Nordic Hamstring Exercise training induces improved lower-limb swing phase mechanics and sustained strength preservation in sprinters

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Nordic Hamstring Exercise (NHE) training improves eccentric hamstring strength and sprint performance. However, detraining causes rapid reductions of achieved adaptations. Furthermore, the transfer of improved hamstring capacity to swing phase mechanics of sprints is unknown. This longitudinal study aimed (a) to quantify NHE-induced adaptations by camera-based isokinetic assessments and sprint analyses, (b) to relate the magnitude of adaptations to the participants’ initial performance level, (c) to investigate the transferability to sprints, and (d) to determine strength preservation after 3 months. Twelve sprinters (21 years, 1.81 m, 74 kg) were analyzed throughout 22 weeks. They performed maximal sprints and eccentric knee flexor and concentric knee extensor tests before and after a 4-week NHE training. Sprints and isokinetic tests were captured by ten and four high-speed cameras. The dynamic control ratio at the equilibrium point (DCRe) evaluated thigh muscle balance. High-intensity NHE training elicited significant improvements of hamstring function (P range: < .001-.011, d range: 0.44-1.14), thigh muscle balance (P < 0.001, d range: 0.80-1.08) and hamstring-related parameters of swing phase mechanics (P range: < 0.001-0.022, d range: 0.12-0.57). Sprint velocity demonstrated small increases (+1.4%, P < 0.001, d = 0.26). Adaptations of hamstring function and thigh muscle balance revealed moderate to strong transfers to improved sprint mechanics (P range: < 0.001-0.048, R^2 range: 34%-83%). The weakest participants demonstrated the highest adaptations of isokinetic parameters (P range: 0.003-0.023, R^2 range: 42%-62%), whereas sprint mechanics showed no effect of initial performance level. Three months after the intervention, hamstring function (+6% to +14%) and thigh muscle balance (+8% to +10%) remained significantly enhanced (P < 0.001, ηp^2 range: 0.529-0.621). High-intensity NHE training induced sustained improved hamstring function of sprinters, which can be transferred to swing phase mechanics of maximal sprints. The initial performance level, NHE training procedures and periodization should be considered to optimize adaptations.
1 | INTRODUCTION

The Nordic Hamstring Exercise (NHE) is an effective resistance training exercise to selectively improve eccentric hamstring strength and thigh muscle balance (strength ratio of the knee extensors and flexors) by posing supramaximal eccentric loads on the athlete's posterior thigh muscles.1-3 As the biarticularly working hamstrings possess a major role in locomotion,4 Nordic Hamstring Exercise training also promotes sprint performance.5-7 Within 4- to 10-weeks, NHE interventions elicited strength adaptations of moderate to large effect sizes.8-12 Conversely, corresponding improvements in sprint performance were generally negligible to small6-9 and independent of NHE-induced increased hamstring strength.5 In contrast, NHE peak moments showed a significant, but moderate correlation to 20 m-sprint times ($R^2 = 27\%$).13 This impaired transferability is attributable to the bilateral and monoarticular nature of NHEs.1 Predominantly, NHEs are conducted with partner assistance and proportionately “high” exercise volume (>5 repetitions per set) whilst most athletes are not able to perform a single NHE in a controlled fashion.2,3 Furthermore, NHE training which ensures a sufficiently high time under tension at comparably long hamstring muscle length is lacking.10 Due to insufficient strength capacities of the athletes and the inadequate abutment at the heels, this procedure causes a small active range of motion (ROM = ~30°) potentially impairing the subsequent adaptations. Evidence suggests that low-volume high-intensity NHE training is better suited to elicit worthwhile changes.11,12 However, standardized NHE training studies are rare which imply NHEs with a constant movement speed across the full ROM (from 90° to 20° of knee flexion) and which assess NHE execution quality by kinematic analyses.10

There is equivocal evidence about whether NHE-induced adaptations persist after 3-4 weeks of detraining11 or not.6,12 In contrast to traditional training which incorporates both concentric and eccentric muscle actions, eccentric-only training elicits long-lasting strength gains, especially if high intensities are implemented.14,15 Depending on the stimuli and the athletes’ performance level, the repeated bout effect lasts between several weeks up to 6 months.15,16 Longer detraining periods (>4 weeks) after NHE interventions have been yet to be investigated.

Previously published NHE studies imply several limitations. Their major disadvantage is the missing quantitative assessment of execution quality (eg, ROM to downward acceleration) of predominantly soccer players. Furthermore, the effects of NHE training on sprint velocity are rare8 and analyses of sprint mechanics following NHE training are lacking. Usually, the effect of NHE training on split times have been investigated.5-7,9,13 NHE-induced adaptations of isokinetic outcome parameters relied on dynamometer-based data6 which include considerable discrepancies to camera-based analyses.17,18 Additionally, low compliance19 and high athletes’ performance level5,7 diminished NHE-related effects. Thus, it has to be verified how strong NHE-induced adaptations are related to enhanced swing phase mechanics of maximal sprints. Consequently, the merger of standardized NHE training procedures, underlying sprint mechanics and associated camera-based isokinetic assessments in a cohort of sprinters is required.

Therefore, this longitudinal study aimed (a) to quantify NHE training adaptations by camera-based isokinetic assessments and sprint analyses, (b) to relate the magnitude of adaptations to the participants’ initial performance level, (c) to investigate the transferability to sprints, and (d) to determine strength preservations after 3 months.

