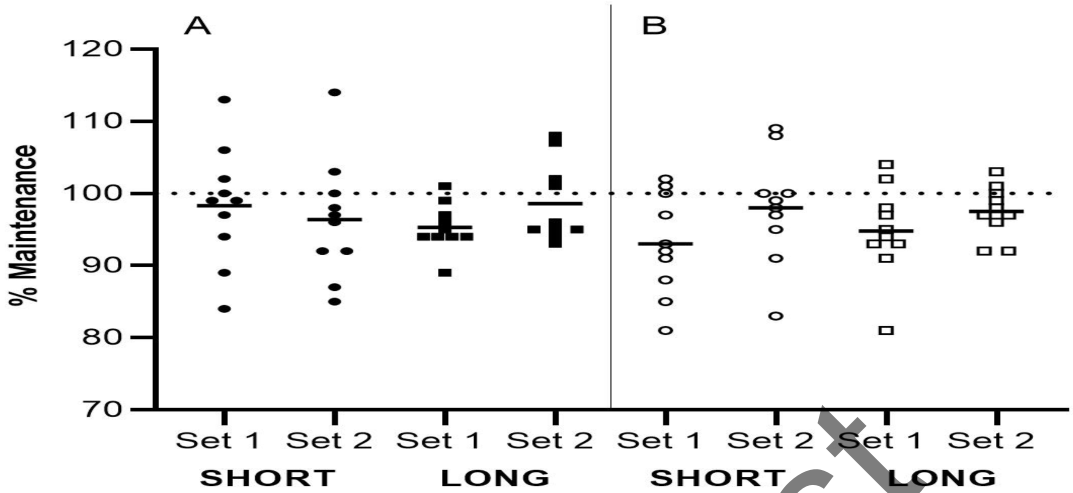
Abbreviations: SHORT, one-minute inter-set rest interval; LONG, three-minute inter-set rest interval; A) Dominant Limb, B) Non-Dominant Limb.

Figure 3. Mean and Individual Changes in Eccentric Hamstrings Average Force for SHORT and LONG ISRI Conditions.



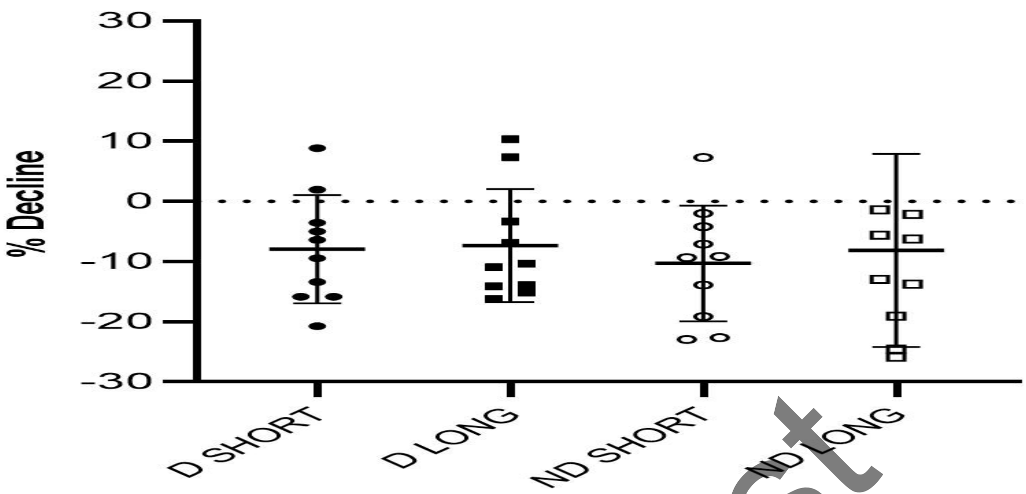
Abbreviations: SHORT, one-minute inter-set rest interval; LONG, three-minute inter-set rest interval; A) Dominant Limb, B) Non-Dominant Limb.

Figure 4. Mean and Individual Changes for Percent Maintenance of Eccentric Hamstrings Peak Force in SHORT and LONG ISRI Conditions.



