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Agreement between methods and terminology used to assess the kinematics of the Nordic hamstring exercise

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ABSTRACT

The Nordic hamstring exercise (NHE) is employed as a component of preventative training programmes to minimise hamstring strain injury risk. Variation in the methods and terminology used to assess the NHE makes comparison between studies difficult. We aimed to compare the utility of kinetic and kinematic metrics by comparing several collected concurrently. 18 male recreational rugby union participants completed 3 bilateral NHE repetitions on a hamstring device equipped with in-line strain gauge load cells, integrated with a 3-dimensional motion tracking system. Mean break-point angle occurred after the angle at first acceleration (121.5 ± 10.4° vs. 119.2 ± 7.1°) whereas break-torque angle (BTA) occurred later in the NHE action (126.0 ± 9.8°) showing highest correlation to the angle at greatest acceleration (123.9 ± 7.9°, r = 0.85). Future research should consider movement quality as the angular velocity of the knee joint at BTA demonstrated large variation (*range* = 3.6–93.4 deg·s^{1}), with high intrasubject variability of relative trunk-to-thigh angle at peak-torque (*range* = 0.4–44.7°). This study proposes standardisation of methods and terminology used to define the NHE. Measuring BTA is recommended to represent the point at which hamstring muscle failure occurs, specific to the proposed injury mechanism during high-speed running.

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KEYWORDS
Nordic hamstring exercise; hamstring strain injury; kinematics

Introduction

As hamstring strain injuries (HSI) are common in football (12% of total injuries over 2 seasons) and have frequent reoccurrence within 2 years (14–63%) (De et al. 2012; Orchard & Seward, 2002; Woods et al. 2004), prevention of initial injury is critical. Nordic hamstring exercise (NHE) training has attracted much interest in the literature, due its success in reducing HSI, by up to 51% (Van Dyk et al. 2019) when included in prevention programmes (Arnason et al. 2008; Petersen et al. 2011; Van Der Horst et al. 2015). The NHE has been proven to elicit positive strength and anatomical adaptations in the knee flexors (Presland et al. 2018; Timmins et al. 2016) yet the mechanism of this effect is debated (Presland et al. 2018; Timmins et al. 2016; Van & Bosch, 2017). Following the development of a novel hamstring training device (NordBord) by Opar et al. (2013), much of the subsequent research has centred on using Nordic eccentric knee flexor strength as a kinetic measure. Furthermore, there has been a rise in the use of kinematic variables, sometimes in place of force measurement, to provide a biomechanical analysis of the NHE action (Alt et al. 2018; Delahunt et al. 2016; Ditroilo et al. 2013; Jeffery, 2018; Lee et al. 2018, 2017; McGrath et al. 2020; Muggleton, 2015; Šarabon et al. 2019; Sconce et al. 2015). To determine NHE kinematics a range of methods have been employed including video camera, 2D motion analysis, electrogoniometry, 3D motion capture systems and other custom set-ups (Alt et al. 2018; Delahunt et al. 2016; Ditroilo et al. 2013; Jeffery, 2018; Lee et al. 2018, 2017; McGrath et al., 2020; Muggleton, 2015; Šarabon et al., 2019; Sconce et al., 2015). However, variation in the methods used and a lack of clarity and inconsistency when defining terminology in the literature has made comparison between similar NHE studies difficult. Some studies have selected different kinematic metrics for analysis, used different terminology to represent the same metric, or used metrics interchangeably, which can be problematic when comparing findings (Table 1).

During the NHE a point is normally reached where the knee flexors of an individual can no longer resist the increasing extending moment due to body weight at a lengthening moment arm. This has been termed the, "break-point angle" in earlier literature (Sconce et al., 2015). It is well documented in the research that eccentric strength is an important concept of NHE performance (Bourne et al., 2015; Opar et al., 2015), with a "loss of control" indicating that torque has exceeded the capability of the knee flexor muscles, causing the participant to "break" and fall to the floor. Sconce et al., (2015) demonstrated that the BPA, determined by video analysis software to be a valid field-based measure of eccentric knee flexor torque when measured by isokinetic dynamometry. A lower BPA (greater knee extension relative to the forward horizontal) strongly correlated to a larger eccentric knee flexor torque (average of right and left limbs) (r^2 = 0.65, n = 16, p < 0.001). Visually assessing BPA is useful for those practitioners with limited equipment requiring an approximate indication of an

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Table 1. Kinematic metrics and their definitions used in Nordic hamstring exercise literature. Average results (Mean or Mean±SD) reported for each metric.

