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Review

The effects of the Nordic hamstring exercise on sprint performance and eccentric knee flexor strength: A systematic review and meta-analysis of intervention studies among team sport players

Iker J. Bautista[a,*], Juan Vicente-Mampel[a], Luis Baraja-Vegas[a], Víctor Segarra[d], Fernando Martín[b], Bas Van Hooren[c]

[a] Department of Physiotherapy, Catholic University of Valencia, Spain
[b] Department of Physical Education and Sports, University of Valencia, Spain
[c] Department of Nutrition and Movement Sciences, UNTRIM School of Nutrition and Translational Research in Metabolism, Maastricht University Medical Centre+, The Netherlands
[d] ProElite Performance, CESADE Physiotherapist Clinic, Spain

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ABSTRACT

Objectives: The primary aim of this study was to investigate the effects of the Nordic hamstring exercise (NH_E) on sprint performance (i.e., 5, 10 and 20 m) and explore associations between study characteristics and sprint outcomes in team sport players. Secondary aims were to (1) investigate the effects of the NH_E on eccentric strength of the knee flexors (ES_{KF}) with categorical subgroup analysis to determine differences between recreationally, well-trained individuals and young athletes, (2) determine the relation between ES_{KF} and sprint performance in team sport players, and (3) explore the effect of study characteristics (i.e., weekly volume, time duration and body mass) on ES_{KF}.
Methods: Electronic databases were searched until the 20th of June 2020. 17 studies met the inclusion criteria. Random-effects meta-analyses were used to determine the mean difference (MD) or standardized change of mean difference (SCMD) between NH_E and control group for sprint time and ES_{KF}, respectively.
Results: NH_E interventions showed a positive effect on sprint performance (−0.04 s [−0.08, −0.01]). Sub-group meta-analyses indicated no significant differences in 5 and 20 m sprint performance ($MD_{sprint(5m)} = -0.02$ s [−0.10, 0.06]) and ($MD_{sprint(20m)} = -0.05$ s [−0.30, 0.19]), respectively. A significant difference was however found for 10 m sprint performance ($MD_{sprint(10m)} = -0.06$ s [−0.10, −0.01]). Meta-analysis on the effects of the NH_E on ES_{KF} showed a significant benefit of 0.83 SCMD [0.55, 1.12] in favour of the intervention group.
Conclusions: Studies with some concerns or high risk of bias show that training programs involving the NH_E can have small beneficial effects on sprint performance in team sport players. Studies with some concerns or high risk of bias showed moderate beneficial effects on ES_{KF} among a sample of relatively untrained individuals. However, for well-trained team sport players, the improvements in ES_{KF} were less consistent, suggesting a higher training intensity during the NH_E may be required to induce adaptations.

Practical implications

The findings of this review have several practical applications. First, our findings show that the NH_E might be used to improve sprint performance. This is an important finding as this suggests coaches can implement this exercise to improve proxies of performance, which could lead to a better implementation of this exercise. However, it is important to note that an optimal stimulus should also include other exercises (e.g., sprint training) to optimize performance and minimize injury risk. Additionally, further research is required to investigate if other exercise interventions are more effective than the NH_E. Further, the variability in weekly volume in the included studies was large, with interventions ranging from 40 to 82 reps per week (see Supplementary file Tables 4 and 5). A high numbers of set and repetition can cause acute undesired fatigue and may lead to more muscle soreness, both of which potentially reduce the compliance with the exercise.[1,2] Our findings show that the weekly volume of the NH_E can be relatively small (23–48 reps), whilst still being effective at improving eccentric strength of the hamstrings and hence potentially sprint performance. Further, although volume is typical manipulated in studies investigating the effects of the NH_E on various performance and

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* Corresponding author.
E-mail address: ij.bautista@ucv.es (I.J. Bautista).

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injury related outcomes, our findings suggest that intensity is also an important variable to take into account, since a higher intensity is potentially required to continuously induce training adaptations in stronger individuals.

1. Introduction

Hamstring injuries are one of the most common and severe non-contact injury in sports involving high-speed running such as soccer, rugby, baseball,[3–7] with the biceps femoris long head being the most commonly affected muscle.[3,5,8–10] Modifiable risk factors for hamstring injuries include low levels of (eccentric) hamstring strength, [8,11] shorter biceps femoris long head fascicle length,[3] higher levels of eccentric strength asymmetries,[12] and poorer fatigue-resistance as well as lumbo-pelvic control.[13]

A training program that includes the Nordic hamstring exercise (NH_E) can effectively modify several of these risk factors. Specifically, intervention studies involving the NH_E have shown increases in biceps femoris fascicle length,[14–17] as well as improvements in eccentric strength of the knee flexors (ES_{KF}).[18,19] These findings were confirmed in a recent meta-analysis, where Cuthbert et al.[20] showed that 6 or more weeks of training using the NH_E resulted in increases in fascicle length (ES = 2.58) as well as in eccentric strength (ES = 2.12). When the NH_E-based training protocol has adequate compliance (e.g., >96%) it is also effective at reducing hamstring injury incidence.[1,21] However, the compliance is often low in practice in both recreational and professional athletes, which therefore reduces the effectiveness of the exercise.[2,22]

Low compliance with the NH_E is related to several factors, such as muscle soreness as a result of performing the exercise.[22] Another reason for the low adoption rate may be that coaches are often mostly interested in exercises that (directly) improve the performance of their athletes, rather than injury preventative exercises, although such exercises may indirectly also improve the team's performance by having more players available. Nevertheless, interventions that can improve both performance and prevent injuries may therefore see a higher adoption and hence higher injury preventative effect in practice.