The study hypotheses were:

1. Standardized high-intensity NHE training causes moderate to large improvements of eccentric hamstring strength and thigh muscle balance, but small improvements of sprint performance and swing phase mechanics.
2. Weaker participants demonstrate significantly greater adaptations.
3. The transfer of these adaptations to maximal sprints is negligible to small.
4. Three months after the intervention, the formerly increased strength level is reduced to the baseline level.

2 | MATERIAL AND METHODS

2.1 | Study design

This longitudinal study lasted 22 weeks (Figure 1 bottom) and followed a within-subject design with repeated measures.10 Throughout the entire study (4-weeks baseline, 4-weeks NHE intervention, 2-weeks adaptation and 12-weeks retention), the participants executed their usual sprint and resistance training, without performing any additional NHEs.
2.2 | Participants

Twelve regional to national class male sprinters (mean ± SD, age: 21.3 ± 2.1 years, body height: 180.9 ± 8.0 cm, body mass: 74.9 ± 10.8 kg) gave their written informed consent to voluntarily join the study. They were familiar to resistance training, but not to NHE. They differed in training history (range: 2-17 years), training volume (4-12 h/week) and performance level (100-m-time: 10.99-12.66 seconds). All participants were free of thigh muscle and/or knee injuries within the last two years. The local ethics commission confirmed that the requirements of the Declaration of Helsinki were met.

2.3 | Instruments

2.3.1 | Sprint analysis

Sprint analyses were performed on an indoor synthetic running track. A three-dimensional, 10-camera motion analysis system (VICON MX40, Vicon Motion Systems Ltd) (Figure 1A) recorded the kinematic raw data (200 fps) within a calibrated volume of 800 × 200 × 200 cm (L × W × H) (Figure 1A). To create a lower-limb model consisting of nine rigid segments, twenty-eight spherical, retroreflective markers (Ø = 8 mm) were attached bilaterally to anterior and posterior superior iliac spines, greater trochanters, lateral and medial condyles of femurs, tibias, lateral and medial malleoli, heads of the first and fifth metatarsals, second proximal phalanges, lateral, medial and backside of calcanei.

2.3.2 | Isokinetic tests & NHE training

All isokinetic tests and NHE training sessions were conducted using an isokinetic dynamometer (IsoMed 2000, D&R Ferstl GmbH) (Figure 1B-D). Raw data were recorded by the manufacturer's computer software IsoMed analyze V.2.0 (200 Hz) and synchronized with the signals of four high-speed video cameras (acA640-120gc, Basler AG) capturing the motion (100 fps) during isokinetic tests (pre and 2 weeks post intervention) and selected NHE training sessions (TEMPLO 8.2.358, Contemplas) (Figure 1 bottom). Four spherical retroreflective markers (Ø = 8-16 mm) per body side were attached on top of bony landmarks (acromion, trochanter major, lateral femoral epicondyle, fibula head/lever arm). Two headlights (Bar Fly 200, Kino Flo® Lightning Systems) improved the markers’ visibility. The measuring volume was statically calibrated with a rigid frame of 90 × 60 × 60 cm (L × W × H). Kinematic recording and analyses were performed with VICON Peak Motus (V10.0.1, Vicon Motion Systems Ltd).

During NHE training, a sagittal live video feedback (30 fps) was provided by a webcam (C200, Logitech, Apples). A stick figure moving at target speed was overlaid on a 17" monitor (710N, SAMSUNG) ensuring high execution quality. Assisted NHEs were conducted via rope-controlled resistance provided by the examiner. It was transferred to the back part of a climbing harness (Petzl, Crolles, France) worn by the participants (Figure 1C).

After a general warm-up, the training sessions started with a specific preparation including submaximal NHEs (2 × 5 repetitions at 60%-80% up to downward acceleration angle, 3 minutes interset rest) with the heels fixed at a doorway pull-up bar (Denqbar DQ-0161).10

2.4 | Procedures

2.4.1 | Sprint analysis

At pre and 2 weeks post intervention, sprint analyses and camera-based isokinetic tests were conducted on a single day (Figure 1 bottom). Individual body dimensions and segmental inertial properties were determined (body mass, body height, segment lengths, minimal and maximal segment circumferences). After an individual warm-up, each sprinter ran up to four maximal sprints wearing his own spikes (run-up of 30-40 m before entering the measuring volume).

2.4.2 | Isokinetic tests

After a 30-minute break, unilateral knee flexor and extensor tests with extended hip joints were conducted. They followed a protocol with proven reliability.20 A double shin pad was attached to the motor-driven axis. In a pre-activated muscular state (~50% of maximal effort) at 90° knee flexion, the dynamometer axis was aligned with the participants’ lateral femoral epicondyle by use of a laser pointer.17,18 The pad’s distal part was fixed by a strap 2-3 cm proximal to the medial malleolus. After a static gravity correction measurement, an isokinetic warm-up consisting of each six submaximal (~50%-80%), discrete concentric (con) and eccentric (ecc) repetitions of the respective muscle group was conducted. The testing order was stratified such that limbs and muscle groups (H = hamstrings, Q = quadriceps) were alternatingly tested and slow velocities were executed prior to fast ones.20,21 For knee flexion (110-0° ROMknee), participants laid prone by pushing their trunk with the hands to the lounger (Figure 1B). Knee extensions (0-90° ROMknee) were performed in supine position with handgrips providing sufficient stability.18

Each test consisted of five discrete movements (two submaximal, three with maximal effort) at 15°/s (only Hecc
(A) and (B) depict the experimental setup, with (C) and (D) showing participants engaged in the training sessions.