Terminology	Definition	Average results (Mean±SD)
Break-point angle (BPA) (Sconce et al., 2015)	The knee angle relative to the forward horizontal at which the individual can no longer resist the increasing gravitational moment and falls to the floor	n = 16 male (n = 7) and female (n = 9) soccer players Break-point angle = 41 ±8.1° *where vertical start position = 90° and full horizontal extension = 0° i.e. a smaller angle indicates closer to the floor*
Chinese University of Hong Kong (CUHK) Nordic break-point test (Lee et al., 2017) (Lee et al., 2018)	The angle between the line joining hip and knee markers and initial vertical position of each participant. Angle metric determined by the first appearance of the angular velocity that is greater than 10 deg·s^{-1} The angle between the initial vertical position and the maximum point. The angle (pitch) is determined by the first appearance of the angular velocity (x-axis) that is greater than 10 deg·s^{-1}	n = 33 male 2nd division football league players CUHK test = 17.76 ±6.61° (Lee et al., 2017) *video-analysis *where vertical start position = 0° and full horizontal extension = 90° i.e. a larger angle indicates closer to the floor* n = 25 male professional football players CUHK test = 40.78 ±15.77 (Lee et al., 2018) *smart-phone measure *where vertical start position = 0° and full horizontal extension = 90° i.e. a larger angle indicates closer to the floor*
Angle at downward acceleration (angle at DWA) (Ditroilo et al., 2013) (Delahunt et al., 2016)	The angle characterising the point in time when the control of the forward fall is lost, translating into a sudden increase in downward velocity. This variable is measured by the angle corresponding to the initial point of the time window that yielded the highest slope difference	n = 18 male university students Angle at DWA = 68.1 ±8.0° (Ditroilo et al., 2013) n = 29 healthy recreationally active males Angle at DWA = 76.9 ±3.8° (Delahunt et al., 2016) *where vertical start position = 90° and full horizontal extension = 0°*
Peak knee angular velocity (pVelocity) (Ditroilo et al., 2013) (Delahunt et al., 2016)	The maximum knee joint velocity	n = 18 male university students pVelocity = 81.3 ±23.8 deg.s^{-1} (Ditroilo et al., 2013) n = 29 healthy recreationally active males pVelocity = 117.7 ±16.4 deg.s^{-1} (Delahunt et al., 2016)
Angle of peak velocity (angle@pVelocity) (Delahunt et al., 2016) (McGrath et al., 2020)	The knee joint angle at which peak velocity occurs	n = 29 healthy recreationally active males angle@pVelocity = 41.8 ±5.6° (Delahunt et al., 2016) n = 33 elite male rugby league players angle@pVelocity = 37.7° (IQR 42–32) (McGrath et al., 2020) *single-leg NHE* *both studies ~ vertical start position = 90° and full horizontal extension = 0°*
Knee angle (°) at 20°/s (McGrath et al., 2020)	The angle corresponding to the start of the NHE forward movement in a maximal effort	n = 33 elite male rugby league players Mean knee angle at 20°/s = 80.43° (IQR 85–76) *single-leg NHE*
Knee angle (°) at 60°/s (McGrath et al., 2020)	The angle corresponding to the period when the athlete begins to accelerate during the NHE movement	n = 33 elite male rugby league players Knee angle at 60°/s = 67.26° (IQR 72–61) *single-leg NHE*
Elapsed time period (ms) between 20–60°/ (McGrath et al., 2020)	The time under load during the contraction between the start of the NHE movement and when the athlete begins to accelerate	n = 33 elite male rugby league players Elapsed time period between 20–60°/ = 369.1 ms (IQR 288–430) *single-leg NHE*
Elapsed time period (ms) between 20°/s-peak velocity (McGrath et al., 2020)	The time under load during the contraction between the start of the NHE forward movement and peak velocity	n = 33 elite male rugby league players Elapsed time period between 20°/s-peak velocity = 623.3 ms (IQR 555–723) *single-leg NHE*
Time under tension (s) during NHE (t_{NHE}) (Alt et al., 2018)	The time under tension achieved during each NHE repetition	n = 16 regional to national class male sprinters Assisted NHE (6 sessions) = 6.8 ±0.6s Unassisted NHE (6 sessions) = 4.4 ±1.1s
Range of motion (°) of the knee joint (ROM_{knee}) (Alt et al., 2018)	The ROM of the knee joint during each NHE repetition. The knee flexion angle at DWA, is identified as the highest angular acceleration in the knee extension velocity-knee flexion angle-time curve	n = 16 regional to national class male sprinters Assisted NHE (*1 session) = 81.44 ±5.5° Unassisted NHE (6 sessions) = 72.7 ±8.3° *where vertical start position = 0° and full horizontal extension = 90°*
Mean knee extension velocity (°/s) (Mean ω_{KE}) (Alt et al., 2018)	The mean knee extension velocity reported between the first derivative of the moment-time and knee flexion angle-time curves of each NHE repetition	n = 16 regional to national class male sprinters Assisted NHE (*1 session) = 12.2 ±1.1°/s Unassisted NHE (6 sessions) = 17.3 ±4.9°/s
Range of motion (°) of the hip joint (ROM_{hip}) (Alt et al., 2018)	The ROM of the hip joint achieved during each NHE repetition	n = 16 regional to national class male sprinters Assisted NHE (*1 session) = 10.8 ±4,5° Unassisted NHE (6 sessions) = 15.9 ±6.3°
Maximum hip flexion (°) angle (HF_{max}) (Alt et al., 2018)	The maximum hip flexion angle reported between the first derivative of the moment-time and knee flexion angle-time curves of each NHE repetition	n = 16 regional to national class male sprinters Assisted NHE (*1 session) = 9.2 ±6.8° Unassisted NHE (6 sessions) = 17.0 ±8.2°
Range of motion to downward acceleration (DWA) in relation to ROM_{knee} (ROM_{DWA}) (Alt et al., 2018)	Percentage (%) of ROM to DWA in relation to the ROM achieved by the knee joint	n = 16 regional to national class male sprinters Assisted NHE (*1 session) = 99.6 ±1.8% Unassisted NHE (6 sessions) = 68.5 ±24.4%

athlete's eccentric strength. Smartphone applications such as iOS Nordics software (Balsalobre, 2017) that digitise NHE video clips into a two-dimensional space, provide a low-cost alternative to laboratory devices. This application provides an indirect measure of moment; however, no research has explored how well such proxy values correspond to knee flexor torque values from an instrumented hamstring device, making comparison to HSI risk factor force values given in the literature challenging. There are other limitations to this approach such as the validity of measures for those athletes that can reach full knee extension during a bodyweight NHE. Additionally, the inter-subject variation in NHE technique, where hip position control and movement speed can influence muscle length and torque production (Hegyi et al., 2019; Marušič et al., 2020; Šarabon et al., 2019) poses a problem for determining an accurate BPA.

In order to examine NHE performance parameters, metrics relating to angle and velocity have most commonly been applied to measure NHE loss of control; these include break-point angle and angles at specific velocities (Alt et al., 2018; Delahunt et al., 2016; Ditroilo et al., 2013; Lee et al., 2018, 2017; McGrath et al., 2020; Sconce et al., 2015). Similarly to Sconce et al., (2015), studies by Lee et al., (2018, 2017) employed 2D motion analysis to determine BPA, and further developed a smartphone (iPhone 5s) camera approach to measure the BPA (CUHK test). However, they used the angle (pitch), relative to the initial vertical starting position at which angular velocity (x-axis) initially exceeded 10 $deg{\cdot}s^{-1}$, rather than visual inspection of a loss of control relative to the horizontal as used by Sconce et al. (2015). Other research has used motion capture and custom electrogoniometry systems to measure kinematics (Alt et al., 2018; Delahunt et al., 2016; McGrath et al., 2020; Šarabon et al., 2019). Ditroilo et al. (2013) was the first study to use a single axis electrogoniometer and data acquisition system to record NHE knee joint angle. The metric most closely relating to BPA was the angle characterising the end of trunk control termed, "angle at downward acceleration" identified as the point on the curve of a graph where a sudden increase in velocity occurred. This point was determined by computing a slope function over adjacent 200 ms time windows (100 ms overlap) and the slope difference between one-time window and the previous one was calculated. The angle corresponding to the initial point of the time window that yielded the highest slope difference was reported as the angle at DWA.