While research on the NH_E as an injury prevention exercise has been rising over the last decade,[14,23–26] there has also been a growing interest on the effects that this exercise can have on proxies of sports performance such as sprint performance.[27,28] Several recent studies have shown that the NH_E can improve sprint performance and a wide variety of physical performance measures such as jumping, change of direction and repeated sprint ability in handball and soccer players.[27,29] These studies reported that the NH_E intervention lasted no more than 10 min, making it a time-efficient training method to improve proxies of performance. However, conflicting results have been shown for the effects of the NH_E on performance related outcomes.[30,31] For example, a study performed by Mendiguchia et al.[30] revealed that NH_E intervention group showed smaller improvement in sprint performance compared to a sprint training group. In contrast, Freeman et al.[32] showed better improvements in sprint performance after an intervention program using NH_E in comparison to a sprint training group. Yet, other studies report improvements of sprint performance when compared to continued 'normal' sports practice.[29,33]

To the author's knowledge there is no systematic review and meta-analysis that summarizes the results of studies that have investigated the effects of the NH_E on sprint performance, adequately assesses their scientific rigor and attempts to explore which variables can be modified to increase the effectiveness of the interventions. Therefore, the primary aim of this study was (a) to investigate the effects of the NH_E on sprint performance (i.e., 5, 10 and 20 m) and explore relations between study characteristics (e.g. number of sessions per week, weekly volume, study duration and study type) and sprint outcomes in sport team players. Such information may be of interest to coaches as well as researchers interested in hamstring injury prevention as well as performance enhancement. Further, improvements in strength are often considered as an important contributor to improvements in performance.[34] Indeed, in a descriptive-correlation study (n = 119), Markovic et al.[35] showed a large correlation (r −0.52, $p < 0.001$) between 20 m sprint performance and ES_{KF} in soccer players. Consequently, the relatively large proportion of sprint variance explained by ES_{KF} suggests that both variables are related and that improvements in ES_{KF} could lead to improvements in sprint performance and potentially to improvements in performance in other tasks as well. A second aim was therefore (b) to examine the effects of the NH_E on $ES_{KF,}$ with subgroup analysis to determine differences between recreationally, well-trained and young athlete category levels (c) determine the relation between ES_{KF} and sprint performance across studies, and (d) further explore the effect of study characteristics on ES_K. This information can in turn provide indications on variables that can be manipulated to improve ES_K, which in turn might improve sports performance.

Finally, several studies have shown different training effects between recreationally active and well-trained individuals. For example, a study performed by Suarez-Arrones et al.[31] showed that professional soccer players with previous experience in NH_E programs (i.e., one year of systematic training) showed less improvement in ES_{KF} in comparison to those players without prior NH_E training experience (3.19% vs. 15.6%, respectively). Further, a study among recreationally active males found a very large increase in peak eccentric knee flexors strength (ES = 2.09) after 5 weeks of training using NH_E.[14] Therefore, a third aim of this review was (e) to explore if the effects of the NH_E on ES_{KF} differed between recreationally active and well-trained individuals.

2. Method

Study design: the design of this systematic review was developed through the Reporting Items for Systematic Reviews and Meta-analysis (PRISMA) statement guidelines.[36] The protocol was pre-registered on the Open Science Framework after searches and data extraction, but before data analysis (10.17605/OSF.IO/AJ7W8).

Eligibility criteria: to be included, studies had to: (a) be a minimum of 4 or more weeks, (b) use the NH_E as the main exercise, (c) include a control group that continued with their current training dynamics or performed another type of intervention (e.g., sprint intervention) and (d) be performed on team sports players (e.g., soccer, handball, hockey, etc.). However, for our secondary aim regarding the effect of the NH_E on ES_{KF}, studies among well-trained team sport players, amateur/healthy participants or young athletes were also included to allow comparisons between different training levels. Both randomized controlled studies (RCS) as well as non-randomized intervention studies (NRIS) were included as there only few studies that investigated the effects of the NH_E on sprint performance. Conference abstracts were excluded due to the difficulty in obtaining full methods and complete data sets. Studies were excluded if they included individuals with known pathologies and/or injuries. Finally, only articles written in English were considered for this meta-analysis. Due to limited numbers of intervention studies we decided not to restrict the inclusion criteria to males or females only.