**familiarization**
- Time: 48-72 h
- Description: discrete, unilateral isokinetic strength tests (left and right) concentric and eccentric knee flexor (15, 30, 150°/s) and extensor (30, 150°/s) tests
- Method: dynamometer-based assessment

**baseline**
- Time: 4 weeks
- Description: discrete, unilateral isokinetic strength tests (left and right) concentric and eccentric knee flexor (15, 30, 150°/s) and extensor (30, 150°/s) tests
- Method: dynamometer-based assessment

**pre (p0)**
- Time: 48-72 h
- Description: discrete, unilateral isokinetic strength tests (left and right) concentric and eccentric knee flexor (15, 30, 150°/s) and extensor (30, 150°/s) tests
- Method: sprint analysis & camera-based assessment

**4-week NHE training**
- Time: 4 weeks
- Description: 4 weeks with 3 sessions per week (Mon, Wed, Fri) each 3 sets of 3 eccentric NHE repetitions at a constant target knee extension velocity of ~15°/s across a ROM_knee of ~90-100° 10 sec interrepetition rest & 5 min interset rest
- Methods: camera-based assessment (Alt et al. 2018, SJMSS)

**post (p1)**
- Time: 1 week
- Description: discrete, unilateral isokinetic strength tests (left and right) concentric and eccentric knee flexor (15, 30, 150°/s) and extensor (30, 150°/s) tests
- Method: dynamometer-based assessment

**1 week post (p2)**
- Time: 1 week
- Description: discrete, unilateral isokinetic strength tests (left and right) concentric and eccentric knee flexor (15, 30, 150°/s) and extensor (30, 150°/s) tests
- Method: dynamometer-based assessment

**2 weeks post (p3)**
- Time: 12 weeks
- Description: discrete, unilateral isokinetic strength tests (left and right) concentric and eccentric knee flexor (15, 30, 150°/s) and extensor (30, 150°/s) tests
- Method: sprint analysis & camera-based assessment

**14 weeks post (retention)**
- Time: 14 weeks
- Description: discrete, unilateral isokinetic strength tests (left and right) concentric and eccentric knee flexor (15, 30, 150°/s) and extensor (30, 150°/s) tests
- Method: dynamometer-based assessment
because it represents the NHE target movement speed), 30°/s and 150°/s, respectively.20-22 The last three repetitions were selected for further analysis. A 1-min-interset rest ensured sufficient recovery.20 Strong verbal encouragement promoted maximum exertion.

2.5 | NHE training

At pre, all participants were familiarized to the NHE training procedures by executing 3 sets of single assisted eccentric NHEs (1 minute interset rest) (Figure 1 bottom). The participants kneeled on the lounger's edge so that the knee axis' orientation matched the dynamometer's axis (Figure 1C,D). The 4-week NHE training consisted of six assisted and six unassisted sessions in which the training modality gradually alternated (Figure 1 bottom). The assisted NHE ensured a high time under tension at comparably long hamstring muscle length.10 The participants were instructed to meet the following execution criteria: (a) to execute NHEs with a constant movement speed of ~15°/s (~6 seconds time under tension) across the largest possible ROMknee (~90°) with (b) minimal hip flexion whilst (c) the hands are held beside the shoulders. During assisted NHEs, the examiner adjusted the resistance according to the live feedback to optimally realize the target speed (Figure 1C). During unassisted NHEs, the participants tried to maintain the target speed and muscle activation as long as possible. The interrepetition and interset rest periods were set at 10 seconds and 5 minutes, respectively. After each repetition, the examiner gave instant verbal feedback to the participant's execution quality (eg, movement speed and hip flexion). Each repetition was executed solely eccentrically with maximal effort.10

2.6 | Data processing

2.6.1 | Inverse dynamic model for sprint analysis

Kinematic raw data were analyzed with VICON Nexus (V2.3) and filtered by a recursive 4th order Butterworth low-pass filter (40 Hz cutoff frequency). According to the anatomical landmark scaled model of Lund et al (2015),23 lower-limb inverse dynamics were performed by Anybody™ Modeling System (AnyBody Technology). Standing reference trials served to create stick figure models used to scale cadaver datasets into subject-specific joint parameters. The inverse dynamic model was adjusted to the participants' individual whole-body anthropometrics. The distribution of body mass was accomplished according to Hanavan (1964).24 Further data processing was conducted with custom-made Matlab routines (R2013b, The MathWorks). Kinematic and kinetic variables were time-normalized to the swing phase which was determined as the time between take-off of one leg to touchdown of the same leg identified by the vertical displacement of the toe markers. Peak moments of inertia and corresponding data were extracted from the entire swing phase of the sagittal plane. Joint moments are presented as external moments normalized to body mass. Sprint velocity was calculated for each step as horizontal velocity of the center of mass after take-off of the respective foot. A total of 171 eccentric phases of the hamstrings and 234 eccentric hamstring peak moments during the swing phase were used for further analyses.

