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Outcomes of a randomized controlled trial of neuromuscular training with real-time biofeedback in young female athletes

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Abstract

Background A large body of scientific work has been focused on reducing the high incidence rate of anterior cruciate ligament (ACL) injuries in young female compared to male soccer players. The purpose of this study was to determine the effects of a randomized clinical trial to reduce a risk factor of ACL injuries, knee abduction moment (KAM), with neuromuscular training and biomechanical biofeedback in adolescent female athletes.

Methods A prospective, randomized, active comparator, open blinded, end-point trial was conducted with 150 (age: 13.3 ± 2.2 yrs, height: 156.1 ± 1 0.6 cm, mass: 50.2 ± 11.3 kg) female soccer players. Each participant received neuromuscular training and randomized into one of three arms: 1) an active control, considered sham biofeedback (NMT), 2) a knee-focused biofeedback group (NMT + K), and 3) a hip-focused biofeedback group (NMT + H). The participants completed two assessments: a baseline session prior to the intervention and a post-intervention session. The primary outcome measure was change knee abduction moment during a double leg drop vertical jump (DVJ). Additionally, an unplanned single leg cutting task was also recorded. As an exploratory outcome measure, athletic exposures and ACL injuries were recorded weekly for six months following the post-test session.

Results A statistically significant reduction in KAM, during the DVJ, was found in all three intervention groups from baseline to the post-test ($p < 0.05$). However, statistically significant improvements in KAM during cutting was only observed in the NMT + H intervention group ($p < 0.05$). ACL injuries were not reported in any intervention group during the six months of follow up.

Conclusions While female soccer players involved in neuromuscular training programs regardless of intervention group exhibit significant improvements in KAM during a double leg landing, those that engage in hip-focused biofeedback compared to knee-focused or sham biofeedback exhibit decreased KAM during an unanticipated cutting maneuver.

Trial registration The Institutional Review Board at High Point University approved the study protocol. The clinical trial was registered at Clinicaltrials.gov (Identifier: NCT02754700) on 28/04/2016..

Keywords Anterior cruciate ligament, ACL, Biomechanics, Knee abduction, Knee injury prevention, Valgus, Randomized clinical trial, Female athlete, Neuromuscular training

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Background

The status quo as it relates to programs that aim to reduce the risk of anterior cruciate ligament (ACL) injury in adolescent female athletes is to train all individuals with numerous modalities in a comprehensive pre-season program or abbreviated in-season warmup [1–11]. Plyometric training combined with biomechanical analysis and technique training are common components in programs that successfully reduced ACL injury rates [5, 9, 12]. However, current neuromuscular training (NMT) programs need to train a large number of female athletes to prevent just one ACL injury [13, 14]. Additionally, incorporating these multifaceted techniques increases the complexity and may negatively affect compliance rates and widespread implementation [9, 15]. Unfortunately, even with the considerable research performed in this field, the overall incidence of ACL injury in females and increased incidence ratio compared to males participating in similar sports has not declined [16–20].

Knee abduction load (peak external moment) has been associated with risk of injury in a prospective study of female athletes and is often targeted in training interventions through proper landing and movement biomechanics [21]. Previous studies have also identified imbalances in hip function as a potential factor related to lower extremity and ACL injuries in this population [22, 23] and have shown that knee abduction load increases during maturation without an increase of hip utilization [24, 25]. Therefore, it is important to also recognize proximal mechanisms, namely the activation of hip extensors, that may influence these high-risk biomechanical movements [26]. Standard neuromuscular training programs incorporate instructor-driven technique feedback to reduce these risk factors associated with knee injury [27], but may not consistently improve the associated high-risk biomechanics [28]. Innovative biofeedback modalities that quantify and focus on underlying mechanisms responsible for high-risk biomechanics may be necessary to optimally modify movement technique and reduce risk of injury. Biofeedback training may be utilized by an athlete to learn how to change their biomechanics through rapid dissemination of data during (real-time) or immediately after a task [29, 30]. Therefore, incorporating biofeedback training may foster the translation of improved biomechanics in various sporting tasks and improve the retention of these learned movement patterns.

This paper describes the primary outcome of a six-week comprehensive neuromuscular training program with augmented biofeedback: Real-time Optimized Biofeedback Utilizing Sport Techniques (ROBUST). The effectiveness of biofeedback, when combined with traditional neuromuscular prophylactic training, was assessed in this trial. Furthermore, we aimed to determine which feedback was more beneficial in this athletic population: targeting the risk of injury (knee abduction load) or targeting an underlying neuromuscular component of injury (underutilization of the hip musculature). The purpose was to describe the biomechanical change in a risk factor of ACL injury following neuromuscular movement training using biomechanical biofeedback during a six week intervention. Our central hypothesis was that biofeedback methodology would maximize the effectiveness of neuromuscular prophylactic interventions. More specifically, we hypothesized that young female athletes following both knee- and hip-focused biofeedback training would exhibit reduced knee abduction moment during double-leg jump landings. Additionally, during a high-risk unplanned cutting task, we hypothesized that only the hip-focused biofeedback training group would exhibit significantly reduce knee abduction moment following the intervention.

Methods

Participants

A total of 150 female youth soccer players participated in this study (age:13.3 ±2.2 yrs; height: 156.1 ±10.6 cm; mass:50.2 ±11.3 kg). Participants were enrolled in a prospective, randomized, active comparator, open blinded, end-point trial of a six-week comprehensive neuromuscular training program. This study adheres to CONSORT guidelines. Active controls were utilized for ethical reasons based on the effectiveness of NMT on reducing risk of knee injury [8, 9, 31, 32]. An a priori power analysis was conducted that showed a minimum of 40 participants in each group were required to achieve 80% power (alpha level 0.05)[33]. An equal sample size of $N= 50$ ($N =150$ total) was randomized in computer-generated blocks to three study arms described below. We assumed 20% of loss to follow up, expecting a sample size of 40 to remain in each group. Participants were randomized into the three study arms using a random sequence of numbers stored in a spreadsheet only accessible to unblinded study staff and assigned in the randomization scheme according to the order they were enrolled in the study. The three study arms were as follows: 1) NMT: active control group of neuromuscular training with sham biofeedback, 2) NMT +K: intervention group of neuromuscular training with knee-focused biofeedback, and 3) NMT +H: intervention group of neuromuscular training with hip-focused biofeedback. The inclusion criteria consisted of 1) female between the ages of 9 and 19 ys, 2) participating on a competitive soccer team at the time of enrollment, 3) not currently injured or unable to participate in sport due to injury, and 4) able to commit to participating in the 6-week intervention. A written participant consent, and/or parental consent and participant assent as appropriate based on age was obtained.