Search Strategy: the primary search focused on studies reporting on the effect of the NH_E on sprint performance and ES_{KF} in team sports players. The final search date was the 20th of June 2020. Searches were performed though MEDLINE/PubMed, Web of Science, SPORTDiscus and Ovid. A PICO strategy was used to build search criteria for electronic databases. The PICO consisted of terms

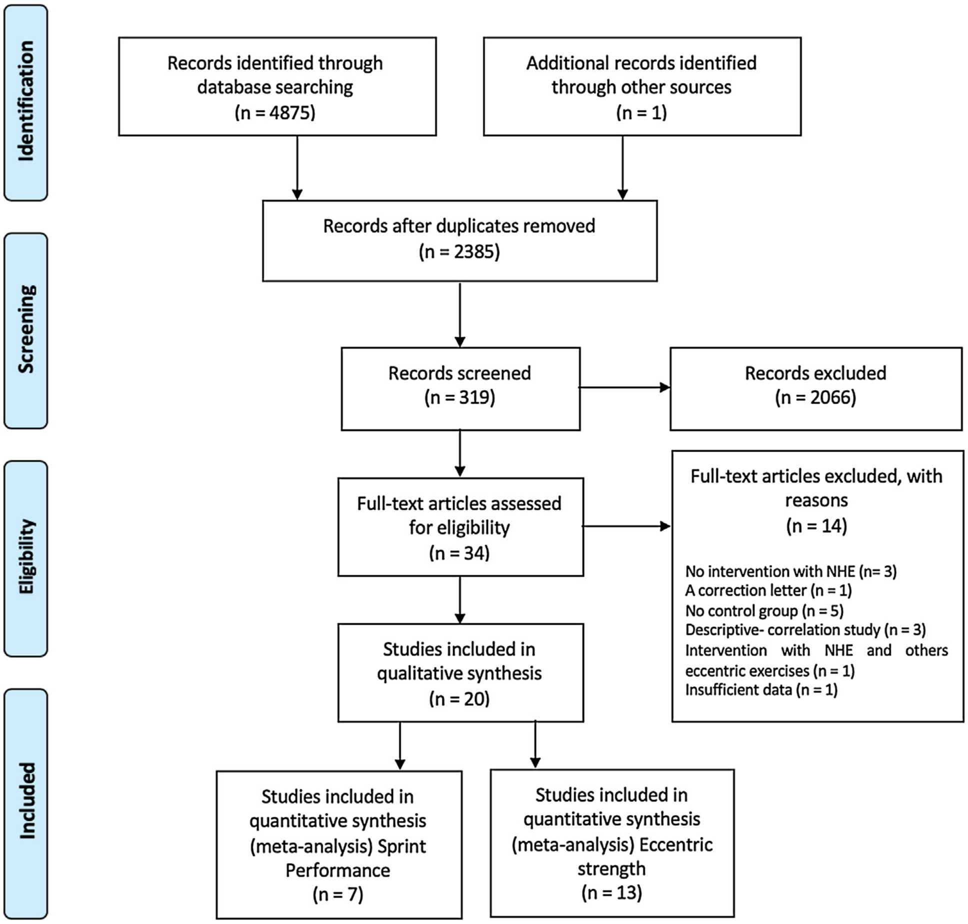

Fig. 1. PRISMA flow chart.

for sprint performance, NH_E and ES_{KF}. The search string used for MEDLINE/PubMed is reported in Supplementary File A.

Methodological Quality and risk of bias: two researchers (JVM and LBV) independently assessed the methodological quality of the studies using the risk of bias 2 (RoB 2) or risk of bias in non-randomized studies of interventions (ROBINS-I) Cochrane Bias Assessment Tool.[37] In case of disagreement between the scores provided, the primary author (IJB) made the final decision. A more extensive description of the risk of bias assessment procedure is found in Supplementary File B.

Statistical analyses: the sample size, and means, standard deviation, 95% confident intervals of sprint time (s) (i.e., 5, 10 and 20 m), as well as levels of eccentric knee flexor strength (i.e., peak eccentric strength during the NH_E and/or isokinetic evaluation, in Nm) were extracted independently by two authors from the included studies. A complete description of the statistical analysis can be found in Supplementary File C. For sub-group analyses on the effects of training level on adaptations we categorized studies (or sub samples within a study) into either recreationally trained or well-trained individuals. The study sample was categorized as well-trained if they had been training for at least 5 years. Note that this classification does not account for the skill level of the individual. For example, participation in (inter)national championships does not necessarily indicate that an individual is well-trained.

3. Results

Search results: Fig. 1 shows the flow chart with the different phases of the search and selection of studies included in this review. The number of search results was 4875 records. After elimination of duplicates (2385), another 2351 studies were excluded based on abstract and another 14 studies based on full-text assessment. A total of seven studies were therefore included in the present review on sprint performance[27,29–33,38] and 13 on ES_{KF}.[14,17,18,30–33,38–44]

Study quality and bias results: the RoB 2 and ROBINS-I scores of included studies is reported in Supplementary Fig. 21 (sprint time) and in Supplementary Fig. 22 (eccentric strength). Visual inspection of the contour-enhanced funnels plots and egger test indicated no presence of asymmetries, both in sprint performance and ES_{KF} (see Supplementary File D).