There is limited research measuring both kinetic and kinematic variables simultaneously whilst performing the NHE (Alt et al., 2018; McGrath et al. 2020; Šarabon et al., 2019). Whilst investigating the determinants of hamstring fascicle length, McGrath et al. (2020) used a hamstring device with load cells to measure eccentric knee flexor strength during an NHE (NordBord) to record average peak force across three NHE repetitions. 3D motion capture documented kinematics, specifically the corresponding knee angle at 20°/s (classed as the start of the movement), 60°/s (period where the athlete begins to "accelerate") and peak angular velocity (classed as the "*loss of control*" of the movement). BPA was referred to as the "angle of loss of control", which would indicate that the peak angular velocity metric was used, according to the previous definitions in the study. However, the loss of control metric used to define break point in previous research (Lee et al., 2017; Sconce et al. 2015) relates to assessing the NHE visually from camera footage, or as in the CUHK test, determined by the first instance of a velocity greater than 10 $deg{\cdot}s^{-1}$ (Lee et al., 2018). This is unrelatable to the velocity measures and method used in McGrath et al. (2020) where a velocity of 20°/s was only regarded as the start of the NHE movement.

Due to their practical value in the field and lower cost, there has been a rise in the utility of portable devices to assess eccentric strength during the NHE, compared to the traditional use of isokinetic dynamometry to determine knee flexor torque. Wiesinger et al. (2020) found moderate correlations between eccentric peak torque measured on a Nordic hamstring device compared to a dynamometer ($r = 0.58$) with a systematic and proportional bias towards lower values (~28%) and a high typical error (~19%). Peak torques were reached at more extended knee joint angles on dynamometry, suggesting each device may measure a different trait with the two measures being unrelatable (Wiesinger et al., 2020). Peak torque can only be reached within the ROM of the NHE action (Cuthbert et al., 2020) before the participant "breaks" and falls, compared to the ROM available through the action performed on dynamometry. Therefore, BTA during a NHE action could be a more useful determinant of where muscle failure is occurring rather than angle of peak torque on dynamometry. Where the torque is being produced in the muscle is of importance as current research suggests having strong and long hamstring muscles is effectual for injury prevention and a faster return-to-play following injury (Brukner, 2015). The study aimed to compare the utility of different metrics to explain NHE performance and technique by comparing several kinetic and kinematic variables collected concurrently. Subsequently, we hope to propose a standardised, consolidated list of kinematics that can be used in the literature to purposefully assess the NHE action, allowing easier comparison between similar studies.

Methods

Participants

A total of eighteen male ($n = 18$) recreational rugby union players of various playing positions and experience were recruited as participants (mean±SD age 20 ± 3 years, height 182 ± 6.7 cm, and body mass 91.0 ± 47.4 kg). Participants were recruited from the same University sports team to ensure data would be based on players with similar conditioning levels. All participants completed a personal injury and training history questionnaire, with all reporting having some previous training experience of the NHE. Collected injury history confirmed all participants to be medically cleared and not currently carrying an injury which would affect completion of the NHE trials. Exclusion criterion included any participants not medically cleared from disease or any person carrying a trunk or lower limb musculo-skeletal injury that would affect performance of the NHE. The study was approved by the University's Ethics Committee and all participants provided written informed consent to participate in the spirit of the Helsinki Declaration, after having all procedures explained to them.

Study design

A range of kinematic and kinetic metrics were obtained (Table 2) to comprehensively explore the phenomena of the NHE and offer detailed insight into its action, which has been a limitation in previous studies. These metrics were chosen as the NHE action involves initial forward flexion, a break region (loss of control) and a continual acceleration after break. Each component of the action has an associated knee joint angle, a velocity, and an acceleration. We propose that performance (strength, angle and velocity) and exercise quality (relative thigh-to-trunk angle and knee joint velocity) variables are relevant, and important NHE action metrics to measure. Within the context of this study, the dependent variables were all the metrics assessed and the independent variables were torque and angle. Participants were asked to abstain from strenuous exercise and ingesting caffeine or alcohol 48 h prior to the testing. All participants were given the same verbal instructions for controlling NHE quality, and encouragement was provided throughout.

Materials and equipment

The NHE was performed on a custom-made NHE device with in-line strain gauge load cells (Omega, Engineering Inc. Norwalk, USA) attached at the rear in a fixed position relative to the knee to measure torque. The transducers were calibrated and therefore will provide the same force measurements as other existing hamstring devices (Lodge et al., 2020; Opar et al., 2013). This custom device was used as it can concurrently measure torque and angle (HA*L*HAM®) (Sconce et al., 2021). Raw data were sampled at 125 Hz via a Phidget Bridge data acquisition board (Phidgets Inc., Calgary, Canada) then exported in .CSV format and processed in Excel spreadsheets (Microsoft Corp., Redmond, Washington) on a personal computer. A laboratory grade 3-dimensional motion tracking system (Liberty® Polhemus, Colchester, Vermont, USA) was integrated with the NHE device and used as the reference measurement system for the kinematic variables. As magnetic-based systems can be disturbed by metallic objects (Nixon et al., 1998) the capture areas were scanned first using the sensors to confirm the absence of distortion. For this reason, the NHE device was manufactured primarily of non-ferrous materials. Polhemus Liberty® software was used to collect orientation data at 240 Hz from two sensors located at the thigh (positioned laterally on the upper leg equidistant from the greater trochanter and lateral femoral epicondyle) and the trunk (positioned laterally equidistant from the greater trochanter and the shoulder bursa). The system was calibrated to measure the orientations of the trunk and thigh relative to an initial vertical kneeling position. Additionally, the original method of obtaining BPA through high speed camera (Casio Exlim-F1 camera 60 Hz) and motion capture (Kinovea Version 0.8.15) was used to determine the angle which showed a visual loss of control from the greater trochanter (hip) to the lateral femoral condyle (knee) relative to the horizontal from the recorded video (Sconce et al., 2015).

Table 2. Proposed agreement of terminology and definitions to assess the kinetics and kinematics of the Nordic hamstring exercise action.