2.6.2 | Analysis of isokinetic tests

Raw data (200 Hz) were recorded by the manufacturer's software (IsoMed analyze V.2.0) and stored as ASCII files. A custom-made software (C++) isolated the isokinetic ROM (±1% deviation of angular velocity) and filtered the data (recursive 5th order Butterworth low-pass filter, 6 Hz cutoff frequency). Camera-based knee and hip angles were determined three-dimensionally and sagittal plane kinematics were extracted.17,18 For each testing condition, the trial with the highest gravity-corrected peak moment was used for statistical analyses. For each angular velocity, the dynamic control ratio at the equilibrium point (DCRe) with the highest moment (each combination of the three flexor and extensor movements) was identified.21,22 Peak power was calculated as product of actual camera-based angular velocity and the moment value at time of peak power.17 Data obtained from tests at 150°/s were associated with swing phase mechanics of maximal sprints because DCRe parameters are most reliable at that angular velocity.22 As bilateral differences were beyond the study's scope, the values of both limbs were averaged and normalized to body mass. Preservation was assessed by comparing the values at baseline and retention (Figure 1 bottom).
2.6.3 | Analysis of NHE training

The intended execution criteria (see 2.5.) were predominantly fulfilled so that a high training quality (e.g., ROM to downward acceleration) was realized. NHE repetitions which did not meet these execution criteria have neither been repeated nor excluded from analysis. The associated kinematic and kinetic analyses of assisted and unassisted NHE training have been previously reported.10

2.7 | Statistical analysis

The Kolmogorov-Smirnov ($P \leq 0.05$) and Levene’s test ($P \leq 0.05$) confirmed normal distribution and variance homogeneity of all data. Two-way ANOVAs with repeated measures identified the effects of NHE training on isokinetic parameters (factors: time, angular velocity). Bonferroni post hoc tests ($P \leq 0.05$) determined the actual $P$-values between the six isokinetic test sessions. The partial eta-squared ($\eta_p^2$) served as effect size ($\eta_p^2 \geq 0.26$ large; $0.26 > \eta_p^2 \geq 0.13$ moderate, $0.13 > \eta_p^2 \geq 0.02$ small; $\eta_p^2 < 0.02$ negligible).25 One-tailed dependent t-tests examined differences between isokinetic and sprint parameters obtained at pre and 2 weeks post intervention (Figure 1 bottom). Effect sizes of t-tests were rated by the Cohen’s $d$ ($d \geq 0.8$ large; $0.8 > d \geq 0.5$ moderate, $0.5 > d \geq 0.2$ small; $<0.2$ negligible), whereas the smallest worthwhile change was set at $0.5 \times$ SD to identify at least moderate effects.25 For selected parameters, two-tailed Pearson correlation analyses determined the linear regressions’ strength ($r \geq .9$ very strong, $.9 > r \geq .7$ strong, $.7 > r \geq .5$ moderate, $.5 > r \geq .3$ weak, $r < .3$ negligible).26 Accordingly, the classification thresholds of the corresponding coefficients of determination ($R^2$ values) were 81%, 49%, 25% and 9%. Their respective 90% confidence intervals were determined via bootstrapping with 2000 iterations. All statistical tests were calculated with SPSS V.23.0 (SPSS Inc). The level of significance was set at $P \leq 0.05$.

3 | RESULTS

3.1 | NHE-induced adaptations

A standardized 4-week high-intensity NHE training regimen with a compliance of 92% ($n = 3$) to 100% ($n = 9$) elicited significant improvements of hamstring function, thigh muscle balance and lower-limb swing phase mechanics (Table 1). Strong adaptations became apparent for peak moments$_{\text{Hecc}}$ (+15.5%, $P < 0.001$, $d = 1.14$), peak power$_{\text{Hecc}}$ (+14.6%, $P < 0.001$, $d = 0.89$) as well as for DCRe angles (+13.5%, $P < 0.001$, $d = 1.08$) and DCRe moments (+10.9%, $P < 0.001$, $d = 0.80$). Angles of peak moment$_{\text{Hecc}}$ and knee flexion angles at peak power$_{\text{Hecc}}$ remained unchanged ($P > 0.05$). Concerning sprint mechanics, NHE training caused moderate to weak changes of hip flexion angles at peak knee joint moment (+4.7%, $P < 0.001$, $d = 0.57$) and mean knee extension velocity (+1.8%, $P = 0.022$, $d = 0.43$) (Figure 2). Sprint velocity significantly increased in all participants (+1.4%, $P < 0.001$, $d = 0.26$) with concomitantly small improvements of peak moments$_{\text{knee}}$ (+5.2%, $P < 0.001$, $d = 0.36$), peak power$_{\text{knee}}$ (+7.2%, $d = 0.31$) and hip flexion angles at peak knee joint power (−5.1%, $P < 0.001$, $d = 0.34$) (Table 1). The weakest participants demonstrated the highest adaptations of isokinetic parameters ($P$ range: <0.001-0.023, $R^2$ range: 42% to 62%), whereas sprint mechanics were unaffected ($P > 0.05$) by participants’ initial performance level (Table 1).

3.2 | Transferability to swing phase mechanics of sprints

Nordic Hamstring Exercise-induced adaptations of peak moments$_{\text{Hecc}}$ revealed strong relationships to increased knee ($P < 0.001$, $R^2 = 83$%) and hip joint ($P < 0.001$, $R^2 = 72$%) peak moments during the late swing phase of maximal sprints (Table 2). Significant associations to sprint-related knee and hip joint peak moments became apparent for peak power$_{\text{Hecc}}$ ($P$ range: .002-.007, $R^2$ range: 53% to 65%) and DCRe moments ($P$ range: .001-.029, $R^2$ range: 39% to 65%) as well. Improvements of DCRe angles were strongly related to enhanced swing phase kinematics ($P = 0.001$, $R^2 = 68$% to hip angle@peak power$_{\text{knee}}$).

