Pilot and Feasibility Studies

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Four-week Nordic hamstring exercise intervention for individuals with ACL reconstruction via hamstrings tendon autograft: feasibility of a pilot randomized controlled trial

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Abstract

Background The Nordic hamstring exercise (NHE) has been widely used among uninjured, athletic populations to mitigate the risk of hamstring injury, yet little is known about its utility as an intervention for individuals who undergo ACL reconstruction with hamstring tendon autograft (ACLR-HT). Understanding the feasibility of NHE as a means of enhancing hamstring function may aid in the development of evidence-based recommendations to guide hamstring recovery. Our aim was to determine the feasibility of conducting a pilot NHE trial among individuals with ACLR-HT.

Methods We used a single-blind randomized controlled trial with parallel arms to investigate individuals 18–35 years with primary, unilateral ACLR-HT. Twenty-three participants were randomized to a standardized, 4-week (10 session) progressive NHE intervention ($n=17$) or usual care control ($n=6$) group at a 3:1 ratio. Those randomized to the control group were eligible to open-enroll in the intervention group at the completion of the original study period. Primary feasibility outcomes included recruitment uptake, protocol adherence, dose goal attainment, and retention. Exercise perceptions and safety were also assessed. Summary statistics were used to descriptively report all findings.

Results Two control participants were open-enrolled in the intervention group after completing their original study period ($n=19$). All participants (88.5% recruitment uptake) adhered to the exercise protocol (100%) and 18 participants (94.7%) attained the total exercise dosage goal. A 100% retention rate was observed, as all participants (intervention 17 randomized, 2 open-enrolled; control 6) returned for their follow-up assessment.

Conclusions A standardized, 4-week progressive NHE protocol is feasible for individuals with ACLR-HT. Positive perceptions of exercise, minimal exercise-related discomfort, and no reported adverse events further support the acceptability of this protocol and the likelihood of successful implementation in future efficacy trials.

Trial registration ClinicalTrials.gov, NCT05738200. Registered 2 November 2022—retrospectively registered, https://clinicaltrials.gov/study/NCT05738200.

Keywords Clinical trial, Eccentric exercise, Semitendinosus

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Key messages regarding feasibility

- What uncertainties existed regarding the feasibility? The NHE has been widely used among uninjured, resistance-trained athletic populations to mitigate the risk of a hamstring strain, yet little is known about its utility as an intervention for individuals who undergo ACLR-HT. Based on the mechanistic foundation of eccentric exercise and literature supporting the efficacy of NHE for uninjured individuals, implementing it in a population with documented hamstring neuromuscular deficits appears warranted. Considering that hamstring weakness persists well beyond the completion of rehabilitation, it is essential to investigate whether NHE is viable to implement among those with a history of ACLR-HT.
- What are the key feasibility findings? We observed 88.5% recruitment uptake, 100% adherence, 94.7% dose goal attainment, and 100% retention, suggesting a standardized, 4-week (10-session) progressive NHE protocol is feasible for individuals with ACLR-HT who are discharged from physical therapy. Positive perceptions of exercise, minimal exercise-related discomfort, and no adverse events reported further support the acceptability of this protocol and the likelihood of successful implementation in future efficacy trials.
- What are the implications of the feasibility findings for the design of the main study? Our findings collectively support the progression to an efficacy trial among individuals with ACLR-HT, where there is an ongoing need to investigate the effects of isolated NHE on hamstring neuromuscular function and ACL loading mechanisms. If efficacious, large-scale effectiveness trials and prospective monitoring of reinjury rates will be necessary to translate this work to clinical practice and injury risk reduction programs.

Background

Approximately 175,000 Americans are conservatively estimated to undergo anterior cruciate ligament reconstruction (ACLR) each year [1], with more than 1 in 3 performed using a hamstring tendon (HT) autograft [2]. A recent survey [3] of global trends further identified HT as the most common graft choice for primary ACLR at 53%, increasing in use over the past three decades. Unfortunately, a recent meta-analysis [4] and prospective data [5] report a greater incidence of graft failure when using HT, highlighting the importance of understanding modifiable factors related to the risk of reinjury in this growing population.