The Institutional Review Board at High Point University approved the study protocol. The clinical trial was registered at Clinicaltrials.gov (Identifier: NCT02754700) on 28/04/2016.

Intervention

Testing and training occurred at the High Point University Human Biomechanics and Physiology Laboratory. The participants were not given the knowledge that they were receiving specific arms of biofeedback that could be different than their fellow participants. Interventionists responsible for delivering the neuromuscular training and all other investigators were blinded to the group status during data collection (baseline, post), management and analysis. The neuromuscular training program was performed three times per week, with augmented biofeedback (according to group assignment) one time per week [33]. This resulted in 18 total sessions over 6 consecutive weeks. Each session lasted 90 min with a 9–10 min active warm-up, and 3 separate 27–30 min sessions of each of the following: resistance training, technique/plyometric training, and core strength training. Training was overseen by a licensed athletic trainer with expertise in ACL injury risk screening and training.

The neuromuscular training program [33] was designed from recommended guidelines and modified from a number of studies that have been scientifically developed to reduce knee injuries in female athletes and specifically applied with techniques for an external focus of attention [4, 9, 27, 30, 34, 35]. Please see Taylor et al. [33] for a detailed description of the intervention.

The biofeedback portion (10 min) was provided once weekly with a three-dimensional motion analysis system, consisting of fifteen digital high-resolution cameras (Kestrel, Motion Analysis Corporation, Rohnert Park, CA), and two time-synchronized, embedded, oversized force platforms (AMTI, Watertown, MA) (See Supplemental Materials). Specifically, the participants were withdrawn from the typical neuromuscular intervention at various times once a week. Participants were instrumented with retroreflective markers as previously described [33] by the same interventionist. A real-time skeleton avatar was displayed with a participant-specific model on a large screen during the session (Visual3D, C-Motion, Inc. Germantown, MD). In addition, a line graph showing real-time internal hip extensor moment (NMT +H), or external knee abduction moment (NMT +K) was displayed with a highlighted goal region that they were encouraged to attain that was progressively adjusted each week. The active control group (NMT) had a sham biofeedback session (line graph representing sagittal plane knee range of motion) to match volume, though their “goal region” to attain did not encourage alteration of their current squatting pattern. Members of the hip-focused group were instructed to watch the real-time graph and activate posterior-chain muscles throughout the movements to increase the hip extensor moment feedback with the hypothesis that an underlying mechanism of injury might relate to underutilization of the hip musculature. Individuals in the knee-focused group were instructed to maintain knees over toes and to push laterally through their feet. The active control group was instructed to perform the same movements with a sham biofeedback avatar. During biofeedback for each group, a series of 10 repetitions of three exercises (double-leg squat, single-leg squat, and single-leg jump landing) were performed through the six-weeks [33].

Data collection

Independent of the biofeedback intervention group, each participant completed a pre-testing baseline session and a post-testing session. During the pre-test, participants completed an electronic REDCap (Research Electronic Data Capture) [36] with the following data collected: demographic information, sport participation history, lower extremity injury history, parents’ height for calculation of pubertal stage, and a menstrual history. Lower extremity biomechanics during double leg landing and unplanned single leg cutting were collected during pre- and post-testing sessions. Participants performed these tasks on a synthetic turf surface, while wearing standardized cleats (adidas ×15.2; Beaverton, Oregon, USA). As described in detail [33], each participant had 43 retroreflective markers secured at anatomical landmarks with double-sided tape for for 3-dimensional biomechanical analysis by the same researcher throughout the study. Three-dimensional motion capture was sampled at 200 Hz and kinetic data sampled at 1200 Hz with Cortex software (version 7; Motion Analysis Corp, Santa Rosa, California, USA).

Each participant performed three trials of a drop vertical jump (DVJ) (Fig. 1). Participants stood on top of a 31-cm box and positioned their feet 35-cm apart and arms at their side. They were instructed to drop down directly off the box and immediately jump vertically towards an overhead target that was placed at their previously determined maximal vertical countermovement jump reach [37]. Participants also performed an approach run with unanticipated cue to either perform a plant with a of 90° sideways cut (CUT) (Fig. 1) or a plant with a 180° backpedal [38]. The purpose of the backpedal was to provide an additional movement so the participant could not preplan the cut while approaching. Three trials of each movement were randomized and performed on each leg.