Participant characteristics of nordic hamstring exercise (NH_E) on sprint performance: the total sample size across all studies was 91 and 74 participants for the experimental and control groups, respectively. The main characteristics of the studies included in this review in terms of participants, intervention protocols and main findings are described in Supplementary file Table 4 and Supplementary File E.

Participant characteristics of nordic hamstring exercise (NH_E) on eccentric strength of knee flexors: in studies that investigated the effects of the NH_E on improvements in ES_{KF}, total sample size corresponded to 341 participants (i.e., 182 in NH_E group vs. 159 in control group) from 13 studies (with a total of 14 effect sizes because one study[41] contributed with two effect sizes). The main characteristics of the studies included in this review in terms of participants, intervention protocols and main findings are described in Supplementary file Table 5 and Supplementary File E.

Meta-analysis results on sprint performance (5, 10 and 20 m): the meta-analysis on the effects of NH_E on sprint performance showed a statistical significant difference (Z-value = −3.04, p = 0.010) by −0.05 [−0.09, −0.01] s in favour of the NH_E groups

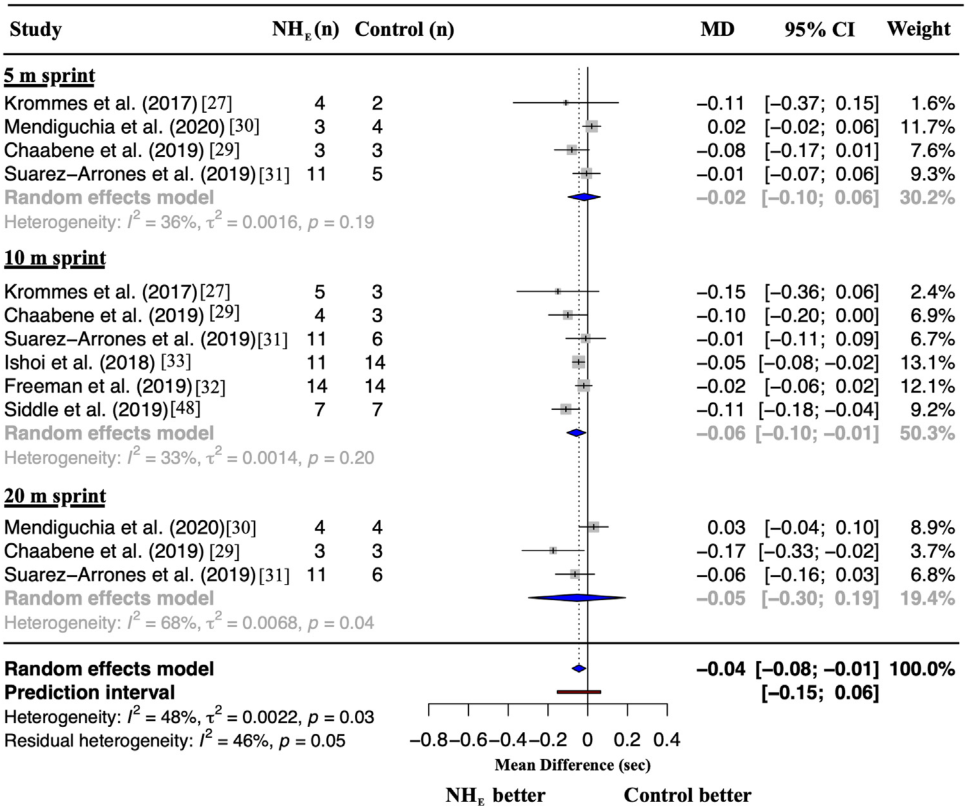

Fig. 2. Forest plot, 95% confidentce interval (CI95%) and prediction interval (PI) of Nordic hamstring exercise (NH$_E$) on sprint performance (i.e., 5, 10, 20 m). MD = mean differences.

when combined over all distances. The prediction interval and heterogeneity are illustrated in Fig. 2 and GRADE quality evidence is provided in Supplementary file Table 9. The prediction interval revealed that NH$_E$ interventions have a probability of a true-positive effect of 0.81 in a future setting. Counter-enhanced funnel plot as well as p-curve analysis showed no evidence of publication bias (Supplementary File D). The sensitivity analysis showed that two studies[29,30] added 27% of heterogeneity (see Supplementary File F for more details).