3.3 | Strength preservation

Three months after the NHE intervention (baseline vs. retention), hamstring function (+6% to +14%) and thigh muscle balance (+8% to +10%) of sprinters remained significantly ($P \leq 0.05$) enhanced (Figure 3). Peak moments$_{\text{Hecc}}$ and DCRe moments revealed strong time effects ($P < 0.001$, $\eta_p^2$ range: 0.529-0.621) without any significant changes between values obtained 2 weeks post intervention post 3 (2 weeks after intervention) and retention ($P > 0.05$). For peak moments$_{\text{Hecc}}$, adaptations significantly increased with higher movement speed ($P = 0.023$, $\eta_p^2 = 0.354$) (Figure 3A). After 3 months, strength preservation of peak moments$_{\text{Hecc}}$ remained persistently large at 150°/s and moderate at 30°/s. DCRe moments were moderately improved at both angular velocities (Figure 3B).
### Table 1: NHE-induced adaptations of selected camera-based isokinetic parameters obtained at 150°/s and of selected swing phase mechanics of maximal sprints

| Parameter                        | Time          | Mean ± SD       | \(P\) (one-tailed \(t\)-test) [95% CI] | \(d\) [90% CI] | Mean benefit (range) | \(P\) (two-tailed Pearson correlation) | \(R^2\) [90% CI] |
|----------------------------------|---------------|-----------------|----------------------------------------|----------------|----------------------|----------------------------------------|------------------|
| **Camera-based isokinetics @ 150°/s** |               |                 |                                        |                |                      |                                        |                  |
| Peak moment _Hecc_ [Nm/kg]       | Pre           | 2.04 ± 0.30     | <0.001 [+0.22; +0.42]                  | 1.14           | +15.5%               | .006                                   | −0.736           |
|                                 | 2 wk post     | 2.36 ± 0.25     | \[0.66; 1.62\]                         | −0.02          | +0.3%                | .077                                   | 54.2% [15.3%; 80.4%] |
| Knee angle at peak moment _Hecc_ [°] | Pre           | 41.0 ± 6.4      | 0.439 [+2.1; −1.8]                     | −0.27; 0.22    | (+8.7% to −10.0%)    | .077                                   | 41.7% [6.9%; 70.9%] |
|                                 | 2 wk post     | 41.1 ± 5.3      | \[−0.27; 0.22\]                       | −0.27; 0.22    | (+8.7% to −10.0%)    | .077                                   | 41.7% [6.9%; 70.9%] |
| Contractional work _Hecc_ [J/kg] | Pre           | 1.87 ± 0.29     | 0.011 [+0.03; +0.21]                   | 0.44           | +6.5%                | .023                                   | −0.646           |
|                                 | 2 wk post     | 1.99 ± 0.25     | \[0.15; 0.73\]                        | −0.20% to +22.5%| +15.5%               | .006                                   | −0.736           |
| Peak power _Hecc_ [W/kg]         | Pre           | 3.85 ± 0.65     | <0.001 [+0.30; +0.83]                  | 0.89           | +14.6%               | .021                                   | −0.654           |
|                                 | 2 wk post     | 4.41 ± 0.58     | \[0.45; 1.34\]                        | −0.08% to +49.1%| +15.5%               | .003                                   | −0.784           |
| Knee angle at peak power _Hecc_ [°] | Pre           | 40.2 ± 6.1      | 0.487 [+2.3; −2.3]                     | 0.01           | −0.1%                | .272                                   | 61.5% [22.2%; 81.9%] |
|                                 | 2 wk post     | 40.2 ± 5.6      | \[−0.29; 0.30\]                       | −0.29; 0.30    | (+15.9% to −12.6%)   | .018                                   | −0.665           |
| DCRe moment [Nm/kg]              | Pre           | 2.01 ± 0.31     | <0.001 [+0.12; +0.31]                  | 0.80           | +10.9%               | .003                                   | −0.784           |
|                                 | 2 wk post     | 2.22 ± 0.23     | \[0.42; 1.18\]                        | −0.7% to +32.8%| +15.9%               | .003                                   | −0.784           |
| DCRe angle [°]                   | Pre           | 41.0 ± 5.5      | <0.001 [+3.3; +7.8]                    | 1.08           | +13.5%               | .018                                   | −0.665           |
|                                 | 2 wk post     | 46.6 ± 4.5      | \[0.58; 1.59\]                        | +0.4% to +32.0%| +15.9%               | .018                                   | −0.665           |
| **Swing phase mechanics**        |               |                 |                                        |                |                      |                                        |                  |
| Sprint velocity [m/s]            | Pre           | 9.38 ± 0.50     | <0.001 [+0.07; +0.19]                  | 0.26           | +1.4%                | .223                                   | 44.2% [8.1%; 82.5%] |
|                                 | 2 wk post     | 9.51 ± 0.48     | \[0.13; 0.39\]                        | +0.1% to +3.1% | +1.4%                | .223                                   | 44.2% [8.1%; 82.5%] |
| Peak moment _knee_ [N/m/kg]      | Pre           | 2.65 ± 0.39     | <0.001 [+0.08; +0.19]                  | 0.36           | +5.2%                | .110                                   | 0.82 [−1.9%; 3.5%] |
|                                 | 2 wk post     | 2.79 ± 0.38     | \[0.19; 0.52\]                        | +1.6% to +12.4%| +5.2%                | .110                                   | 0.82 [−1.9%; 3.5%] |
| Hip angle at peak moment _knee_ [°] | Pre           | 72.9 ± 6.0      | <0.001 [+2.3; +4.5]                    | 0.57           | +4.7%                | .130                                   | 0.82 [−1.9%; 3.5%] |
|                                 | 2 wk post     | 76.3 ± 5.7      | \[0.32; 0.82\]                        | −0.7% to +8.2% | +4.7%                | .130                                   | 0.82 [−1.9%; 3.5%] |
| Work _knee_ [J/kg]               | Pre           | 3.61 ± 0.41     | 0.011 [+0.02; +0.18]                   | 0.21           | +2.7%                | 0.129                                  |                  |
|                                 | 2 wk post     | 3.71 ± 0.48     | \[0.06; 0.36\]                        | −2.8% to +8.2% | +2.7%                | 0.129                                  |                  |
| Peak power _knee_ [W/kg]         | Pre           | 50.8 ± 11.5     | <0.001 [+2.1; +5.2]                    | 0.31           | +7.2%                | .172                                   |                  |
|                                 | 2 wk post     | 54.5 ± 11.4     | \[0.16; 0.46\]                        | +2.2% to +18.8%| +7.2%                | .172                                   |                  |
| Knee angle at peak power _knee_ [°] | Pre           | 50.6 ± 7.7      | <0.001 [−1.7; −3.4]                   | 0.34           | −5.1%                | .197                                   |                  |
|                                 | 2 wk post     | 48.0 ± 7.0      | \[0.20; 0.49\]                        | −2.2% to −9.0% | −5.1%                | .197                                   |                  |
| Maximal angular velocity _knee_ [°/s] | Pre           | 1309.0 ± 132.0  | 0.012 [+7.4; +88.0]                    | 0.38           | +3.6%                | .061                                   | −0.555           |
|                                 | 2 wk post     | 1356.7 ± 133.3  | \[0.10; 0.66\]                        | −5.1% to +13.0%| +3.6%                | .061                                   | −0.555           |
| Mean angular velocity _knee_ [°/s] | Pre           | 603.5 ± 25.1    | 0.022 [−0.9; +22.5]                    | 0.43           | +1.8%                | .234                                   |                  |
|                                 | 2 wk post     | 614.2 ± 25.5    | \[0.05; 0.80\]                        | −3.7% to +6.8% | +1.8%                | .234                                   |                  |