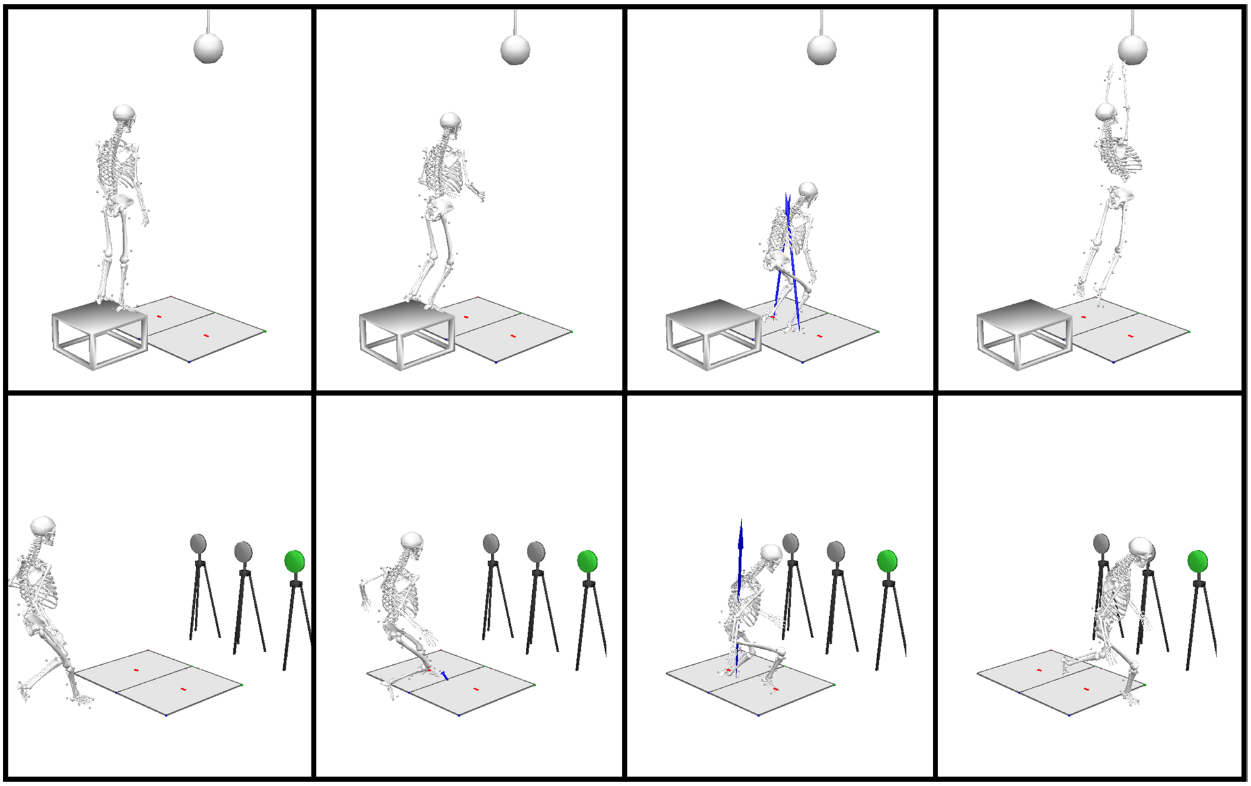

Fig. 1 Top row illustrates the drop vertical jump (DVJ) task. Bottom row illustrates the unanticipated cutting (CUT) task

Participants ran at 75% of their maximal speed from a distance of 5 m away from the force platforms. A light disc positioned in front of the participants (FITLIGHT trainers™, FITLIGHT Sports Corp., Aurora, Ontario, Canada) would illuminate when they passed 2 m in front of the force platforms indicating whether they were to plant and cut sideways at 90° or plant and backpedal to the starting point. Timing gates (TracTronix, Lenexa, Kansas, USA) were positioned 2.5 m apart so that the approach velocity of each trial could be calculated. Approach velocities were not statistically different ($p > 0.05$) among groups or between sessions (NMT: baseline 2.93 ± 0.36 m/s, post 2.97 ± 0.26 m/s; NMT + K: baseline 2.92 ± 0.34 m/s, post 2.86 ± 0.29 m/s; NMT + H: baseline 2.95 ± 0.36 m/s, post 2.95 ± 0.34 m/s). Trials were repeated if the participant did not land cleanly on the force platform. Cutting and backpedas were randomly ordered. Backpedals were not analyzed for this study, only the DVJ and CUT. Instructions of all tasks were provided by the same member of the research team at pre-test and post-testing sessions who was blinded to group membership.

Athletic exposures and ACL injuries were recorded each week for six months following the post-test session using a monthly electronic survey (REDCap) [36] using previous methodology described by Paterno et al. [39]. Participants were asked to report any knee injury and athletic exposures. Athletic exposures were defined as any participation in a soccer game or practice. Individual mean imputation was utilized to account for missing survey data in the instance a participant did not complete one of their surveys (31.3%) [40].

Data and statistical analysis

Kinematic marker data and ground reaction forces (GRF) were lowpass filtered at 12 Hz and used to calculate joint moments through inverse dynamics in Visual 3D (v6, C-Motion Inc.) [24, 41]. Joint moments were analyzed during the landing phase for each task, defined from initial contact on the force platform (GRF > 10 N) until toe off from the force platform (vertical GRF < 10 N) [24]. Net external abduction moment was calculated and represents the abduction external load on the joint, with negative values representing knee abduction based on the analysis convention. The primary outcome variable was peak knee abduction moment during the DVJ and CUT for each group during baseline and post-testing [33].

An intention-to-treat analysis approach was used in all student participants ($N = 150$, 50 in each group) with multiple imputation for participants with missing outcomes using PROC MI (SAS v9.4) for each testing session. Five sets of imputation were generated, with final results analyzed using PROC MIANLYSIS (SAS v9.4). The secondary analysis took a per-protocol approach. To assess intervention effects on post-test outcomes while controlling for potential baseline differences, an analysis of covariance (ANCOVA) was conducted with post-test measures as the dependent variable, baseline measures as the covariate, and group (three levels: NMT, NMT +K, NMT +H) as the between-subjects factor. To confirm that groups were equivalent at baseline, a one-way analysis of variance (ANOVA) was performed on baseline measures. Paired t-test were used to determine baseline to post-test differences in peak knee abduction moment in each group. One-tailed tests of significance were utilized to support the directional hypothesis of reduced knee abduction following the intervention ($p < 0.05$).

The open-source statistical parametric mapping (SPM) package [42] was utilized to statistically compare knee abduction moment time series data in MATLAB ($p < 0.05$). A SPM paired t-test model was utilized to identify significant differences between baseline and post-test for each group at specific time points during the stance phase of landing and cutting [43].