Terminology	Definition
Kinetics	
Peak force	NHE bilateral maximum force value
Peak torque	NHE bilateral maximum torque value
Peak torque/kg	NHE bilateral maximum torque value normalised to body mass
Kinematics	
Break-point angle (BPA)	The knee angle relative to the horizontal (full extension = 180°) at which the individual can no longer resist the increasing gravitational moment and falls to the floor
Break-torque angle (BTA)	A new term to represent the definitive peak torque value and its corresponding thigh angle. A valid measure must show a clear torque peak point and subsequent drop-off representing a clear loss of NHE control
Relative trunk-to-thigh angle (RTA)	The angle between the thigh and the trunk throughout the NHE ROM, representing hip angle
Angular velocity of the knee joint (AVK)	Represents the angular velocity of the knee joint throughout the NHE
First acceleration (fAcc)	The point at which angular acceleration first starts to increase on the curve of a graph, manually picking out the time point that shows the first instance of significant acceleration. Representing the first loss of control occurring in the NHE action.
Angle of first acceleration (angle@fAcc)	The angle at which fAcc occurs
Acceleration elbow (eAcc)	The elbow point manually picked out on the acceleration curve representing the greatest release of NHE control occurring
Angle at acceleration elbow (angle@eAcc)	The angle at which eAcc occurs
Peak acceleration (pAcc)	The maximum acceleration value
Angle at peak acceleration (angle@pAcc)	The angle at which pAcc occurs
Peak velocity (pVelocity)	The maximum knee joint angular velocity
Angle at peak velocity (Angle@pVelocity)	The knee joint angle at which peak velocity occurs
Angle at the last instance of 10 deg·s^{-1} (angle@last10 deg·s^{-1})	The last instance of 10 deg·s^{-1} before a constant downward acceleration occurs

Procedures

A standardized warm-up was performed by each participant prior to the trials, consisting of 3 min on a stationary bike and a series of dynamic movements such as walking lunges, squats, and leg swings (2 sets of 10 repetitions). A warm-up set of 3 submaximal bilateral NHEs were performed prior to the maximal trials (1 set of 3 repetitions) per person. The rest period between each trial was long enough to allow the participant to comfortably recover before the next maximal effort. All participants had some previous experience of resistance training and the Nordic exercise. Verbal instruction on NHE technique quality was given to all participants by the researcher. Participants assumed a kneeling position on the device with their ankles secured in place approximately superior to the lateral malleolus, 0.6 m away from the lateral femoral epicondyle (Figure 1). To allow subsequent synchronisation of the load cells and Polhemus data sets, each participant was asked to tap the thigh sensor at the beginning of each NHE trial. The tap was detected as a sudden movement on the accelerometers and sampled synchronously with the load cells. By manually identifying the tap signal on each trace the Polhemus system was synchronised. Participants started each trial in a fully extended hip and 90° knee position before commencing any forward movement. From this position each participant performed the NHE by a forward rotation about the knee. Participants were informed to gradually lean forward at the slowest possible speed, maximally resisting the movement with both legs, whilst holding the hips fixed in line with the knee and shoulder bursa joints throughout the range of movement (Mjølsnes et al., 2004). The knee flexors provided the main resistance against gravity to control descent into the prone position. Participants were asked to keep hands facing forward and elbows pointing down, ready to buffer the fall. This action was performed until the participant could no longer withstand the torque around their knees caused by the increasing moment arm of their weight as they leaned forwards (Petersen et al., 2011; Sconce et al., 2015) (Figure 1). The load cells attached to the device produced force-time traces in line graph format, showing both individual right and left limb, and combined limb total forces. Torque was then calculated for each NHE trial from the force traces and the distance measured from the set pivot point to the centre of the ankle restraints (0.6 m).

Statistical analysis

54 conventionally performed NHE trials were considered for analysis. Any mis-trials were discounted (n = 6), including where any participants reached full extension (due to lack of a break-point), and the absence of a tap signal on the thigh sensor (affecting the synchronisation process). Peak torque was measured, and trials were rejected when there was no clear peak, an extended flattened period, or when there was no definite drop-off period (n = 4). NHE angular metrics were calculated by using 90° as the vertical starting position and full knee extension as 180°. The data were statistically processed in GraphPad Prism 8.43 (GraphPad Software Inc). The Shapiro-Wilks test was used for testing of normality. To determine a relationship between the angular metrics, a Pearson correlation coefficient was calculated. Significant differences between values were also identified, with significance set at $p < 0.05$. Variability in ranges have been reported for relevant metrics where thresholds have been previously defined. Mean differences of all measurements were reported with their 95% confidence intervals.

Results

Descriptive statistics for each metric are shown in Table 3 and reported as mean ± standard deviation. Intra-reliability for each metric for every accepted trial is reported in Table 4. The lowest mean value for a knee angle was angle@last10deg·s^{-1} (117.3 ± 6.8°), with the next nearest mean values reported for angle@fAcc and BPA (119.2 ± 7.1° vs. 121.5 ± 10.4°) with BPA reporting greatest correlation to the angle@fAcc metric (r = 0.87) as seen in the correlation matrix (Figure 2). BTA occurred later in the NHE action (126.0 ± 9.8°), with BTA showing greatest correlation to the angle@eAcc (r = 0.85) (Figure 2). Angle@pVelocity occurred at a mean difference of 19.6° after BTA. There was large variability seen in the AVK mean difference (29.2 ± 22.6 deg·s^{-1}) and range (3.6–93.4 deg·s^{-1}) at BTA (IQR = 15.5–30.3 deg·s^{-1}). Large variability was also reported for the RTA mean difference (16.7 ± 10.8°) and range (0.4–44.7°) at BTA (IQR = 6.5–24.4°). These are indicated in Table 3 and Figure 3.

Discussion

With little agreement between previously used NHE kinematics reported in the literature, we aimed to assess the utility of different metrics to explain NHE performance and technique by comparing several kinetic and kinematic variables collected

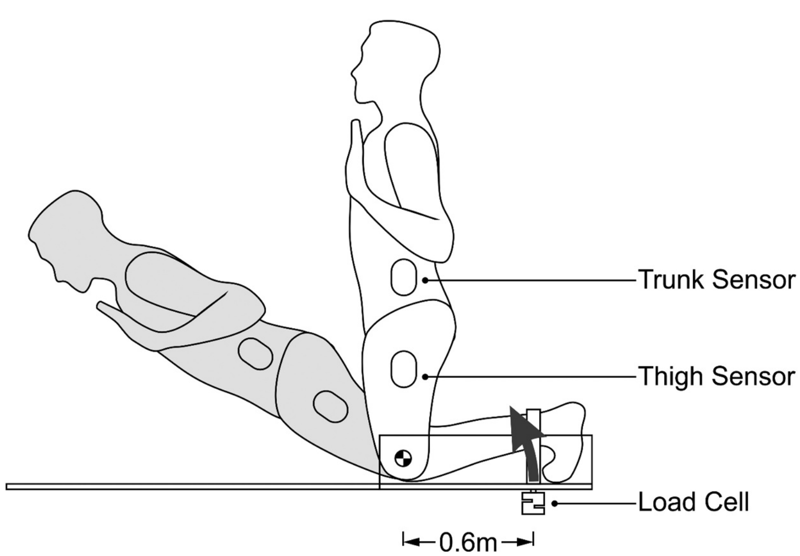

Figure 1. A computer-aided design of the custom device used to collect kinetic and kinematic metrics during the execution of the Nordic hamstring exercise trials.