Sub-group meta-analyses indicated no statistically significant differences in 5 and 20 m sprint ($MD_{sprint(5m)} = -0.03$ s [−0.11, 0.06]; see Supplementary file Table 9 and $MD_{sprint(20m)} = -0.07$ s [−0.32, 0.19]; see Supplementary file Table 4), respectively. A statistically significant difference was however found for 10 m sprint ($MD_{sprint(10m)} = -0.06$ s [−0.11, −0.01]; see Supplementary file Table 9. When we performed a separate meta-analysis for each distance (i.e., all participants of each study being allocated to only one distance each time), the results were largely similar with a MD of −0.02 [−0.10, 0.06] s (prediction interval = −0.22, 0.18 s, probability of true-positive effect = 0.61), −0.06 [−0.10, −0.01] s (prediction interval = −0.17, 0.06 s, probability of true-positive effect = 0.80) and −0.05 s [−0.30, 0.19] (prediction interval = −1.32, 1.21 s, probability of true-positive effect = 0.62), for 5, 10 and 20 m sprint, respectively, see Supplementary file Table 9 and Supplementary File F for sensitivity analysis. In addition, when meta-analysis results were compared between randomized vs. non-randomized studies, no-significant differences were found between subgroups (p = 0.361). However sprint time results from randomized control studies were more imprecise (MD = −0.04 s [−0.09, 0.02]) in comparison to NRIS (MD = −0.07 s [−0.13, −0.01]). More details in Supplementary File F.

Meta-analysis results on eccentric strength of knee flexors: the meta-analysis on the effects of NH$_E$ on ES_{KF} showed a significant (Z-value = 5.17, p = 0.0004) improvement of 0.83 SMD's (0.55, 1.12) in favour of the intervention group. Forest plot and the heterogeneity is illustrated in Supplementary file Fig. 19 and Supplementary file Table 9 for GRADE quality evidence. The prediction interval of ES_{KF} indicates that NH$_E$ interventions have a probability of 0.97 for a true-positive effect in future settings (see Table 1 for more detail). In addition, counter-enhanced funnel plot, p-curve analysis and estimated power are provided in Supplementary File D. The sensitivity analysis showed that three studies[14,18,31] added the most heterogeneity (see Supplementary File G for more details). With respect to ES_{KF} assessment characteristics (i.e., category, assessment device, strength measures relative to body mass [isokinetic and Nord-Board], angular velocity in isokinetic exercise and study type), subgroups analysis revealed that when ES_{KF} were expressed relative to body mass, irrespective of assessment device, heterogeneity disappeared, for more details see Table 1. When meta-analysis results were compared between randomized vs. non-randomized control studies, no-significant differences were found between subgroups (p = 0.078). However eccentric knee flexor strength results coming from NRIS were more imprecise in comparison to RCT's (see Table 1 for more details).

Meta-regression showed that body mass, weekly volume and intervention duration were not significantly associated with improvements in ES_{KF} (see Supplementary file Table 10). In well-trained players, the association between ES_{KF} and body mass was significant, while the association between ES_{KF} and weekly volume and intervention duration were not significant. Finally, for studies that measured NH$_E$ and sprint performance (i.e., sprint 10 m, k = 4), meta-regression models showed that ES_{KF} had a very large but non-significant association with the $MD_{sprint10m}$ see Supplementary file Table 10.

Similarly, body mass showed a large but non-significant association with $MD_{sprint10m}$ ($R^2 = 0.68$, $F[1,2] = 4.32$, $p = 0.173$,

Table 1
Subgroups analysis for eccentric strength of knee flexors (ES_{KF}) in relation to category, assessment device, strength measures relative to body mass and angular velocity in isokinetic device.

Independent variable	n NH_E	n Control	Total N	k	ES	$CI_{95\%}$	I_2	Effect descriptor	Probability true-positive effect
Category	ES = 0.83 [0.54, 1.12], t = 6.30, p = 0.0001, PI = –0.06, 1.73						13.2%		
Well-trained players	74	57	131	5	0.80	−0.06 to 1.66	53%	Moderate	84
Amateur/Healthy individuals	69	67	136	6	0.92	0.42–1.43	6.7%	Moderate	95
Young athletes	39	35	74	3	0.73	0.49–0.96	0%	Moderate	99
Assessment device	ES = 0.84 [0.54, 1.12], t = 6.30, p = 0.0001, PI = –0.06, 1.73						17.2%		
Isokinetic	90	81	171	8	0.86	0.48–1.24	1.5%	Moderate	97
NordBord	92	78	170	6	0.81	0.16–1.44	32.4%	Moderate	89
Strength measures relative to body mass (all devices)	ES = 0.84 [0.54, 1.12], t = 6.30, p = 0.0001, PI = –0.06, 1.73						3.2%		
No	62	65	127	7	1.02	0.36–1.68	44.7%	Moderate	91
Yes	110	86	196	7	0.67	0.47–0.86	0%	Moderate	100
Strength measures relative to body mass (isokinetic)	ES = 0.79 [0.40, 1.18], t = 4.92, p = 0.0026, PI = –0.13, 1.70						0%		
No	37	36	98	3	0.84	−1.07 to 2.74	54%	Moderate	71
Yes	53	45	72	4	0.79	0.14–1.44	0%	Moderate	95
Strength measures relative to body mass (NordBord)	ES = 0.81 [0.16 1.44], t = 3.25, p = 0.023, PI = –0.69, 2.30						32.4%		
No	37	36	72	3	1.07	−1.19 to 3.34	59.2%	Moderate	73
Yes	57	41	98	3	0.52	0.24–0.80	0%	Small	96
Angular velocity Assessed (only for isokinetic device)*	ES = 0.79 [0.40, 1.18], t = 4.92, p = 0.0026, PI = –0.13, 1.70						0%		
60	48	42	90	4	0.88	0.07–1.68	14.3%	Moderate	82
120	35	32	67	3	0.63	−0.25 to 1.63	0%	Moderate	79
Study type	ES = 0.83 [0.54, 1.12], t = 6.30, p = 0.0001, PI = –0.06, 1.73						13.2%		
RCT	134	131	265	12	0.90	0.56–1.24	12%	Moderate	96
NRIS	48	28	76	2	0.55	−1.00–2.11	0%	Small	69