Results

One hundred and fifty female participants were block (age) randomized into NMT groups ($N = 50$; age:13.3 ± 2.1 yrs; height:157.0 ± 10.6 cm; mass:50.2 ± 11.2 kg), NMT + K ($N = 50$; age:13.3 ± 2.3 yrs; height: 155.3 ± 9.8 cm; mass:49.8 ± 10.9 kg), and NMT + H ($N = 50$; age:13.2 ± 2.1 yrs; height: 156.1 ± 11.5 cm; mass:50.6 ± 11.9 kg) and completed initial baseline testing. Of these, 140 participants (93.3%) completed the 6-week intervention and post-test (Fig. 2). Of the 10 participants that did not complete the intervention, 9 participants completed pre-test and several training sessions, however elected to withdraw from the study due to time commitment issues and 1 participant elected to withdraw following an ankle injury unrelated to the study. Each group completed comparable sessions of NMT and biofeedback sessions during the 6-week period (Training: NMT 15.1 ± 2.5 sessions, NMT + K 15.5 ± 2.0 sessions, NMT + H 15.6 ± 2.1 sessions; Biofeedback: NMT 5.7 ± 0.7 sessions, NMT + K 5.7 ± 0.5 sessions, NMT + H 5.9 ± 0.3 sessions). Of the 140 participants that completed the intervention and post-test, thirteen did not complete testing for the CUT due to equipment malfunction (NMT: $n = 4$, NMT + K: $n = 5$, NMT + H: $n = 4$). These missing observations were imputed for the intention-to-treat analyses.

Following the post-test session, surveys reporting athletic exposures for a total of six months were collected from each participant (Fig. 2). Weekly athletic exposures for cutting and pivoting sports were not statistically different ($p > 0.05$) among groups (NMT 4.89 ± 1.25 exposures, NMT + K 4.96 ± 1.82 exposures, NMT + H 4.80 ± 1.41 exposures). There were no ACL injuries reported during the six-month period among any of the intervention groups.

Discrete variables

An ANCOVA was performed on post-test peak knee abduction moment during the drop vertical jump, with baseline measures entered as a covariate and intervention group as the between-subjects factor (Table 1). Baseline knee abduction was a significant covariate (t(136) = 9.83, $p < 0.001$). Neither the NMT + K (t(136) = 0.59, $p = 0.28$) nor the NMT + H group (t(136) = –0.31, $p = 0.38$) differed significantly from the reference group (NMT) after adjusting for baseline. A one-way ANOVA on baseline knee abduction during the drop vertical jump revealed no significant differences between groups, F(2,137) = 0.528, $p = 0.591$, indicating that the groups were comparable at baseline. However, paired t-tests identified statistically significant baseline to post-test improvement during the drop vertical jump for the primary outcome variable of peak knee abduction moment (Fig. 3) in all three groups during (Table 1; NMT: $p = 0.001$, $d = -0.48$; NMT + K: $p = 0.003$, $d = -0.42$; NMT + H: $p = 0.002$, $d = -0.45$). The intention-to-treat analysis confirmed these results with significant improvement in each group (NMT: $p < 0.001$, $d = -0.58$, NMT + K: $p = 0.010$, $d = -0.38$, NMT + H: $p = 0.001$, $d = -0.46$). A 22.7% mean improvement peak knee abduction moment, the primary outcome in this RCT ($p > 0.05$).

For the unanticipated cut, the ANCOVA (Table 1). revealed that baseline knee abduction was a significant covariate in the post-test measure (t(123) = 8.66, $p < 0.001$). The NMT + H showed decreased knee abduction moment during cutting compared to the reference group (NMT) (t(123) = 1.68, $p = 0.048$), whereas the NMT + K did not differ statistically (t(123) = 0.53, $p = 0.298$). A one-way ANOVA on baseline unanticipated cutting knee abduction moments revealed no significant differences between groups (F(2,124) = 1.32, $p = 0.271$), indicating that the groups were comparable at baseline. The NMT + H intervention group was the only group that exhibited statistically significant differences in peak knee abduction moment (Fig. 4) during the unanticipated cutting task with paired t-test (Table 1; NMT: $p = 0.49$, $d = 004$; NMT + K: $p = 0.377$, $d = -0.05$; NMT + H: $p = 0.003$, $d = -0.44$). This was confirmed with the intention-to-treat analysis that showed statistically significant reduction in peak knee abduction moment in the NMT + H group from baseline to post-test during the CUT (NMT: $p = 0.417$, $d = 0.04$, NMT + K: $p = 0.17$, $d = -0.15$, NMT + H: $p = 0.01$, $d = -0.35$). The improvement in peak knee