Deficits in multimodal hamstring strength are uniquely observed in patients who undergo ACLR with HT autograft (ACLR-HT) and persist for years beyond return to unrestricted physical activity [6–8]. Cadaveric [9], musculoskeletal modeling [10], and in vivo [11] experiments have demonstrated the importance of hamstring function relative to ACL loading mechanisms, suggesting that such deficits may contribute to higher rates of reinjury [4]. Post-traumatic muscular impairments that occur following ACLR are multifactorial, due in part to a cascade of peripherally and centrally mediated mechanisms [12], which appear to drive persistent dysfunction. Unfortunately, hamstring function is drastically underrepresented in the context of recovery from ACLR [13], presenting a critical barrier to the development of targeted, evidence-based treatment recommendations.

Identifying interventions well suited to combat known muscular impairments by addressing both peripheral and central mechanisms is essential to restore hamstring function—compelling evidence demonstrates the ability of eccentric exercise to do so [14, 15]. A wealth of high-quality research has been conducted relative to the assessment and treatment of primary hamstring injury (i.e., strain) via eccentric exercise [16]. Most notably, the Nordic hamstring exercise (NHE) has been widely used among uninjured, resistance-trained athletic populations to mitigate the risk of hamstring strain [17], yet little is known about its utility as an intervention for individuals who undergo ACLR-HT. Based on the mechanistic foundation of eccentric exercise and literature supporting the efficacy of NHE for uninjured individuals, implementing it in a population with documented hamstring neuromuscular deficits appears warranted. Considering that hamstring muscular deficits persist well beyond the completion of rehabilitation [6, 8, 18], it is essential to investigate whether NHE is viable to implement among those with a history of ACLR-HT. NHE is reported to preferentially activate the medial hamstrings [19], which remain impaired to a greater extent than the lateral hamstrings [7], further supporting the use of this intervention for individuals who undergo ACLR-HT. Although eccentric exercise is a recommended component of rehabilitation after ACLR, clinical practice guidelines continue to emphasize the quadriceps [20], offering little-to-no consensus-based guidance for hamstring recovery via eccentric exercise.

Understanding the feasibility of NHE as a means of enhancing hamstring function among individuals with ACLR is a necessary first step in the development of evidence-based treatment recommendations to guide hamstring recovery in this population. Feasibility studies provide essential information relating to the acceptability and practicality of interventions intended to have a broad

clinical impact and inform the implementation of future large-scale trials [21]. Therefore, our primary aim was to determine the feasibility of conducting a pilot NHE trial among individuals who had undergone ACLR-HT. To do so, we specifically assessed recruitment uptake, protocol adherence, dose goal attainment, and retention. Secondarily, we described perceptions of the exercise protocol (familiarity, difficulty, and motivation), characteristics of exercise delivery (use of feedback), and intervention safety.

Methods

Trial design

As part of a small-scale, pilot randomized controlled clinical trial with parallel arms (NCT05738200), we conducted a preliminary analysis to investigate the feasibility of implementing a 4-week NHE protocol among individuals with a history of ACLR-HT who had completed their formal rehabilitation programs. Improvements in strength and muscle size have been shown in as little as 4 weeks (3 sets of 6–10 repetitions 2×/week) of NHE training in physically active adults [22], suggesting this would be a reasonable low-end exercise volume to consider in our study. Participants completed either 2, 12, or 13 study visits in total (Fig. 1). At the completion of the baseline assessment, participants were randomized to an intervention (INT) or control (CON) group at a 3:1 allocation ratio. As a component of our pilot clinical trial, we chose to emphasize the intervention group to gain a better appreciation for the magnitude of the effect expected when designing a future large-scale clinical trial. Additionally, we felt it was important to include a control group to demonstrate our ability to conduct the study in a manner consistent with a future clinical trial. Participants randomized to INT returned for 10 study visits over a 4-week duration, whereas those randomized to CON were instructed to go about their normal daily routines. After 4 weeks, INT (Visit 12) and CON (Visit 2) participants returned for their follow-up assessments. At this time, participants randomized to CON were given the option to complete the intervention via open enrollment. This option was included for practical purposes as it would avoid withholding a potentially beneficial intervention and inform the future design and enrollment of a