Table 3. Mean±SD for each metric considered in the study. Variability and interquartile ranges (IQRs) also reported for every metric.

Metrics	Mean±SD	Range (Min-Max)	IQR (Q1-Q3)
Kinetics			
Peak force (N)	249.4 ± 116.8	84.1–527.9	164.4–333.3
Peak torque (Nm)	149.7 ± 70.1	50.5–316.7	98.6–200.0
Peak torque/kg (Nm/kg)	1.6 ± 0.7	0.4–3.2	1.0–2.2
Kinematics			
BPA (°)	121.5 ± 10.4	103.0–145.0	113.0–130.0
BTA (°)	126.0 ± 9.8	108.8–149.4	117.8–131.5
AVK (deg·s^{-1}) at BTA	29.2 ± 22.6	3.6–93.4	15.5–30.3
RTA (°) at BTA	16.7 ± 10.8	0.4–44.7	6.5–24.4
fAcc (deg·s^{-2})	21.1 ± 10.0	6.7–52.8	14.4–26.8
Angle@fAcc (°)	119.2 ± 7.1	108.1–134.3	112.9–125.2
eAcc (deg·s^{-2})	54.1 ± 27.8	21.0–121.9	34.1–76.9
Angle@eAcc (°)	123.9 ± 7.9	111.1–143.8	117.7–129.8
pAcc (deg·s^{-2})	222.5 ± 61.8	87.9–340.9	194.4–267.6
Angle@pAcc (°)	134.0 ± 7.6	121.8–150.7	128.2–140.0
Angle@last10deg·s^{-1} (°)	117.3 ± 6.8	103.9–129.4	111.7–123.5
pVelocity (deg·s^{-1})	101.0 ± 24.0	40.1–155.8	82.9–119.1
Angle@pVelocity (°)	145.6 ± 7.1	132.2–160.9	140.4–150.0

concurrently on a hamstring device. Although BPA, BTA, CUHK Nordic break-point test and angle at DWA are similar metrics, they have all been measured differently in the literature, both by method and definition, making comparison to the reported results in this study difficult (Table 1, Table 3). Throughout the discussion angular results from other studies have been re-calculated so they represent full extension as 180° to allow comparison. BPA BTA, CUHK Nordic break-point test and angle at DWA Mean±SD (139 ± 8.1°; 107.76 ± 8.1°; 130.78 ± 8.1°; 111.9 ± 8.0°; 103.1 ± 3.8°) shows variability between studies in the literature and differs to BPA, BTA and angle@ last10deg·s^{-1} in this study (121.5 ± 10.4; 126.0 ± 9.8; 117.3 ± 6.8). However, angle of pVelocity results (145.6 ± 7.1°) showed consistency with the literature when calculated to full extension = 180° (138.2 ± 5.6°; 142.3°) (Delahunt et al., 2016; McGrath et al., 2020). Kinematic studies are limited in number and present differences in participant ability (elite/recreational), gender, training experience and NHE familiarisation, so discrepancies between studies are to be expected. We propose a consolidated list of kinematic metrics that can be used to assess each part of the NHE action (Table 3) to assist a standardised approach in future research.

The mean relative knee angle reported for each angular metric provides some useful commentary as to the sequence of the NHE action, however technique needs to be considered when discussing the validity of these metrics. Angle@last10deg·s^{-1} shows the closest association to angle@fAcc (117.3 ± 6.8° vs. 119.2 ± 7.1°) however there was a large variation in acceleration reported at fAcc (6.7–52.8 deg·s^{-2}), unrelatable to 10 deg·s^{-1}. This could be indicative of difference in technique where some individuals were able to descend gradually at the start of the NHE, whilst others demonstrated a more uncontrolled acceleration and less effective "hold" before "breaking". IQRs for fAcc suggest a baseline and threshold of 14.4–26.8 deg·s^{-2} to be considered for instance, of first acceleration (Table 3). Exploring the angular velocity of the knee joint at BTA shows large variation in the data set (*range* = 3.6–93.4 deg·s^{-1}) (Table 3 and Figure 4). Future work will be required to regulate descent speed more effectively across participants.

Exercise quality

Most studies to date have not considered exercise quality through kinematic feedback. Bourne et al. (2019) states that a NHE trial is deemed acceptable when the force output reaches a distinct peak (indicative of maximal eccentric strength), followed by a rapid decline in force, occurring when the participant can no longer resist the effects of gravity and therefore trials were discounted if no peak was evident. An improvement in NHE performance (how well the subject delays the "break" of the fall) was elicited in Delahunt et al. (2016) after a 6 wk eccentric training intervention. A longer control of the forward fall component of the NHE/smaller angle at DWA (where full extension = 0°) was reported (73.7° vs. 68.1° p = 0.022, Cohen's d = 0.90). Therefore, NHE training should improve an individual's ability to reach a lower NHE position and thus a larger BTA. A distinct torque drop-off period, representative of an obvious release of control should be evident, as it has importance in ensuring a supramaximal break-point and subsequently determining an accurate BTA. BTA could theoretically be an important metric to assess *proxy* muscle length changes i.e. the angular range over which the torque can be produced within the hamstrings. It is an indicator measure of the trade-off point (torque-muscle length) at which hamstring muscle failure ensues, providing a more specific metric relative to the proposed injury mechanism at which HSIs occur during high-speed running. Table 4 reports small CV values for BTA across all participants (0.4–5.0%) indicating its potential use as a reliable metric that is reproducible. It is a well-defined measure with no arbitrary thresholds, compared to other kinematic measures that require measurement of a specific velocity threshold or time-point.