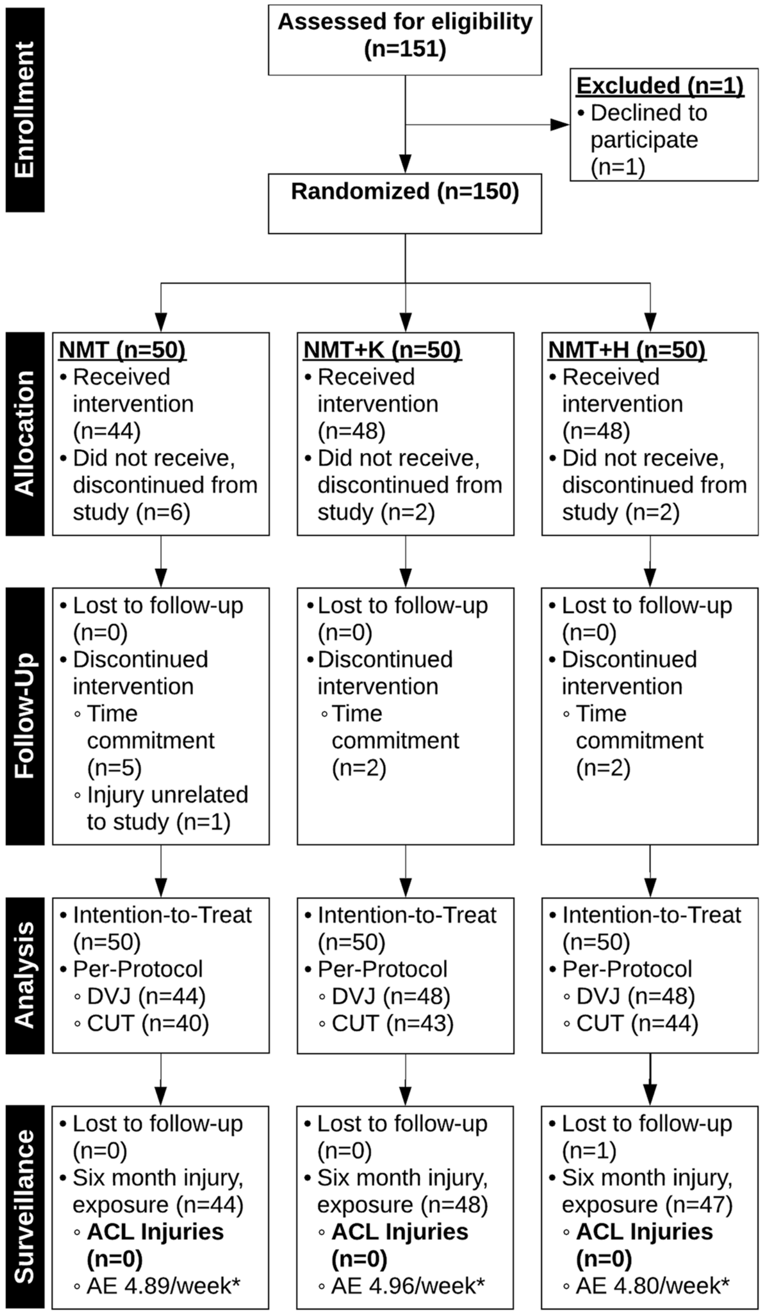

Fig. 2 CONSORT Flow Diagram. *Athletic Exposures (AE) calculated over the 6-month surveillance period, presented as the average weekly exposure during cutting/pivoting activities

abduction in the NMT +H intervention group was 22.5% during the cutting task. The improvement (post-test minus baseline) in NMT +H was significantly greater compared to NMT ($p = 0.02$).

Curve analysis

During the DVJ, all three groups significantly reduced ($p < 0.001$) the magnitude of knee abduction moment when examining the time series data through statistical parametric mapping (Fig. 5). The statistical differences between baseline and post testing emerged at approximately 30% of stance in each group (NMT 30.2%, NMT +K 30.8%, and NMT +H 31.1%). Statistical differences between baseline and post-testing remained different through 77.2% of stance in NMT +H, 65.8% of stance in NMT +K, and 58.2% of stance in NMT. Like the discrete

Table 1 Knee abduction moment during drop vertical jump and unanticipated cut testing at baseline and post-test

	Baseline (Nm)	**Post-Test (Nm)**	**ANCOVA**	**Paired T-Test, Cohen's Effect Size**
	Mean [95% CI]	**Mean [95% CI]**		
Drop vertical jump[a]				
NMT	– 21.4 [– 25.4, – 17.4]	– 16.6 [– 19.7, – 13.5]		*$p = 0.001$, $d = -0.48$
NMT + K	– 19.5 [– 23.2, – 15.8]	– 14.6 [– 17.6, – 11.7]	$p = 0.28$ (vs NMT)	*$p = 0.003$, $d = -0.42$
NMT + H	– 22.2 [– 26.9, – 17.8]	– 17.6 [– 21.1, – 14.1]	$p = 0.38$ (vs NMT)	*$p = 0.002$, $d = -0.45$
Unanticipated cutting[b]				
NMT	– 25.0 [– 30.4, – 19.6]	– 25.0 [– 29.6, – 20.5]		$p = 0.49$, $d = 004$
NMT + K	– 23.6 [– 28.9, – 18.3]	– 22.8 [– 28.0, – 17.6]	$p = 0.30$ (vs NMT)	$p = 0.377$, $d = -0.05$
NMT + H	– 29.5 [– 35.3, – 23.8]	– 22.9 [– 27.8, – 18.0]	*$p = 0.048$ (vs NMT)	*$p = 0.003$, $d = -0.44$

[a] Baseline knee abduction was a significant covariate during drop vertical jump ($t(136) = 9.83$, $p < .001$)

[b] Baseline knee abduction was a significant covariate during unanticipated cutting ($t(123) = 8.66$, $p < .001$)

[*] statistically significant difference ($p < 0.05$)