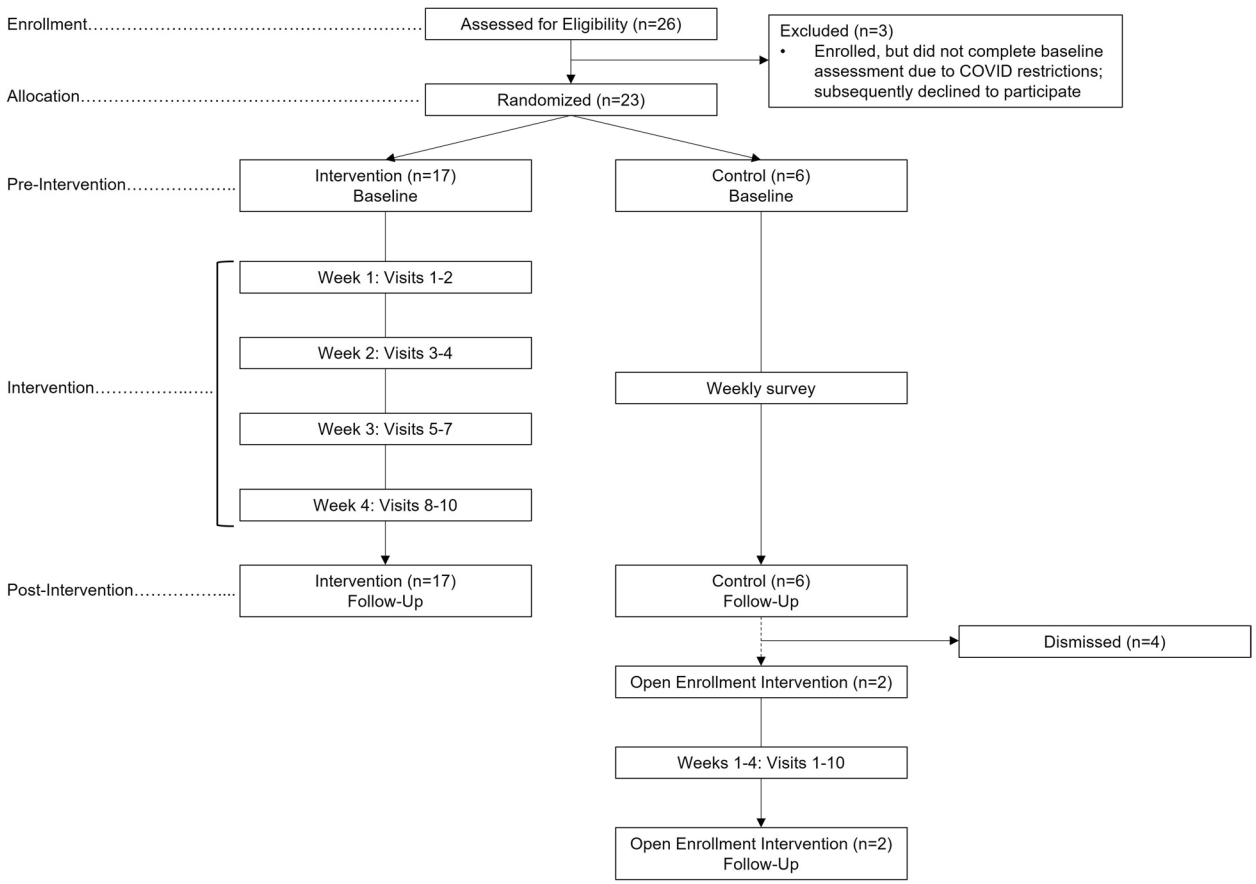

Fig. 1 Flow diagram of study procedures

larger clinical trial. Those who chose this option returned for 11 additional study visits to complete the intervention (10 study visits over 4 weeks) and repeat their follow-up assessment. All outcome assessments and intervention sessions took place in a university research laboratory.