Most studies reported hip flexion to start fully extended at the beginning of the NHE movement (0°) (Ditroilo et al., 2013; Lee et al., 2017; Pollard et al., 2019) and then remain extended throughout, rejecting any trials with "over-excessive hip flexion" (Muggleton, 2015). However, this was nearly always measured via visual inspection rather than by objective measurement of hip angle. Participants in this study were asked to perform the NHE using a slow approach with hips remaining fully extended throughout the ROM, and this was visually checked by the researchers. Alt et al., (2018) reported a similar mean hip flexion for unassisted NHE trials (17.0 ± 8.2° vs. 16.7 ± 10.8°)however, technique proved problematic to control and enforce between participants in this study due to varied individual techniques, and a lack of previous familiarisation, which may go some way to explaining the high intrasubject variability of RTAs at peak-torque (*range* = 0.4–44.7°) (Table 3 and Figure 4). The main limitation of this study has been a lack of familiarization in terms of NHE technique instruction prior to the kinematic testing, resulting in poor exercise quality. It is proposed that trunk flexion should be controlled more stringently using real-time kinematic feedback as studies have shown that greater hip flexion during the NHE can produce larger torque values at the same knee angle compared to a standard hip position (Hegyi et al., 2019; Šarabon et al., 2019) influencing the torque-length relationship. This is due to the increased lever arm of the centre of mass about the knee joint axis increasing the resultant torque.

Table 4. Intra-reliability for each kinematic metric for every accepted trial (44) across all participants (n = 18). Mean±SD, and CV values reported for all participants with accepted trials of 2 or more.

KINEMATICS

Participant	BPA (°)		BTA (°)		fAcc (deg·s^{-2})		Angle@fAcc (°)		eAcc (deg·s^{-2})		Angle@eAcc (°)		pAcc (deg·s^{-2})	
	Mean±SD	CV (%)	Mean±SD	CV (%)	Mean±SD	CV (%)	Mean±SD	CV (%)	Mean±SD	CV (%)	Mean±SD	CV (%)	Mean±SD	CV (%)
1	125.0 ± 3.6	2.8	129.7 ± 4.7	3.6	23.3 ± 5.1	22.1	124.6 ± 2.4	1.9	59.7 ± 26.2	43.9	129.7 ± 2.6	2.0	233.3 ± 33.2	14.2
2†														
3	122.3 ± 2.1	1.7	128.4 ± 3.0	2.3	16.6 ± 3.2	19.2	124.6 ± 2.9	2.3	31.7 ± 8.2	25.8	127.4 ± 1.7	1.3	151.3 ± 98.7	65.3
4	117.7 ± 0.6	0.5	118.5 ± 2.5	2.1	17.4 ± 6.1	34.8	114.1 ± 2.2	1.9	40.6 ± 6.2	15.2	115.9 ± 1.6	1.4	224.0 ± 27.3	12.2
5‡														
6	140.3 ± 5.0	3.6	147.7 ± 2.1	1.4	17.3 ± 8.2	47.5	130.7 ± 4.0	3.1	43.9 ± 22.2	50.5	139.7 ± 3.6	2.6	128.8 ± 34.8	27.0
7														
8	124.0 ± 5.2	4.2	130.4 ± 1.7	1.3	13.2 ± 8.8	67.0	126.0 ± 2.5	2.0	41.9 ± 12.7	30.4	131.6 ± 3.2	2.4	187.6 ± 23.9	12.7
9	134.7 ± 5.5	4.1	128.9 ± 4.1	3.2	24.3 ± 5.2	21.6	125.4 ± 2.7	2.2	56.2 ± 28.0	49.9	131.0 ± 3.2	2.4	313.8 ± 28.5	9.1
10	129.7 ± 1.5	1.2	126.8 ± 1.5	1.2	21.0 ± 6.2	29.7	122.2 ± 0.6	0.5	39.2 ± 6.9	17.5	124.9 ± 1.5	1.2	175.5 ± 21.5	12.3
11	112.3 ± 1.2	1.0	119.9 ± 1.9	1.6	17.4 ± 4.3	24.4	116.7 ± 2.6	2.3	111.9 ± 10.1	9.1	122.2 ± 2.7	2.2	231.9 ± 23.5	10.2
12	112.0 ± 1.0	0.9	128.9 ± 1.0	0.8	22.5 ± 7.9	35.3	110.9 ± 0.9	0.9	88.8 ± 17.3	19.5	120.7 ± 0.7	0.6	224.8 ± 18.6	8.3
13	135.3 ± 3.2	2.4	136.7 ± 6.9	5.0	19.1 ± 11.6	60.9	127.3 ± 4.1	3.2	33.9 ± 19.8	58.5	130.9 ± 3.3	2.5	164.9 ± 32.4	19.6
14	119.7 ± 1.5	1.3	119.8 ± 2.2	1.8	18.1 ± 9.3	51.6	113.5 ± 0.9	0.8	48.2 ± 10.9	22.5	119.7 ± 0.4	0.3	239.3 ± 19.5	8.2
15§	110.0 ± 4.2	3.9	118.6 ± 5.4	4.6	45.1 ± 10.9	24.2	112.7 ± 0.2	0.2	57.3 ± 33.1	57.8	116.2 ± 1.6	1.4	275.2 ± 30.0	10.9
16	105.3 ± 2.1	2.0	111.3 ± 2.8	2.5	29.7 ± 12.7	42.8	110.2 ± 2.7	2.4	71.2 ± 36.7	51.5	113.2 ± 3.6	3.2	286.0 ± 27.1	9.5
17§	120.5 ± 4.9	4.1	135.4 ± 2.4	1.8	20.7 ± 6.3	30.2	115.9 ± 1.3	1.1	55.4 ± 15.9	28.6	120.7 ± 0.5	0.4	199.1 ± 5.3	2.7
18	113.3 ± 0.6	0.5	112.6 ± 0.5	0.4	11.0 ± 3.3	30.2	111.5 ± 0.6	0.6	24.7 ± 0.9	3.5	112.7 ± 0.6	0.6	293.2 ± 36.5	12.5