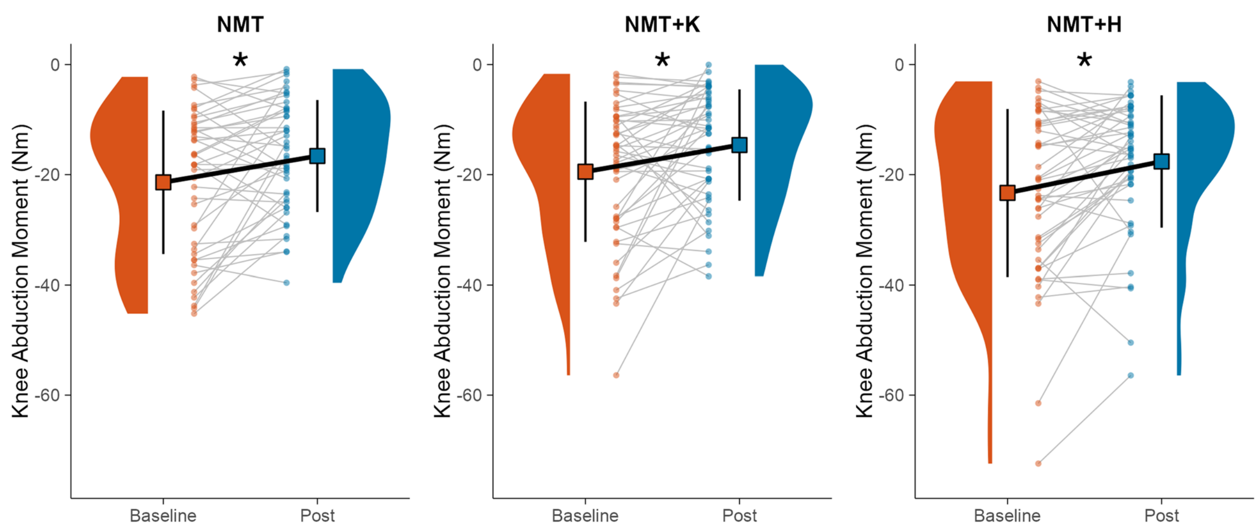

Fig. 3 Square box indicates the group mean (± 1 standard deviation) during baseline and post-testing during drop vertical jump trials for neuromuscular training (NMT), neuromuscular training plus knee focused biofeedback (NMT + K), and neuromuscular training plus hip focused biofeedback (NMT + H). Each individual participant mean of three trials is also indicated by the small circle for each time point with thin line connecting baseline to post-test. Truncated violin plots show the density of the data distribution. (*$p < 0.05$ difference from baseline to post)

analysis of cutting, only the NMT + H group had significant differences ($p < 0.001$) from baseline to post testing with statistical parametric mapping of the time series data (Fig. 6). Participants in NMT + H group reduced knee abduction moment following 6 weeks of training (20.6% to 53.2% stance, $p < 0.001$).

Discussion

High incidence rates of ACL injuries in female athletes outline the necessity of training programs that can modify the high-risk biomechanics associated with injury and decrease the prevalence in this population [27]. These data support the idea that these programs can facilitate neuromuscular adaptations that focus on safe movement patterns, thereby allowing these athletes to adopt muscular recruitment strategies that decrease joint torque and protect the ACL from high impulse loading [44, 45]. Therefore, the question of whether targeting knee abduction moment or targeting hip extensor moment during training can most optimally improve active knee stabilization during sport related tasks was postulated. The salient finding in this study, and in support of our hypothesis, was that knee abduction moment was improved during unanticipated single leg side-step cutting in the hip focused biofeedback group. This was supported in both discrete (peak moment) and continuous time series analysis during early to midstance of the cutting task. Additionally, knee abduction moment (peak and time

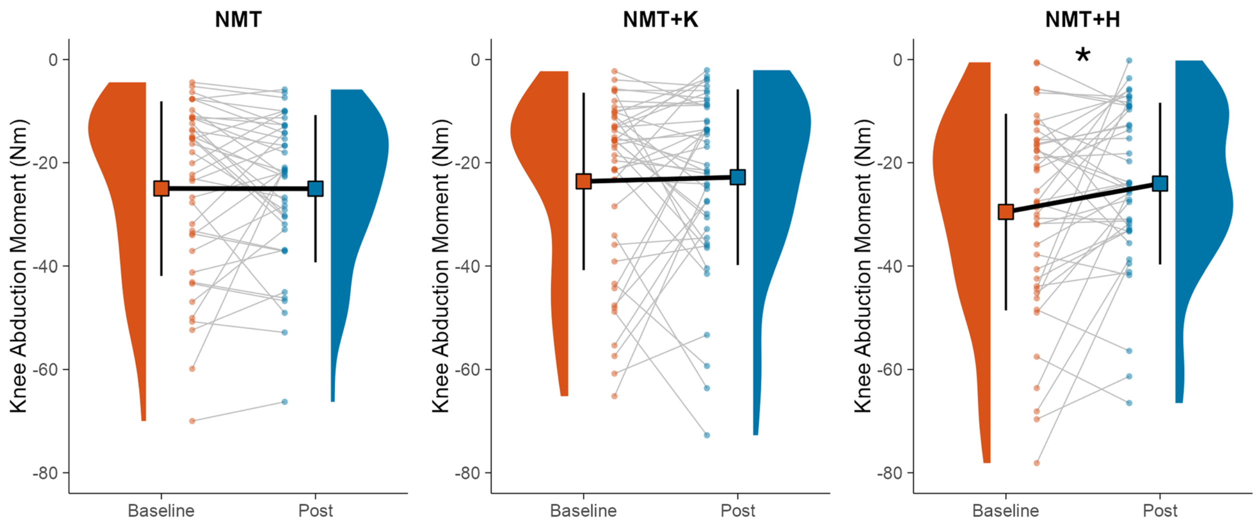

Fig. 4 Square box indicates the group mean (± 1 standard deviation) during baseline and post-testing during unanticipated side-step cut trials for neuromuscular training (NMT), neuromuscular training plus knee focused biofeedback (NMT + K), and neuromuscular training plus hip focused biofeedback (NMT + H). Each individual participant mean of three trials is also indicated by the small circle for each time point with thin line connecting baseline to post-test. Truncated violin plots show the density of the data distribution. (*$p < 0.05$ difference from baseline to post)