Participants

We recruited males and females with a history of ACLR via flyers and word of mouth from the Northwest Ohio region, which included sports medicine and rehabilitation clinics, the University of Toledo student body, and the general population. To be eligible, individuals must have been between the ages of 18–35 with a history of primary, unilateral ACLR-HT and discharged from their formal physical therapy program. Individuals who underwent meniscectomy or meniscus repair at the time of ACLR were included. Given that persistent hamstring strength and morphological deficits are reported years after physician clearance [6–8], we chose to limit enrollment to those discharged from rehabilitation to minimize the confounding factor of a competing exercise intervention and did not restrict time from surgery otherwise to maximize enrollment. Understanding the feasibility of exercise intervention among individuals without routine access to structured rehabilitation was also important, considering the high frequency of this scenario in practice. All participants were asked to avoid any changes in their physical activity or resistance training routines, particularly the addition of hamstrings-targeted exercise, upon enrollment. We excluded those with a history of lower extremity orthopedic surgery prior to their ACL injury, post-surgical complication (e.g., infection, delayed healing), surgically treated multiple ligament knee injury or articular cartilage lesion, additional lower extremity surgery or injury within 6 months, symptomatic or radiographic knee osteoarthritis, concussion within 6 months, cardiopulmonary disorder, neurological or psychiatric disorder, implanted biomedical devices, or those who were taking prescribed medications that could alter neural excitability. Study procedures were approved by the University of Toledo Biomedical Institutional Review Board, and all participants provided verbal and written informed consent.

Procedures

We used a standardized, 4-week (10 session) progressive NHE protocol adapted from Petersen et al. [17] (Table 1). At the completion of their baseline assessment, participants randomized to INT were asked to rate their familiarity with the NHE and were then familiarized (e.g., exercise instruction and demonstration) by an investigator not involved in the assessment of outcomes. Participants cycled on a stationary bike at a self-selected pace for 5 min at the start of each session and were given the opportunity to stretch as desired. All prescribed exercise was performed on a NordBord device (VALD Performance, Charlotte, NC, USA) in a university research laboratory under the supervision of an athletic trainer ($n=2$) or physical therapist ($n=1$) who was trained in the NHE protocol. Participants started in a kneeling position with their knees flexed to 90°, which remained consistent throughout the intervention period, and were instructed to perform the NHE by attempting to resist a forward-falling motion using their hamstring muscles equally from each limb. With their arms crossed over their chest, we further instructed participants to lower their rigid torso slowly (~ 3 s) and as far as possible until they reached a horizontal position or could no longer control their movement. Participants used their hands to break each fall. To minimize undesired hamstrings and gluteal activity, participants used their upper body for support to gently return to the starting position after each completed trial [17]. Each session lasted approximately 15–20 min and a minimum of 24 h was required between sessions. Although a minimum of 48 h was encouraged between sessions, we allowed shorter durations to accommodate the practical difficulties in scheduling if participants did not expect muscle soreness to be a limiting factor in the next session. Self-reported pain or discomfort was recorded at the beginning and end of each intervention session and changes in physical activity were subjectively monitored on a weekly basis.

The supervising investigator provided technique-based feedback immediately following any repetitions that participants deviated from the described instruction. Verbal encouragement was provided to ensure maximal effort was given during each repetition. Additional force-based feedback of asymmetry between limbs was provided by the investigator when large asymmetries in force output were visually observed. As we did not use a specific threshold of asymmetry to ensure feedback could be delivered in real-time,

Table 1 Nordic hamstring exercise protocol

Week	Sessions per week	Sets per session	Repetitions per set	Rest between sets
1	2	2	5	2 min
2	2	2	6	2 min
3	3	3	6–8[a]	3 min
4	3	3	8–10[a]	3 min

[a] Participants were instructed to complete the higher number of repetitions if possible

investigators were instructed to use their clinical judgment when deciding when to provide feedback about any observed asymmetries in force distribution between limbs (e.g., "pull more with your right leg"). Participants were asked to rate their level of perceived exertion and to report open-ended feedback related to their perceptions of the exercise completed after each set. Those randomized to CON were not required to participate in regular exercise and were instructed to go about their normal daily routines during the 4-week study period. CON participants were surveyed weekly about changes in physical activity or questions they had via email or phone call with the intervention team.

Feasibility outcomes

Feasibility, perceptions of the exercise protocol, characteristics of exercise delivery, and intervention safety were assessed as described below.