(Continues)
DISCUSSION

This first NHE intervention study with sprinters aimed (a) to quantify NHE training adaptations by camera-based isokinetic assessments and sprint analyses, (b) to relate the magnitude of adaptations to the participants’ initial performance level, (c) to investigate the transferability of NHE-induced adaptations to maximal sprints, and (d) to determine strength preservations after 3 months. The following discussion is structured according to the four hypotheses.

4.1 Adaptations of isokinetic and sprint parameters

The present results confirmed the hypothesis that standardized high-intensity NHE training causes moderate to large improvements of eccentric hamstring strength and thigh muscle balance, whereas improvements of sprint performance and swing phase mechanics were predominantly small (Table 1). The observed adaptations of +7% (contractional work_{Hec}, \( d = 0.44 \)) to +16% (peak moment_{Hec}, \( d = 1.14 \)) were similar to those reported in previous studies (from +4% to +34%).5-7,9-12 Three of these studies conducted NHEs without partner assistance ensuring a fixed abutment at the heels,11,12 whereas only one controlled execution quality via live feedback and concomitant kinematic analyses.10 High compliance and high intensity were suggested to optimize adaptations of NHE training interventions.11,12,19 Both characteristics were met by the present study. In line with previous findings, knee flexion angles at peak moment_{Hec} remained unaffected.27 Due to the distinctive angular velocity profile during eccentric isokinetic knee flexor movements, knee flexion angles at peak power_{Hec} remained unchanged as well.17,18

To date, only one study analyzed the effects of NHE training on sprint velocity,8 whereas usually split times have been investigated.5-7,9,13 NHE interventions had no,8,9 small7 or moderate to large5,6 effects on sprint performance of predominantly soccer players of different performance levels. Regional to national class male sprinters demonstrated small increases of their maximal sprint velocity (+1.4%, \( d = 0.26 \)) (Table 1) in response to the NHE intervention.

Nordic Hamstring Exercise training improves eccentric hamstring activation which is required at the end of the swing phase in order to decelerate the knee extension and to realize foot ground contact by a powerful pawing action.1,4 The apparently enhanced sprint mechanics during late swing phase provide first insights into short-term adaptations following eccentric hamstring training. This performance enhancement might be attributable to the important biarticular function of the hamstrings in the late swing phase of sprinting.4 These

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TABLE 1 (Continued)

| Parameter | Mean ± SD | \( \mu \) (Pearson) | \( r \) (Pearson) | \( R^2 \) [90% CI] |
|-----------|-----------|-----------------|-----------------|-----------------|
| Peak moment_{Hec} [Nm/kg] | Pre 6.13 ± 1.29 | 6.13 ± 1.29 | 0.011 [0.000; 0.020] | 0.12 [0.06; 0.20] |
| Work_{Hec} [J/kg] | Pre 2.75 ± 0.44 | 2.75 ± 0.44 | 0.007 [0.000; 0.10] | 0.12 [0.04; 0.20] |
| Work_{pre} [J/kg] | 2 wk post 2.80 ± 0.44 | 2.80 ± 0.44 | 0.000 [0.000; 0.10] | 0.00 [0.00; 0.04] |

Note: Significant changes (\( P \leq 0.05 \)) between pre and 2 weeks post intervention (one-tailed t-test) are indicated with * and corresponding correlations between pre-values and percentage changes in relation to 2 weeks post are presented. Coefficients of determination (\( R^2 \)) specify the strength of significant relationships (\( P \leq 0.05 \)).