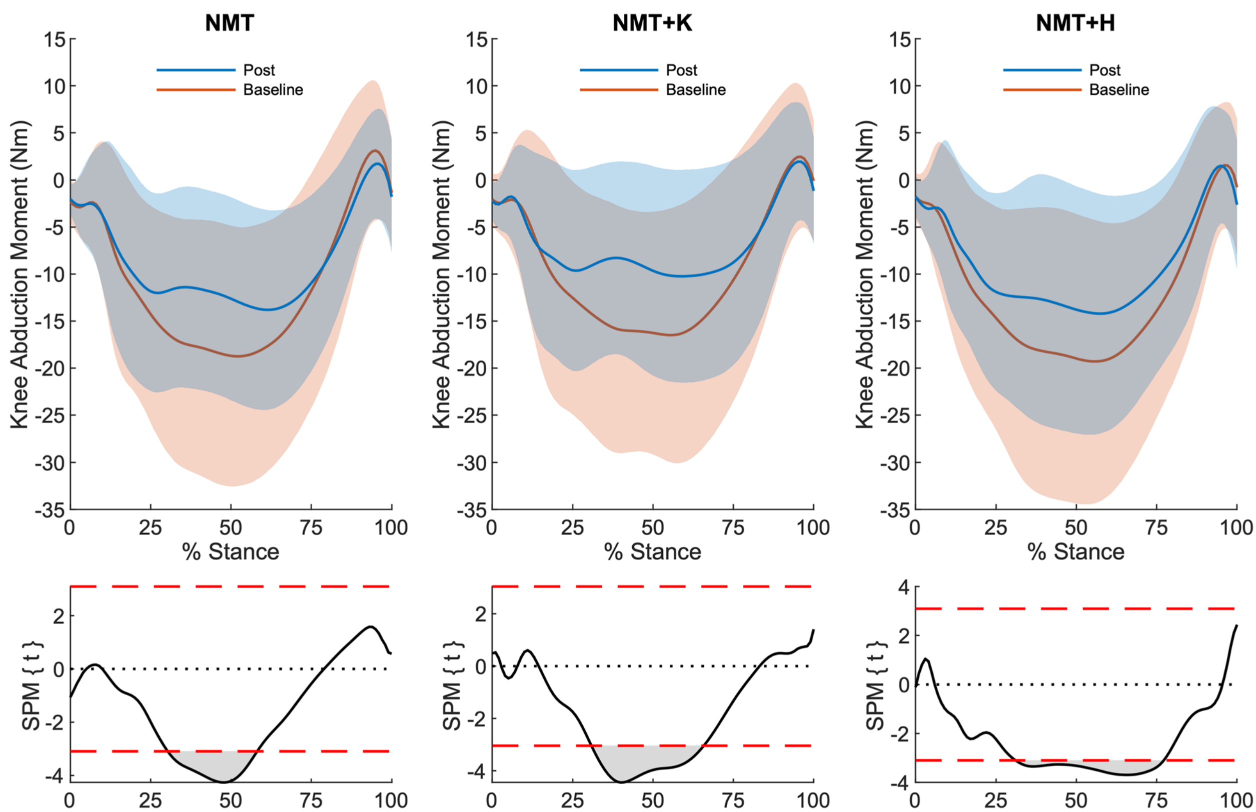

Fig. 5 Top row shows drop vertical jump of each group (mean ± 1 standard deviation shaded) during baseline and post testing. Bottom row shows the corresponding statistical parametric mapping (SPM) analysis to determine baseline to post testing differences between time series data from each group. Red dashed line indicates critical t threshold for significance (shaded region indicates significant differences $p < 0.001$)

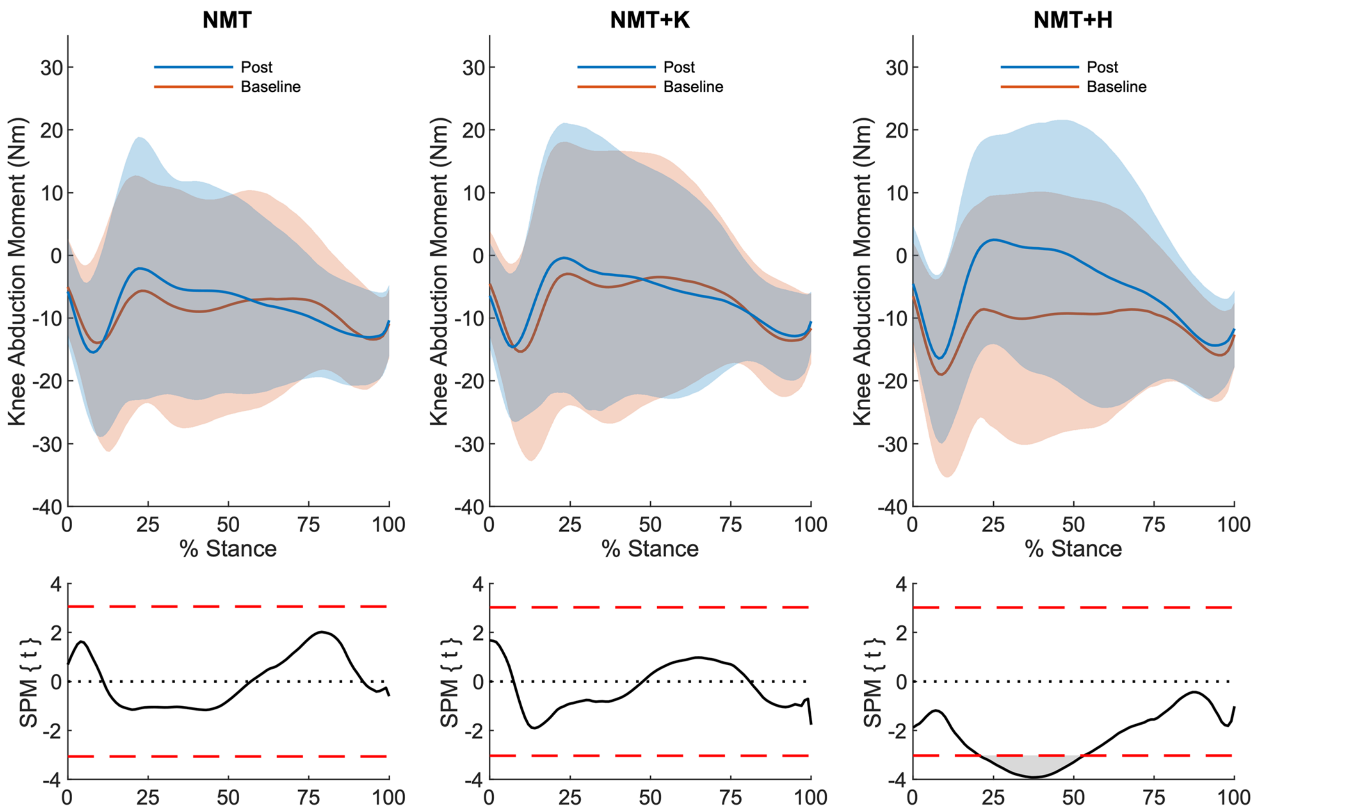

Fig. 6 Top row shows unanticipated cut of each group (mean ± 1 standard deviation shaded) during baseline and post testing. Bottom row shows the corresponding statistical parametric mapping (SPM) analysis to determine baseline to post testing differences between time series data from each group. Red dashed line indicates critical t threshold for significance (shaded region indicates significant differences $p < 0.001$)

series analysis) was improved in the drop vertical jump task in all three groups. Taken together, this would support comprehensive neuromuscular training combined with innovative biofeedback modalities to target underlying hip focused mechanisms which may translate to more dynamic sport related movements. Furthermore, as an exploratory outcome, we systematically included a prospective 6-month injury surveillance period to record both injury and athletic exposures. None of the study participants sustained an ACL injury during this follow-up period.