Pre-intervention

We used a numeric rating scale (0–10) to assess familiarity with NHE at the end of the baseline assessment and prior to beginning the intervention period.

During intervention

We assessed exercise delivery by the number of repetitions that corrective feedback was provided (*n*) and the proportion of participants who required feedback (%). The Borg Rating of Perceived Exertion (RPE, 6–20) was used to assess exercise difficulty immediately following each completed set. Safety was collectively assessed by evaluating the occurrence of adverse events (i.e., any untoward medical occurrence associated with the intervention, but not necessarily caused by it) and quantifying pain or discomfort reported during the intervention period using a visual analog scale and body diagram. Participants drew a vertical line on a 10-cm line with 0 indicating "no pain" and 10 indicating "worst imaginable pain," and placed an "X" on the location of their pain or discomfort using the body diagram. The number and proportion of participants (n, %) who reported pain or discomfort, and the location based on the body region identified, were quantified. Safety outcomes (i.e., adverse events, pain/discomfort) were assessed at the beginning and end of each session.

Post-intervention

We quantified the number of exercise sessions and total exercise volume (sets x repetitions) completed. The proportion of participants who met our a priori protocol goals was quantified to determine adherence ($\geq$80% of prescribed sessions completed) and dose goal attainment ($\geq$80% of prescribed exercise volume completed). As weeks 3 and 4 of the intervention included a range of sets and repetitions, we considered the maximum possible exercise volume when defining feasibility outcomes. Motivation was assessed using the Interest/Enjoyment (7–49) and Value/Usefulness (7–49) subscales of the Intrinsic Motivation Inventory [23], which were modified to align with our intervention. The Intrinsic Motivation Inventory is a multidimensional tool that has been validated to assess participant experiences with a given activity in laboratory experiments. Although seven subscales are available, we chose to quantify constructs most related to intrinsic motivation (interest/enjoyment) and self-regulation (value/usefulness), as these factors impact adherence to exercise prescription. Retention was assessed as the number and proportion of enrolled participants who returned for their follow-up assessment (*n*, %). Recruitment uptake was quantified at the completion of enrollment as the percentage of individuals enrolled relative to those screened (*n*, %).

Randomization

Participants were block randomized (block size of 4) with stratification to either an INT or CON group at a 3:1 ratio. As this study was part of a small-scale, pilot clinical trial, we used a 3:1 allocation to maximize our understanding of the intervention efficacy for future large-scale clinical trials. Control groups are essential to clinical trials, so participants randomized to CON were included in this analysis to report total retention. Group assignment was sealed in opaque envelopes and opened at the completion of the baseline assessment. A separate investigator independent of the study personnel created a randomization scheme using a random number generator in Microsoft Excel to minimize bias. All study personnel contributed to participant recruitment and enrollment, and an investigator not involved in data collection assigned them to one of the groups.

Blinding

We used a single-blind design, in which the investigators ($n=3$) responsible for collecting outcomes data as part of the pilot clinical trial remained blinded to group assignment for the life of the study. At the completion of the baseline assessment, the blinded investigators would leave before the interventionist revealed the group assignment to the participants. In cases when CON participants opted to enroll in the NHE group at the completion of the original 4-week study period, the investigators performing outcomes assessments would become unblinded at the beginning of participants' follow-up assessment.

Statistical analyses

Data were reported descriptively as means (standard deviations), medians [interquartile range], counts (*n*), and percentages (%) for continuous outcomes. Counts and percentages were also used for categorical outcomes. We operationally defined *feasibility* as (1) ≥ 50% recruitment uptake, (2) ≥ 80% adherence, (3) ≥ 80% dose goal attainment, and (4) ≥ 90% retention. Although collectively used to inform the intervention feasibility, each of these outcomes was used as criteria for progression to a full-scale clinical trial based on a stop-amend-go approach [24]. In this way, ≤ 25% recruitment uptake, ≤ 50% adherence, ≤ 50% dose goal attainment, and ≤ 60% retention were considered to indicate the trial was not feasible. Values that fell between the defined ranges would indicate a need for amendment prior to progressing to a full-scale trial. The characteristics of participants who completed the intervention relative to those who did not were descriptively reported to demonstrate the feasibility of recruiting demographically similar groups. Summary statistics were calculated in Microsoft Excel and the Statistical Package for the Social Sciences (v.28, IBM Corp., Armonk, NY, USA) was used for inferential statistical analyses.