Note: (total n) = subjects (control + NH_E group), (k) = number of studies, (*) 180°/seg and 240°/seg was evaluated in one study, [38,42] respectively, however we did not include in the analysis because we had just one measure, n = 14. Probability of true-positive effect = see Supplementary File C for more detail. PI = prediction interval. RCT = randomized controlled trials. NRIS = non-randomized controlled intervention studies.

estimate = −0.009, standard error = 0.004, k = 4). Weekly volume and intervention duration showed weak and non-significant associations with $MD_{sprint10m}$ ($R^2 = 0.02$, $F[1,2] = 0.01$, $p = 0.932$, estimate = −0.0001, standard error = 0.001, k = 4 and $R^2 = 0.02$, $F[1,2] = 0.04$, $p = 0.865$, estimate = 0.001, standard error = 0.006, k = 4, respectively).

4. Discussion

The primary aim of this systematic review was to investigate the effects of the NH_E on sprint performance in team sport players, and to explore associations between study characteristics (e.g. weekly volume, time duration, ES_{KF} and body mass) and sprint performance. A secondary aim was to determine the effect of the NH_E on ES_{KF}, with subgroup analysis to determine differences between recreationally, well-trained and young athletes as categorical variables. Weak evidence from studies with some concerns or high risk of bias shows that the NH_E can improve sprint performance (−0.04 [−0.08, −0.01] s when averaged across all distances) in team sport players. With regard to eccentric strength of knee flexors, moderate evidence from studies with some concerns or high risk of bias showed that the NH_E can improve ES_{KF} by a standardized mean difference of 0.83 [0.55, 1.12] when considering well-trained players, recreationally/untrained and young individuals. However, for well-trained athletes, the improvements were less consistent, altough the effect size was similar (SCMD = 0.80 [−0.06, 1.66]).

Effect of the NH_E on sprint performance: meta-analysis results showed that the NH_E resulted in an improved sprint performance by 0.04 s when averaged across all distances. Heterogeneity (i.e., 48%) was categorized as a moderate. However, the prediction interval contained the null effect (i.e., −0.15, 0.06), suggesting future studies may observe no beneficial effect of the NH_E on sprint performance. Separate meta-analyses for 5, 10 and 20 m showed performance improvements of −0.02 s [−0.10, 0.06], −0.06 s [−0.10, −0.01] and −0.05 s [−0.30, 0.19], which corresponds to approximately 9 cm [−25, 49] improvement during a maximum 5 m sprint, 34 cm [5, 58] during a maximum 10 m sprint and 31 cm [−109, 199] during a maximum 20 m sprint, based on the sprint times reported for these distances in the studies included in this review (see Supplementary File I and Supplementary excel spreadsheet for more details).[45] Although small, these differences are larger than the smallest worthwhile change reported for sprint distances up to 40 m,[45,46] and could result in the player reaching the ball just before the other player and therefore be relevant in practice. For example, Haugen et al.[47] reported a smallest worthwhile change of 0.02 s for 20 m sprint. They also reported that a difference of 30–50 cm can be achieved over a 20 m distance with approximately 0.04 – 0.06 s improvement in sprint time. Such a distance could potentially be decisive in one-on-one duels, although more research is required to confirm the practical relevance of these improvements. It is important to note that these effects are based on both RCS and NRIS. The main difference between study (i.e., RCS vs. NRIS) type was the randomization sequence. In all NRIS included in the present review, the whole team was allocated into an experimental or control group. As a result, some variables such as total volume of sprints performed during intervention could act as confounded variables. Nevertheless, these studies performed in sport team framework (i.e., under “real” conditions) can be very informative.