The baseline measures during both the drop vertical jump and unanticipated cutting significantly predict the post-test measures based on the results of the ANCOVA. During the drop vertical jump, significant improvements across the three groups in knee abduction moment were found. However, given the relationship between baseline and post-test measures, some participants likely still exhibit high levels of knee abduction moment, which may need additional follow-up. Previous studies have identified that female athletes with high levels of knee abduction moment at baseline are potentially more responsive to neuromuscular training than those athletes who do not exhibit the same movement pattern [46, 47]. Furthermore, during the cutting task, the baseline knee abduction moment may be indicative of which athletes may be more likely to need and benefit from an intervention. Additional studies should examine the impact that baseline magnitude of risk may have on those who respond and those who do not respond to neuromuscular training with biofeedback.

While there are many neuromuscular strategies that can influence high-risk loading during dynamic tasks, incorporating kinetic biofeedback during squatting into neuromuscular training programs has been shown to transfer to dynamic drop landings [29]. In this study, we identified improvements in a drop landing across all groups, indicating that neither knee nor hip focused biofeedback significantly influenced the effects of neuromuscular training in such a task. The biofeedback provided a visual of each participant's real-time extensor torque in attempt to promote increased musculature torque rather than consistent verbal instruction during the neuromuscular training, therefore participants may have employed different strategies that did not carry over to a drop landing task. However, with a transfer task that is more demanding and unanticipated (cutting), only the hip focused biofeedback group significantly reduced knee abduction load following training. Therefore, focusing attention on the underlying mechanism (proximal hip) that controls knee loading may be the most effective strategy, as it could be considered a more feasible external focus of control compared to knee extensors. Furthermore, rehabilitation programs that target deficits associated with secondary ACL injuries also identify enhancement of hip strength as an optimal method to improve dynamic knee control. The targeting of such proximal mechanisms, notably hip extension, may therefore transfer motor learning to dynamic unanticipated tasks and potentially result in a greater reduction in the risk of ACL injury in young female athletes. While the technologies utilized in this study might be difficult implement on a wide-scale at present, the future of makerless motion capture and augmented reality is rapidly developing. We aimed to determine if the variables of interest in the biofeedback modality could potentially be utilized in addition to neuromuscular training. The continued development and practical use of such technologies should be further investigated.

The prospective and randomized aspects are strengths of this study. An additional strength was our ability to retain 93.3% of the participants through 6-weeks of a training intervention and biomechanical post-test session. Higher compliance rates of NMT sessions are associated with low rates of ACL injury [15]. Therefore, the strategies used to maintain adherence to our program (i.e. regular correspondence with parents/guardians as well as participants) seem to be an efficient method to promote continued attendance. While the current study is limited to the immediate effects following the intervention, additional analyses will examine the effects of retention on the improvements we identified in knee abduction moments. Furthermore, a variety of secondary kinetic and kinematic biomechanical variables will be analyzed across additional joints and planes of movement during landing and cutting tasks.

The knee abduction moment waveform comparison should be cautiously interpreted for both the drop vertical jump and unanticipated cutting task. Specific non-contact ACL injuries from landing and cutting would typically occur earlier in the stance phase compared to a laboratory-controlled risk screening assessment. However, the greater magnitude of knee abduction moment throughout the stance phases of landing and cutting should be further evaluated to determine relevance to future risk of ACL injury. Additionally, the nature of the prompts and specific exercise progressions during biofeedback should be further investigated. For instance, the instruction in the knee-focused group of “push laterally through their feet” could have induced hip-focused results. However, the intent was to focus on the external biofeedback that was provided on the screen for each of the intervention groups.

Conclusions

The implications from this study highlight the potential transferrable effects that hip-focused biofeedback may have on cutting biomechanics when augmented with neuromuscular training. It is also important to realize that each training group exhibited significant improvements knee abduction moments during a double leg landing task regardless of biofeedback designation. These data, combined with previous literature, signify the importance of neuromuscular training programs that aim to modify the high-risk biomechanics associated with ACL injury.

Abbreviations

ACL	Anterior cruciate ligament
KAM	Knee abduction moment
NMT	Neuromuscular training with sham biofeedback group
NMT + K	Neuromuscular training with knee-focused (external knee abduction moment) biofeedback group
NMT + H	Neuromuscular training with hip-focused (internal hip extension moment) biofeedback group
DVJ	Drop vertical jump
ROBUST	Real-time Optimized Biofeedback Utilizing Sport Techniques
CUT	Unanticipated single leg 90° sideways
GRF	Ground reaction force
SPM	Statistical parametric mapping

Supplementary Information

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Supplementary Material 1: Supplementary video of methods.

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Authors’ contributions

KRF, JBT, MVP, AND, and BH conceptualized and designed the study. KRF, JBT, AND, and AEW collected and analyzed the data. All authors were involved in drafting the manuscript. All authors read and approved the final version of the manuscript.

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Data availability

The datasets used during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Participants were fully informed of the risks and benefits associated with this study and provided written participant informed consent, and/or parental informed consent and participant assent as appropriate. The study protocol was approved by the Institutional Review Board at High Point University and registered as a clinical trial (Clinicaltrials.gov Identifier: NCT02754700, Date Registered 28/04/2016).

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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