Sample size

An a priori sample size estimate suggested we should enroll at least 20 individuals. This estimate follows the sample size simulations of Whitehead et al. [25] to be sufficient to identify safety and feasibility issues within each group [24, 26] and would provide 80% power with 80% confidence of detecting a moderate effect between intervention and control groups (standardized mean difference > 0.6). This magnitude of effect is supported by previous work [22] demonstrating a moderate-to-large magnitude (Cohen's *d* effect size 0.60–0.84) increase in eccentric knee flexion torque and work following 4 weeks of isolated NHE in 20 physically active, uninjured individuals.

Results

Twenty-six individuals with primary, unilateral ACLR-HT were screened for eligibility, with 23 being enrolled and randomized (88.5% recruitment uptake). The period of recruitment and follow-up spanned July 2018 to July 2022, which was substantially prolonged due to COVID restrictions. Participants were randomized to either INT ($n=17$) or CON ($n=6$) groups. Two participants randomized to CON opted to enroll in INT ($n=19$) at the completion of their original study period. All participants randomly assigned completed their group procedures as intended. Demographics were similar between groups at baseline (Table 2). The trial ended when the pre-specified endpoints were met.

Table 2 Participant demographics

	INT ($n=19$)[a]	CON ($n=6$)
Sex	12 female	2 female
	7 male	4 male
Age (years)	22.8 (3.0)	21.8 (3.3)
Height (cm)	173.0 (10.9)	172.7 (9.6)
Mass (kg)	78.2 (17.9)	75.1 (12.3)
Injured limb	8 dominant	3 dominant
	11 non-dominant	3 non-dominant
Time from surgery (months)	49.4 (26.5)	43.2 (23.1)

Abbreviations: *INT* Intervention, *CON* Control

[a] Two participants completed CON first, then open-enrolled in INT

Pre-intervention

Participants reported a median [interquartile range] NHE familiarity rating of 4.5 [8.3].

During intervention

Data are reported here as means (standard deviation), medians [interquartile range], counts (n), and percentages (%). Technique-based feedback was provided on 4.1% (4.4%) of all completed repetitions, with 14 participants (73.7%, $n=14$ of 19) requiring feedback at least once. Force-based feedback was provided on 43.1% (31.9%) of all completed repetitions, with 19 participants (100%, $n=19$ of 19) requiring feedback at least once. Participants reported a median RPE of 11.8 [2.5] and a mean visual analog scale for pain or discomfort of 0.35 cm (0.50 cm) across all study sessions. Fourteen participants (73.7%, $n=14$ of 19) reported muscle soreness or discomfort at least once during the intervention period, with an average of 3.4 (3.0) reports among all participants. Among those who reported muscle soreness or discomfort, the hamstrings were most frequently identified as the body region affected (71.9%, $n=46$), followed by the knee (20.3%, $n=13$), calf (4.7%, $n=3$), and low back (3.1%, $n=2$). No adverse events occurred, and reports of soreness or discomfort did not prevent participants from completing the prescribed exercise.

Post-intervention

Summary statistics for intervention characteristics, adherence, and dose goal attainment are reported in Table 3. Data are reported here as medians [interquartile range], counts (*n*), and percentages (%). All participants adhered to the exercise protocol (100%, $n=19$ of 19) and

Table 3 Intervention characteristics, adherence, and dose goal attainment outcomes from participants who completed the intervention ($N = 19$)

	Mean (standard deviation)
Duration of intervention (days)	25.0 (2.9)
Sessions completed (*n*)	9.8 (0.5)
Percentage of prescribed sessions completed (%) [a]	98.4 (5.0)
100% ($n = 17$)	
90% ($n = 1$)	
80% ($n = 1$)	
Sets completed (*n*)	25.6 (1.4)
Percentage of prescribed sets completed (%)[b]	98.4 (5.5)
100% ($n = 17$)	
92% ($n = 1$)	
77% ($n = 1$)	
Repetitions completed (*n*)	202.5 (12.5)
Percentage of prescribed repetitions completed (%) [c]	98.3 (6.1)
100% ($n = 17$)	
94% ($n = 1$)	
74% ($n = 1$)	
Volume of exercise completed (sets x repetitions)	5197.3 (546.5)
Percentage of prescribed exercise volume completed (%) [d]	97.0 (10.2)
100% ($n = 17$)	
87% ($n = 1$)	
57% ($n = 1$)	