Abbreviations: CI, confidence interval; DCRe, dynamic control ratio at the equilibrium point; H, hamstrings; ecc, eccentric.
numbers emphasize that the NHE is a very effective resistance training exercise to selectively improve eccentric hamstring strength 8-12 as well as sprint performance 5-7,13 and swing phase mechanics.

### 4.2 Influence of performance level

The hypothesis that weaker participants demonstrate significantly greater adaptations was proven true for isokinetic parameters ($R^2$ range: 42%-62%), but not for sprint mechanics ($P > 0.05$) (Table 1). Previous research confirmed that NHE-induced strength adaptations depend on both experience and performance level.5 It could be suggested that besides early progresses in neuromuscular coordination, the hormonal response might be responsible for higher adaptations in weaker athletes.15,28 In contrast, improving sprint performance is more complex. It requires additional technical demands, intermuscular coordination and strength capacities of other muscles apart from the hamstrings such as the hip flexors.1,4,8,9 Regardless of the performance level, the current high-intensity NHE intervention improved hamstring strength, thigh muscle balance, sprint performance and swing phase mechanics in all participants (Table 1).

### 4.3 Transfer of NHE induced adaptations to sprint mechanics

The present results rejected the hypothesis that the transfer of NHE-induced strength adaptations to maximal sprints is negligible to small. Instead, adaptations of peak momentsHecc were strongly related to increased knee ($R^2 = 83\%$) and hip joint ($R^2 = 72\%$) peak moments during the late swing phase of maximal sprints (Table 2). The performance-determining role of knee and hip joint peak moments in sprinting is supported by the empirical evidence that both parameters demonstrated positive significant relationships to running speed.4 Previous research possibly failed to reveal significant associations because sprint times were associated with dynamometer-based strength measures.5 The established relationships rely on inverse dynamic analysis and camera-based isokinetic tests17,18 providing accurate and more detailed information about lower-limb joint mechanics. The significant associations of increased peak powerHecc ($R^2$ range: 53%-65%) and DCre moments ($R^2$ range: 39%-65%) to improvements of knee and hip joint peak moments in sprinting support their informative value in isokinetic assessments.17,18,21 The strong association between improvements of DCre angles and enhanced swing phase kinematics ($R^2 = 68\%$ to hip angle@peak powerHecc)
TABLE 2  Associations between improvements of camera-based isokinetic parameters obtained at 150°/s and improvements of swing phase mechanics of maximal sprints

| Improvements of swing phase mechanics [%] | Improvements of isokinetic parameters @150°/s [%] |
|-----------------------------------------|---------------------------------------------|
| **Sprint velocity [m/s]** | **Peak moment [Nm/kg]** | **Peak power_{\text{knee}} [W/kg]** | **Joint angle@peak power_{\text{knee}}** | **Work [J/kg]** | **Angular velocity_{\text{knee}} [°/s]** |
| | Knee (ecc) | Hip (con) | Knee (ecc) | Hip (con) | Max | Mean |
| Peak moment_{\text{Hec}} [Nm/kg] | P = .306 | P < 0.001 | P < 0.001 | P = 0.011 | P = .863 | P = .588 | P = 0.089 | P = .522 | P = .857 | P = .427 |
| | r = .909 | r = .849 | r = .700 | | R² = 82.6% | R² = 72.1% | R² = 49.0% | [74.7%; 94.5%] | [50.5%; 88.0%] | [14.0%; 75.5%] |
| Contractional work_{\text{Hec}} [J/kg] | P = .620 | P = .233 | P = .192 | P = .947 | P = .648 | P = .308 | P = 0.024 | P = .797 | P = 0.048 | P = .064 |
| | r = .700 | r = .700 | r = .627 | r = .700 | R² = 41.3% | R² = 33.8% | [10.3%; 74.6%] | [2.3%; 82.0%] |
| Peak power_{\text{Hec}} [W/kg] | P = .185 | P = 0.002 | P = 0.007 | P = 0.014 | P = .505 | P = .503 | P = .125 | P = .547 | P = .889 | P = .349 |
| | r = .805 | r = .730 | r = .685 | r = .685 | R² = 64.8% | R² = 53.3% | R² = 46.9% | [48.3%; 88.5%] | [27.7%; 80.0%] | [23.5%; 75.8%] |
| DCRe moment [Nm/kg] | P = .470 | P = 0.001 | P = 0.029 | P = 0.072 | P = .935 | P = .604 | P = 0.018 | P = .884 | P = .533 | P = .113 |
| | r = .808 | r = .627 | r = .700 | r = .700 | R² = 65.3% | R² = 39.3% | R² = 44.5% | [49.5%; 87.3%] | [8.7%; 70.8%] | [13.8%; 74.8%] |
| DCRe angle [°] | P = .211 | P = .133 | P = .185 | P = .209 | P = 0.001 | P = 0.001 | P = .908 | P = .400 | P = .806 | P = .174 | P = .385 |
| | r = −.822 | r = −.822 | r = −.822 | r = −.822 | R² = 67.6% | R² = 67.6% | R² = 89.5% | [46.5%; 89.5%] | [46.5%; 89.5%] | [46.5%; 89.5%] |