KINEMATICS

Participant	Angle@pAcc (°)		Angle@last10deg·s^{-1}(°)		pVelocity (deg·s^{-1})		Angle@pVelocity (°)		AVK (deg·s^{-1}) at BTA		RTA (°) at BTA	
	Mean±SD	CV (%)	Mean±SD	CV (%)	Mean±SD	CV (%)	Mean±SD	CV (%)	Mean±SD	CV (%)	Mean±SD	CV (%)
1	139.2 ± 2.6	1.8	120.5 ± 1.7	1.4	99.9 ± 5.6	5.6	150.0 ± 1.2	0.8	24.8 ± 6.4	25.9	25.5 ± 6.0	23.6
2†												
3	132.5 ± 2.9	2.2	123.8 ± 2.3	1.9	48.6 ± 9.6	19.8	138.4 ± 4.5	3.2	19.6 ± 6.5	33.1	39.6 ± 4.4	11.2
4	124.4 ± 3.1	2.5	109.6 ± 1.1	1.0	93.0 ± 11.9	12.8	136.7 ± 4.5	3.3	25.7 ± 9.7	37.7	26.6 ± 2.6	9.8
5‡												
6	147.2 ± 3.2	2.1	122.9 ± 5.4	4.4	75.4 ± 10.1	13.5	156.3 ± 3.5	2.2	47.5 ± 18.7	39.4	25.9 ± 2.2	8.3
7												
8	140.2 ± 1.5	1.1	118.0 ± 12.2	10.3	92.0 ± 1.0	1.1	149.3 ± 1.6	1.1	18.8 ± 2.9	15.3	15.7 ± 2.3	15.0
9	142.1 ± 5.0	3.5	125.1 ± 1.9	1.6	135.9 ± 18.2	13.4	157.0 ± 5.4	3.4	18.7 ± 8.1	43.2	5.2 ± 5.0	96.5
10	136.7 ± 7.6	5.6	122.3 ± 1.4	1.1	79.3 ± 3.0	3.8	144.9 ± 3.9	2.7	18.4 ± 8.6	46.9	24.7 ± 3.1	12.5
11	132.6 ± 2.7	2.0	115.2 ± 3.1	2.7	117.3 ± 12.8	10.9	145.5 ± 2.4	1.7	20.7 ± 6.9	33.1	15.3 ± 8.0	51.9
12	132.9 ± 2.7	2.0	110.7 ± 1.8	1.6	121.7 ± 5.1	4.2	147.2 ± 2.7	1.8	74.0 ± 26.3	35.6	8.2 ± 6.2	76.3
13	140.7 ± 3.8	2.7	127.1 ± 2.1	1.6	84.9 ± 10.0	11.7	150.1 ± 2.2	1.5	38.9 ± 24.8	63.8	11.5 ± 10.4	90.5
14	130.1 ± 1.0	0.8	113.2 ± 1.0	0.9	103.9 ± 8.7	8.4	145.3 ± 1.3	0.9	26.2 ± 5.1	19.4	4.6 ± 4.2	91.8
15§	123.7 ± 0.2	0.2	106.5 ± 0.7	0.7	106.3 ± 3.0	2.9	135.8 ± 0.8	0.6	40.0 ± 20.0	49.9	12.8 ± 9.6	75.2
16	125.4 ± 0.7	0.6	111.8 ± 2.5	2.2	127.5 ± 9.3	7.3	140.4 ± 1.1	0.8	7.4 ± 2.4	33.2	15.8 ± 4.3	26.9
17§	135.1 ± 1.1	0.8	117.3 ± 0.3	0.3	110.7 ± 0.9	0.9	149.7 ± 0.9	0.6	91.1 ± 3.2	3.5	5.5 ± 0.6	11.0
18	124.2 ± 2.1	1.7	113.4 ± 0.6	0.5	117.7 ± 11.3	9.6	135.6 ± 4.2	3.1	5.8 ± 2.1	36.5	14.0 ± 2.6	18.9

Footnotes:
†Reached full extension during the Nordic exercise
‡No clear peak torque reached
§No clear tap signal for synchronisation of systems

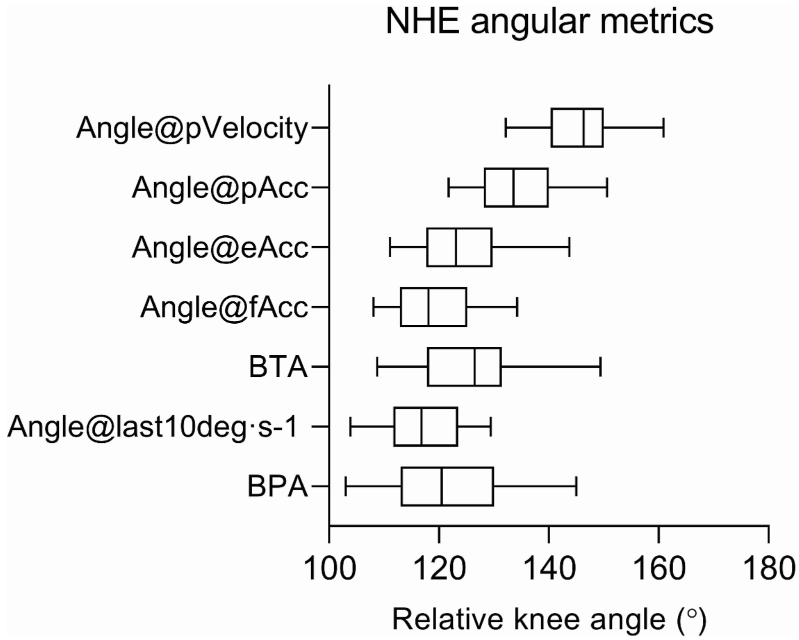

Figure 2. Correlation matrix showing Pearson correlation coefficients between angular kinematic metrics used to explore the NHE action. All metric correlations show statistical significance set at $p < 0.05$.