[a] 10 sessions maximum

[b] 26 sets maximum

[c] 206 repetitions maximum

[d] 5356 volume maximum

18 participants (94.7%, $n = 18$ of 19) attained the total exercise dosage goal. At the completion of the intervention period, participants reported a median of 37 [15.5] for interest/enjoyment and 48 [8] for value/usefulness related to the intervention. A 100% ($n = 19$ of 19) retention rate was observed, as all 19 NHE participants (17 randomized, 2 open enrolled) returned for their post-intervention assessment. All participants randomized to CON returned for post-assessment as well, yielding 100% ($n = 23$ of 23) retention for the entire sample.

Discussion

Our primary aim was to assess the feasibility of a 4-week NHE protocol conducted among individuals who had undergone ACLR-HT to inform its acceptability, practicality, and future implementation. We observed 88.5% recruitment uptake, 100% adherence, 94.7% dose goal attainment, and 100% retention, suggesting the prescribed exercise protocol was feasible in this population. Our findings collectively support the progression to an efficacy trial among individuals with ACLR-HT, where there is an ongoing need to investigate the effects of isolated NHE on hamstring neuromuscular function and ACL loading mechanisms. If efficacious, large-scale effectiveness trials and prospective monitoring of reinjury rates will be necessary to translate this work to clinical practice and injury risk reduction programs.

Pre-intervention familiarity with the NHE varied considerably, from *not familiar* to *very familiar*. Although the NHE is routinely incorporated in team-based injury risk reduction programs [16], not all participants were involved with organized sports, which may have contributed to a lack of familiarity. Participant perceptions were largely positive in terms of how valuable or useful the exercise was to their knee condition and how much interest or enjoyment they experienced while performing it. However, three individuals reported low values ($\leq 9/49$) on each of the Intrinsic Motivation Inventory subscales, indicating that not all participants valued or enjoyed the NHE. Our findings somewhat agree with survey data [27–29] reported among professional cricket and football/soccer teams, in which a majority believed NHE was beneficial in reducing hamstring injuries. While the extent of literature [16, 17, 30, 31] largely supports the ability of NHE programs to reduce injury rates and improve muscular performance in uninjured athletes, low compliance rates present inherent barriers to large-scale implementation.

We observed 100% adherence to a 4-week protocol, yet lower rates (11–21%) have been reported [27–29] among uninjured cohorts for a 10-week Nordic hamstring program. This finding was particularly encouraging as our sample consisted of individuals with ACLR-HT, who are reported to exhibit considerable deficits in medial hamstring strength and size [6, 7]. Although intervention duration likely accounts for a portion of this discrepancy, negative player perceptions and muscle soreness have also been previously cited as barriers to NHE adoption [27–29]. It is possible that injury history contributed to higher motivation and adherence in our sample relative to previous reports in uninjured cohorts. Most participants in our study reported exercise-related muscle soreness or discomfort, which aligns with previous reports [27–29]. However, the magnitude of discomfort never exceeded a minimal clinically important difference ($< 2.7/10$ cm [32]), and the presence of discomfort did not appear to interfere with participants' ability to perform the exercise as indicated by a high proportion of dose goal attainment. Additionally, no adverse events occurred (e.g., muscle injury), which supports the safety of the exercise protocol.