Note: Significant relationships (P ≤ 0.05) are highlighted by gray shading and their coefficients of determination (R² with respective 90% CIs). Abbreviations: ecc, eccentric; con, concentric; H, hamstrings; DCRe, dynamic control ratio at the equilibrium point; CI, confidence interval.
was an unexpected finding. It mirrors the enhanced muscular capacity to produce and withstand high loads at longer hamstring muscle length even further elongating with increasing hip flexion.\textsuperscript{1,4,22} Due to the underlying methodology of the present study, the strength of the obtained relations exceeded previous associations between NHE and sprint performance.\textsuperscript{13} However, the transfer of the bilateral and monoarticular NHE to multiarticular movement of sprinting remains limited. The swing phase is not only steered around the knee joint but hip flexors and extensors are obviously contributing considerably to movement execution, too (Table 2).\textsuperscript{4,8,9} Therefore, sprint-specific strength training programs should also integrate hip-dominant exercises.\textsuperscript{1}

4.4 | Strength preservation

The hypothesis that the formerly increased strength level is reduced to the baseline level 3 months after the intervention is rejected because hamstring function and thigh muscle balance remained significantly enhanced (Figure 3). Recent research examined that adaptations of low-volume NHE training persisted after 4 weeks of detraining,\textsuperscript{11} whereas those of high-volume training diminished more rapidly.\textsuperscript{6,11,12} The present study incorporated low volumes per set (3 repetitions) and week (27 repetitions), thus focusing on maximal intensity and a high time under tension at comparably long hamstring muscle length.\textsuperscript{10} The composition of the cohort might have contributed to sustained adaptations because this was the first intervention study with sprinters. Additionally, they had no prior experience in NHE. As regular sprint training promotes hamstring function,\textsuperscript{8} the regular training program might have assisted to maintain the achieved adaptations. Furthermore, previously unexperienced athletes showed long-lasting strength gains across 3 months of detraining.\textsuperscript{15} Neural adaptations might have been predominant because improvements at higher movement speed exceeded those at lower velocity (Figure 3).\textsuperscript{10,11,16,29} The present findings

\textbf{FIGURE 3} Selected dynamometer-based isokinetic data (mean changes of pooled data) obtained at 15°/s (light gray diamonds), 30°/s (dark gray diamonds) and 150°/s (black diamonds) illustrate the adaptation process of eccentric hamstrings strength (A) and muscle balance between knee flexors and extensors (B) throughout the investigated 22 wk. Significant time effects ($P \leq 0.05$) related to the initial baseline period (b to p0) are indicated with §, # and * for 15°/s, 30°/s and 150°/s, respectively. Dashed lines visualize the spans of negligible, small, moderate, and large effect sizes.
support the assumption that eccentric-only training elicits long-lasting strength gains.\textsuperscript{14,15} If high intensities are implemented, the repeated bout effect lasts between several weeks up to 6 months.\textsuperscript{15,16} This knowledge is important for coaches and scientists to optimally design and periodize sprint-related strength training programs.

5 PERSPECTIVE

A standardized high-intensity NHE training induced sustained adaptations which enhanced sprint performance and swing phase mechanics. Further studies should focus on high NHE execution quality to optimize the magnitude and preservation of achieved effects. High execution quality (eg, high ROM to downward acceleration) will result in high intensity which has been identified to improve adaptations.\textsuperscript{12} Assisted NHEs might contribute to ensure a high activation at comparably long hamstring muscle length\textsuperscript{10} by avoiding a rapid acceleration with concomitant low muscle activation in the second half of the exercise.\textsuperscript{2,3} Further effort is required to overcome the practical challenges (eg, ensuring a high execution quality) and impaired functionality (eg, unilateral NHEs with flexed hip across a reduced ROM) of NHE training. An optimal dose-response relationship has to be established for this supramaximal exercise because it poses an extraordinarily high load on the athletes' hamstrings.\textsuperscript{29} In this context, the guidelines of traditional resistance training (eg, 3-4 sets with 8-12 repetitions) are not adequate and will lead to poor execution quality, impaired adaptations and low compliance.\textsuperscript{19}

Prospective studies dealing with the prevention and prognosis of sprint-related injuries should provide evidence about the practicability and suitability of DCR e moments and angles.\textsuperscript{10,21,22,27} Although hamstring injuries appear as knee muscle injury, the hamstring's biarticular nature renders hip joint mechanics essentially.\textsuperscript{4} Therefore, preventive exercises should incorporate sprint-related knee and hip joint mechanics to adequately prepare for the corresponding loads.\textsuperscript{1}

The present study had several limitations. The within-subject design with repeated measures did not replace a control group. Furthermore, the variability in training history, training volume, performance level and the lack of NHE training experience might have affected the results. Consequently, future intervention studies which investigate NHE-induced effects on sprint performance should analyze homogeneous samples and should include matched controls to take the effect of usual training into account. The determination of individual anthropometric data (eg, by a body scanner) might have reduced measuring inaccuracies of motion analyses. Although the inverse dynamic modelling approach is a well-accepted biomechanical method, its capacity to provide quantitative information about muscle function is limited.\textsuperscript{23} This is particularly valid for the swing phase of sprinting where only moments of inertia enter the calculation of joint mechanics.\textsuperscript{4}

The present results demonstrated that high-intensity NHE training induced sustained improved hamstring function of sprinters, which can be transferred to swing phase mechanics of maximal sprints. The initial performance level, NHE training procedures as well as the periodization should be considered to optimize adaptations.

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