Collectively, our results showed that the mean difference in sprint time for 10 and 20 m after NH_E training were higher than the smallest worthwhile changes reported in these studies and therefore suggest these improvements might be of practical relevance. Nevertheless, the level of evidence was low to very low for the individual distances, and the effect was only statistically significant for 10 m sprint with a probability of true-positive effect of 80%. These findings, and in particular the findings for the other distances should therefore be interpreted with caution. Additionally, Haugen and Buchheit[45] summarized several methodological issues that can affect sprint performance (e.g., single/dual-beamed photocells, floor pods, starting positions, flying start, etc.). In soccer players, a flying start is typical to use to monitor sprint performance. The signal-to-noise ratio is slightly lower for flying start distances up to 2 m than for flying distance in the range of 5–20 m. Heterogeneity in the results obtained in subgroups analysis (see Fig. 2) could therefore partly be explained by the differences in the sprint protocol (see Supplementary file Table 4). In addition, sensitivity analysis revealed that the Mendiguchia et al.[30] study added the most heterogeneity, see Supplementary File F. This is likely because this study used radar gun to assess sprint performance, while the others studies used a photocell system.[27,29,31–33] Meta-regression analyses showed no significant associations between improvements in sprint performance and weekly NH_E volume or study duration.

Effect of the NH_E on eccentric strength: secondary aims of this review were to (1) determine the effect of the NH_E on ES_{KF} and to determine if this effect differed between better and lesser trained individuals, (2) investigate the relation between ES_{KF} and sprint performance across studies, and (3) further explore the effect of study characteristics on ES_{KF}. Moderate evidence coming from studies with some concerns showed that interventions involving the NH_E resulted in significant improvements in ES_{KF} when including all subject groups (i.e., well-trained, amateur/healthy individuals and young athletes). Subgroup analysis showed higher heterogeneity and no significant improvement in well-trained soccer players. Nevertheless, the probability of a true-positive effect in well-trained soccer players was 84% (see Table 1). A lack of significant improvement in well-trained soccer players may be related to (1) their higher training experience, resulting in less consistent improvements in ES_{KF}, (2) low compliance with the NH_E training and (3) only a small number of studies ($n = 5$) investigating effects in well-trained players, which reduces the statistical power.

With regard to the measurement of ES_{KF} in well-trained players, three studies evaluated eccentric strength using a isokinetic device at 60°/s and 180°/s,[18,38,42] whereas two studies[31,32] used the NordBord device. This is an important point to highlight because recently, Wiesinger et al.[48] suggested that the device and the assessment method are important to evaluate the eccentric force of knee flexors. In their study, they showed that there was a poor correlation ($r < 0.58$) between the peak eccentric torque using an isokinetic device vs. measurement using the NH_E. This suggests that the assessments do not represent the same construct. However, the results of our meta-analysis show a similar effect size (i.e., 0.86 vs. 0.81 for isokinetic vs. NordBord, respectively) for improvements in ES_{KF} irrespective of assessment device. It is important to note that the heterogeneity was higher when the NordBord device was used in comparison to isokinetic assessments (i.e., 32.4% vs. 1.5%, respectively), see Table 1 for more details. However, when eccentric strength measures were normalised to body mass, heterogeneity disappeared (0%, for both isokinetic and NordBord, respectively). For this reason, given the relationship between body mass and ES_{KF} in well-trained athletes, it may be recommendable to standardize eccentric strength measures relative to body mass.[49]

Meta-regression further showed that improvements in ES_{KF} in well-trained platers were strongly, but non-significantly associated with improvements in 10 m sprint performance (r 0.91), with each unit increase in standardized mean difference of ES_{KF} being associated with a 0.06 s improvement in sprint performance. Although the association found between these two variables was very large, the number of studies that used well-trained players was low ($k = 4$) and further studies should be performed to investigate the effects in this population. However, a large descriptive-correlational study has shown a moderate relationship (r 0.51) between ES_{KF} and 20 m sprint performance in a sample of professional players, which lends support to our findings.[35]

Meta-regression analysis also showed that the weekly NH_E training volume was not significantly and only weakly associated with improvements in ES_{KF}, with only 5% of the variance of improvements in ES_{KF} being associated with training volume (see Supplementary file Table 10). This finding suggests that a small weekly volume is sufficient to increase ES_{KF}, with further increases having only negligible effects. Indeed, in a direct comparison of different training volumes, Presland et al.[19] recently also observed that a weekly volume of one session per week with only 2 sets of 4 repetitions [average of 32 rep/week] of the NH_E was as effective as a higher volume (2 sessions/week and 4–5 sets x 8–10 repetitions [average of 110 rep/week]) at increasing biceps femoris fascicle length and ES_{KF} in recreationally active males. Small differences in ES_{KF} effect size were also found (2.12 vs. 2.28, respectively) when high volume and low volume were compared in another study.[20] Similarly, a study among high-level soccer players found that a NH_E program performed once a week was equally effective at increasing fascicle length and ES_{KF} as a program performed two times per week (i.e., average weekly volume of 31 vs. 61 reps, for one and two days/week groups, respectively), although effect sizes generally favoured the group performing a higher training volume.