We chose to standardize exercise progression similar to previous investigations of NHE programs [17, 30]. However, participants reported widespread ratings of perceived exertion, ranging from *very light* to *very hard*, which may suggest a need to consider individualized progression in future work. Session RPE has been used in this way, as it accounts for both exercise volume and intensity. For example, a resistance-training study [33] conducted among physically active males progressed (≤ 5, moderate), maintained (≥ 6 and ≤ 8, hard), or regressed (≥ 9, very hard) training load based on perceived exertion using the Borg CR-10 scale (0–10). If applying equivalent criteria to our work, participants reporting ≤ 12 would progress, which equates to our group median. Given that some participants reported lower exertion (i.e., ≤ 12) during sessions that did not result in subsequent load progression, individualized approaches may be appropriate to maximize efficacy. Previous work [31] has considered performance-based criteria to progress NHE intensity, in which external load was added to participants' ability to stop themselves at their end range of motion. If available, instrumented devices (e.g., NordBord) may also be used to create force-based goals to guide NHE progression, yet this remains an area for future study. While the use of objective, force-based criteria is well supported for strength training, resource availability, and cost may limit the scalability of this approach when performing NHE.

Limitations

Our findings should be considered in the context of several limitations. Although the feasibility of our protocol was supported, we recruited a convenience sample of adults within a small region of Northwest Ohio. Therefore, the feasibility of our approach may not be generalizable to adolescents or other settings. Our study sample was similar in baseline demographics between INT and CON groups but varied in time from surgery (6 months to 7 years), as all participants were discharged from their formal physical therapy program at the time of enrollment. Additionally, we did not screen for baseline hamstring impairments, which could have influenced participants' interest in participating in the study. We also permitted shorter durations (24 h) between intervention sessions for practical purposes in several cases where muscle soreness was not reported, yet this could allow delayed onset muscle soreness to affect subsequent strength gains. Although we chose to restrict changes in activities of daily living or exercise routines rather than prohibit specific activities for practical purposes, we did not explicitly survey participants about their recent exercise history, which may influence the magnitude of response to exercise in outcomes studies. Future work is needed to determine the feasibility of embedding standardized NHE or eccentric-biased protocols in rehabilitation, particularly among those with confirmed strength deficits at specified time intervals.

Practical applications

Dose goal attainment was achieved in 18 of 19 participants, supporting the practicality of the exercise protocol and the likelihood of successful implementation in future trials. Although we used an instrumented approach in this study, no additional resources or costs were required, and future work can be easily adapted using non-instrumented techniques as commonly described in athletic cohorts [17, 22, 30]. However, several factors may influence future iterations of NHE interventions in those recovering from ACLR. In our study, most participants required either technique- or force-based feedback, which must be considered relative to exercise supervision. While non-inferior outcomes are reported with no-to-low supervision after ACLR [34], future studies investigating the feasibility of supervision and telehealth alternatives are warranted for NHE or eccentric-biased exercise protocols. Additionally, we chose to implement a single-exercise intervention. Previous investigations [27–29] of athlete perceptions suggest that professional athletes agree NHE has a strong evidence base and is effective in terms of injury reduction, but not more than other exercise programs in isolation in part due to its limited functionality. These perceptions suggest that expanding beyond a single knee-dominant eccentric exercise to create an accessible multimodal exercise protocol, inclusive of both hip- and knee-dominant exercises, may be useful to align with current recommendations for hamstring recovery after ACLR [13].

Conclusions

A standardized, 4-week (10 session) progressive NHE protocol is feasible for individuals who have undergone ACLR-HT. Positive perceptions of exercise, minimal exercise-related discomfort, and no adverse events reported further support the acceptability of this protocol and the likelihood of successful implementation in future efficacy trials.

Abbreviations

ACL	Anterior cruciate ligament
ACLR	Anterior cruciate ligament reconstruction
ACLR-HT	Anterior cruciate ligament reconstruction with hamstrings tendon autograft
CON	Control group
HT	Hamstrings tendon
INT	Intervention group
NHE	Nordic hamstring exercise
RPE	Rating of perceived exertion

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Authors' contributions
GEN conceived the work, managed the regulatory aspects of the study, analyzed the data, and drafted the manuscript. NRG and AMM managed all aspects of intervention delivery. DAS and JLR managed data collection and data processing. All authors made substantial contributions to the design of the work, interpretation of data, and drafting of the manuscript; all have read and approved the final manuscript.

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Data availability
The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
The Biomedical IRB from the University of Toledo approved this study (#202737) and all participants provided verbal and written consent at the time of enrollment.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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