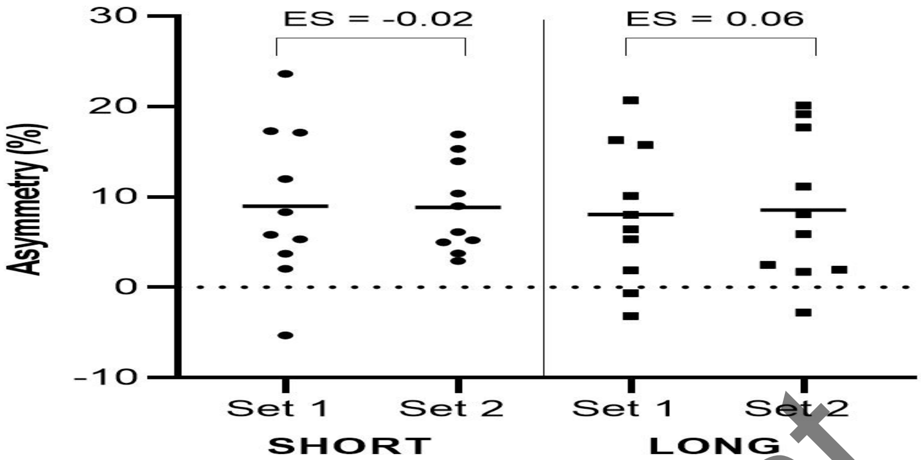
Abbreviations: SHORT, one-minute inter-set rest interval; LONG, three-minute inter-set rest interval; A) Dominant Limb, B) Non-Dominant Limb.

Figure 5. Mean and SD for Percent Decline of Eccentric Hamstrings Peak Force in SHORT and LONG ISRI Conditions.



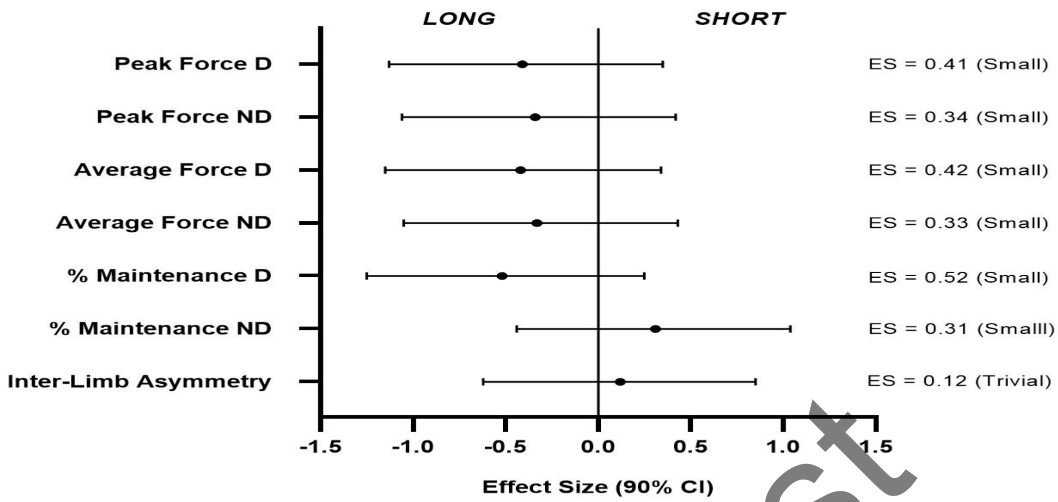
Abbreviations: D SHORT, dominant limb one-minute inter-set rest interval; D Long, dominant limb three-minute inter-set rest interval; ND Short, non-dominant limb one-minute inter-set rest interval; ND Long, non-dominant limb three-minute inter-set rest interval.

Figure 6. Mean and Individual Changes in Eccentric Hamstrings Inter-Limb Asymmetry Between Sets for SHORT and LONG ISRI Conditions.



Abbreviations: SHORT, one-minute inter-set rest interval; LONG, three-minute inter-set rest interval; ES, effect size.

Figure 7. Between Condition Standardised Differences with 90% Confidence Intervals for Force Indices Measures.



Abbreviations: Long, three-minute inter-set rest interval; Short, one-minute inter-set rest interval; D, dominant limb; ND, non dominant limb; ES, effect size including ES descriptor (error bars show the upper and lower CI limits).