Collectively, these findings therefore indicate that the NH_E is a time-efficient intervention, with only approximately 48 repetitions per week being sufficient to improve ES_{KF}. However, the intensity of these repetitions may be important as we found a statistically significant positive association between body mass and improvements in ES_{KF} (r 0.39 and 0.98, explained variance 15% and 97% for all participants and well-trained players, respectively), suggesting that individuals with greater body mass may benefit more from the use of the NH_E for eccentric strength development of the knee flexors. The NH_E is an exercise that is carried out with one's own body mass whereby the mass of the upper body of each athlete and increasing moment arm of this mass in relation to the knee and hip will progressively increase force requirements from the hamstrings during the performance of the exercise. The lack of association between body mass and improvements ES_{KF} in recreational athletes may be because this exercise is already heavy enough for recreationally active individuals with a relatively low body mass. In contrast, for well-trained individuals with a low body mass, the exercise may not be sufficiently heavy to maximize adaptations. In line with our findings of a larger body mas being associated with greater improvements in ES_{KF} among well-trained players (see Supplementary file Table 10), Pollard et al.[16] found that when the NH_E was done with extra-weight (i.e., 2.5 kg–27.5 kg), ES_{KF} improved more in comparison to NH_E performed without added weight (i.e., 81 N [ES = 0.90] vs. 67 N [ES = 0.75], respectively). Collectively, these findings therefore suggest that adding more external load may be required to stimulate continuous adaptations, in particular as training experience increases. While the training volume is relatively easy to quantify as reps x sets x weekly frequency, the intensity of the NH_E is more challenging to quantify. As a result, the exact stimulus (i.e., time under tension and load supported) is not known since it has not been specifically described in any of the studies included in this review (see Supplementary file Table 5). The variability in intensity prescription in NH_E could be contributing to the heterogeneity of results found both in the eccentric strength of the knee flexors and in the improvements in the sprint performance.

Limitations. There are several limitations to this review that should be taken into consideration when interpreting the results. One of the main limitations is the small number of studies that could be included in meta-analysis on sprint performance ($k = 7$) and eccentric knee flexor strength in well-trained team sport players ($k = 4$). As a result, the number of studies included in the meta-regressions is smaller than suggested in the Cochrane guidelines (i.e. at least 10 studies),[37] and care should be taken with interpreting these findings. Nevertheless, the statistical analyses allowed us to establish associations that can have important implications for practice and can provide directions for future research. Further, contour-enhanced funnel plots showed no the presence of asymmetries (see Supplementary File D) and egger's test confirmed these results ($p > 0.05$). P-curve analysis revealed a significant right-skewness test and an evidential value present in both variables indicating that there is a "true" effect behind the data (see Supplementary File D for more detail).

Further, one study failed to adequately randomize the participants,[33] although the authors used a covariate model to control variance in post-measurement. Additionally, in sprint performance studies, two studies[29,31] were not a randomized control trial while in ES_{KF} studies, two studies[31,39] were non-randomized. For this reason, in an attempt to reduce the effect of baseline imbalances on the meta-analyses outcomes, we computed the change score within each group and then calculated the difference in change scores between groups (more details in Supplementary File C). In addition, we based the risk of bias assessments on RoB 2 and ROBINS-I tools and presented the meta-analysis results based on study type, both for sprint performance and eccentric knee flexor strength to determine differential effects between these different study types. In one included study,[32] the control group performed sprint training rather than their continuous practice. We performed a sensitivity analysis to investigate the effects of including this study on the overall effect of the NH_E on sprint performance. Leave-one-out sensitivity analysis showed that exclusion of this study did not substantially change the mean difference (i.e., −0.05 [−0.09, −0.01] s vs.−0.05 [−0.09, −0.02] s; see Supplementary File F). Another limitation was that we included mixed populations ranging from well-trained team sports players to recreationally active individuals and the effects may differ between these different groups. Similarly, different equipment was used to assess the outcomes and training programs differed in their content. However, in an attempt to explore these differences we performed subgroup analyses and meta-regression analyses where possible. In addition, it is important to note that some outcomes variables (i.e., 20 m sprint time) were only investigated by few studies and should therefore be interpreted with care. Finally, because the majority of intervention studies included males (i.e., 86% and 84% of total sample size, for sprint and eccentric strength, respectively), we were unable to compare results based on gender.

5. Conclusions

In conclusion, evidence from studies with some concern or high risk of bias show that the NH_E has a small beneficial effect on sprint performance in team sport players. Further, studies with some concerns or high risk of bias show that the NH_E has a moderate beneficial effect on eccentric strength of the knee flexors among all included training levels. However, for well-trained individuals the improvements in eccentric strength of the knee flexors following NH_E interventions were less consistent. Improvements in eccentric strength showed a large, but non-significant association with improvements in sprint performance in well-trained team sport players. Among all included participants, weekly volume and intervention duration showed, non-significant association with eccentric strength of knee flexors variance, explaining only four and nine percent of the variance, respectively. Similarly, weekly volume and intervention duration explained a total of twenty-two and one percent of the variance in effect size in eccentric strength of knee flexors in well-trained team sport players. Finally, body mass explained more than 90% of variance in the effect size of eccentric knee flexors strength in well-trained team sport players.

Confirmation of ethical compliance

Authors the ethical compliance for this manuscript.

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Appendix A. Supplementary data

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