Heterogeneous groups have been used throughout the research, illustrating differences in participant training experience and level of NHE familiarisation. Sconce et al. (2015) and Ditroilo et al. (2013) used recreational participants whilst Lee et al. (Lee et al., 2018, 2017) and McGrath et al. (2020) tested semi-professional and elite players. McGrath et al. (2020) performed single-leg NHE testing, indicating those participants to be very highly trained. Differences in exercise mode (unilateral/

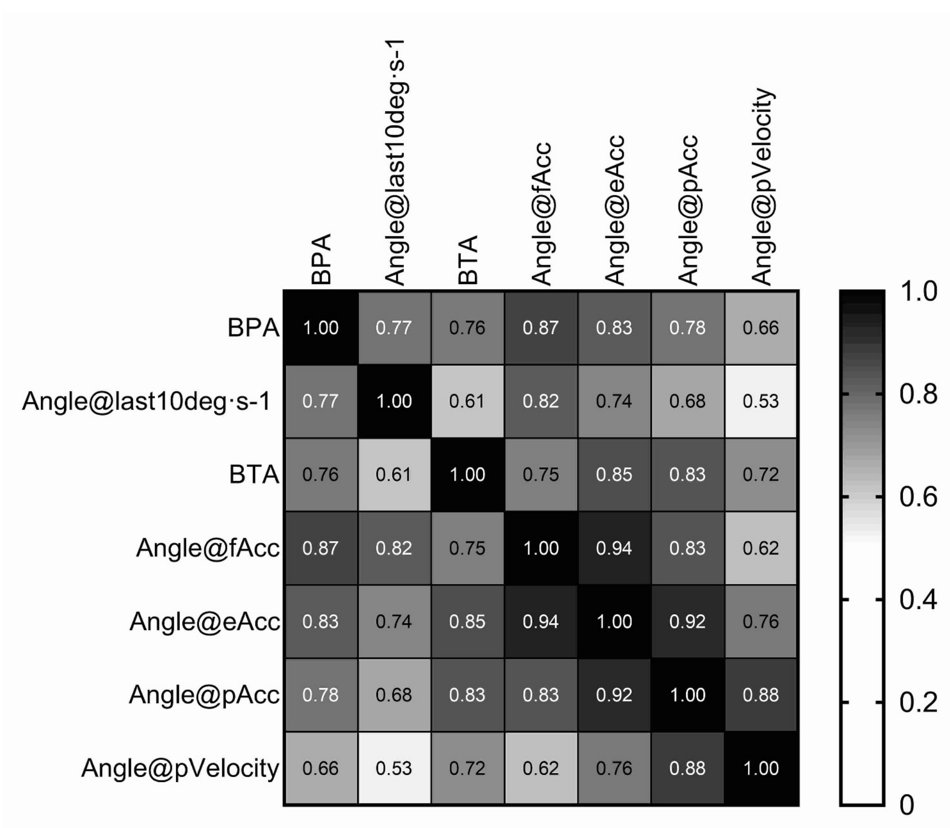

Figure 3. Box and whisker plots comparing the kinematic angular metrics outcomes (n = 44) of the NHE. The boxes represent IQRs and the horizontal lines in the boxes represent median values. The whiskers represent = mean ± 1SD.

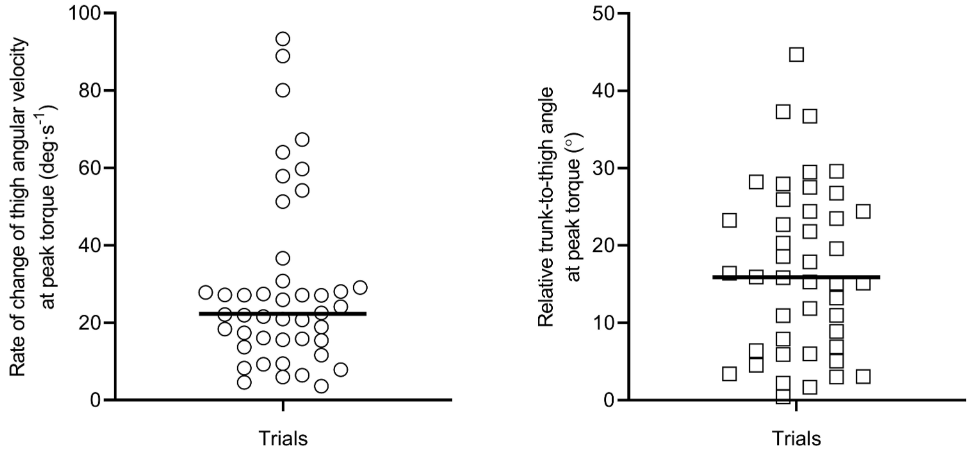

Figure 4. Scatter plots showing the individual data points (n = 44) for angular velocity of the knee joint and relative trunk-to-thigh angle, at peak torque. Wide variability can be seen in the data for both angular velocity of the knee joint and relative trunk-to-thigh angle, suggesting NHE technique differences in individuals.

bilateral), training experience, and NHE familiarisation combined with non-standardised measurement (hip angle, movement speed, distinct peak torque and drop-off) affects technique (Alt et al., 2018; Delahunt et al., 2016; Ditroilo et al., 2013; Lee et al., 2018, 2017; Šarabon et al., 2019; Sconce et al., 2015) and may have influenced kinetic and kinematic values (torque, angular velocity). Moreover, the range of motion in which pVelocity and pAcc occur during the NHE is in the time-period after "break" where inter-subject differences in landing method are likely to influence output measures. Participants were instructed to keep their hands facing forward and elbows pointing down, ready to buffer the fall. Those losing control nearer vertical have potentially more ROM in which to increase velocity. However, those breaking early tended to buffer the fall with further outstretched arms (contrary to instructions) limiting the ROM over which velocity can be generated, which is a recognised limitation of this study and when using these types of measures.

Conclusion

Having made a comparison between method and metrics, this paper proposes standardised terminology, which can be used to describe NHE performance, providing a range of kinematic and kinetic definitions, allowing comparison between research studies. As a training exercise the NHE can be easily replicated in the field but the mechanism of how the NHE produces beneficial muscle architecture adaptations to prevent HSIs is still debated. A laboratory-based approach and scientific rigour are necessary to validate the best methods of collecting NHE kinematics. To measure the effectiveness of the NHE it is important that key metrics can be replicated and reported consistently as a monitoring tool. It is still unclear as to what metrics best assess the Nordic exercise in terms of injury prevention and/or performance improvement i.e. strength, angle or acceleration and velocity. Finding reliable metrics to measure the NHE that can be replicated practically in the field is of importance to practitioners. However, more work is needed to determine the influence of exercise quality and feedback on NHE performance metrics. Future work will look to bridge this gap by assessing the use of sensors and designing more effective feedback to guide hip position and knee extension speed. Simultaneous measurement of kinetics and kinematics on a hamstring device is recommended for capturing BTA, a reliable, reproducible metric representing the proxy length in the hamstrings at which muscle failure occurs. The focus should not just be on hamstring strength maintenance but on torque production over a larger muscle length, replicating more closely the common injury site location during the late-swing sprinting phase.

Disclosure statement

The authors have no relevant conflict of interest to disclose.

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