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Original Article

Strength development following a six-week risk reduction athletic development training program in men and women

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ABSTRACT

This study retrospectively evaluated data from an athlete management system on the impact of a 6-week, 12-session risk-reduction athletic development training program on maximal isometric strength in post-rehabilitative and healthy men and women. Maximal isometric quadriceps and hamstrings strength were evaluated bilaterally before and after the training program. Out of 55 athletes that had participated in the program, a total of 37 athletes' (13–28 years old) recorded outcomes were utilized in analyses. Thirty-one athletes had undergone rehabilitation (post-rehabilitative athletes) after orthopedic knee surgeries. Six athletes with no previous surgeries performed (healthy athletes) also completed the 6-week program. Repeated measures analyses of variance (leg $\times$ time) assessed changes in quadriceps and hamstrings strength at an alpha of $p \leq 0.05$. There was a main effect for time where the post-rehabilitative athletes' quadriceps and hamstrings strength increased by (mean difference $\pm$ standard error) (4.2 ± 0.7) kg ($p < 0.01$) and (4.5 ± 0.9) kg ($p < 0.01$) respectively, with legs (operative [OP]) and non-operative [NOP]) combined. With time points combined, the OP limb was weaker than the NOP limb for quadriceps strength by (2.9 ± 0.7) kg ($p < 0.01$) with no differences in hamstrings strength. For the healthy athletes, there were no changes for quadriceps strength and hamstring strength improved across time by (5.3 ± 1.4) kg ($p = 0.01$) with legs combined.

In conclusion, there were improvements in post-rehabilitative and healthy athletes' isometric strength after the training program. However, between-limb strength asymmetries were still apparent in the post-rehabilitation cohort.

1. Introduction

Orthopedic knee injuries to structures such as the anterior cruciate ligament (ACL) and subsequent surgeries are commonly reported and documented to predispose patients to recurring knee-related issues such as reinjury,[1,2] osteoarthritis,[3] and reduced activity and quality of life.[4] Development of training regimens that can reduce secondary injury rates to enhance the athlete's quality of life should meet recommendations of coaches as well as the practitioners involved in rehabilitative care, yet remain individualized to meet basic training principles such as load and specificity.[5] Thus far, there is a lack of consistent preventative[6] and post-injury protocols[7] administered and documented in the literature.

After surgeries such as anterior cruciate ligament reconstruction (ACLR), patients undergo a course of structured rehabilitation, lasting approximately 8–9 months.[8] This process is designed with the goal of returning the athlete to their pre-injury level of athletic participation.[8,9] Upon clearance from rehabilitation, athletes may still exhibit inter-limb deficits in skeletal muscle strength,[10] function,[11] and size.[12] As the athlete transitions away from traditional physical therapy, their exercise programming may be overseen by athletic trainers and strength and conditioning professionals and post-rehabilitation training protocols are critical at this time for continued development of function, strength, and size, to reduce reinjury risk.

Existing research on the efficacy of post-rehabilitation or preventative programming has evaluated various outcomes such as dynamic strength, functional outcome scale scores, and self-reported function[13] from neuromuscular training,[14] steadiness training,[15] suspension training,[16] and proprioception based training.[17] Outcomes from these indicate limited neural activation, arthrogenic inhibition, and significant atrophy

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Abbreviations

ACL:	anterior cruciate ligament
ACLR	anterior cruciate ligament reconstruction
ANOVA	analysis of variance
CI	confidence interval
HHD	hand-held dynamometer
MVIC	maximal voluntary isometric contraction
NOP	non-operative limb
OP	operative limb
POST	after the training program
PRE	prior to the training program

and have been posed as contributors to the reported deficits,[18–20] yet these factors are not always directly evaluated in clinical settings. Whereas maximal isometric strength is used clinically and often missing within the post-rehabilitative training literature in this population of athletes. Despite the lack of studies investigating the changes in maximal isometric strength with post-rehabilitative training, large between-limb asymmetries in isometric strength are observed post-surgery.[10,12,21] For example, reviews by Lepley and Lisee et al. have reported between-limb asymmetries of 14%–20% from 6- to 12-months post ACL reconstruction.[10,21] Further, in participants that were 2–15 years post-ACL reconstruction, the operative limb has been reported to be 6.4% weaker than the non-operative limb.[18] Therefore, with the intention to bridge rehabilitation and return to functional athleticism, research should directly evaluate metrics that practitioners find valuable and can easily assess in clinical settings such as isometric strength. Further, to improve these metrics (e.g., reduce between-limb asymmetries) training programs should include fundamental strength training principles and exercises that align with the National Strength and Conditioning Association[22] and the American College of Sports Medicine.[23] As such, the purpose of this investigation was to retrospectively evaluate the impact of a 12-session risk-reduction athletic development training program on maximal isometric strength in post-rehabilitative and healthy men and women.

2. Material and methods

2.1. Ethical approval

The study was reviewed and approved as a retrospective chart review by University of Kansas Medical Center Human Research Protections Program (STUDY00148827) in accordance with the eclaration of Helsinki. The review board determined that informed consent was not required from participants due to the retrospective design.

2.2. Study design

To retrospectively evaluate the efficacy of programming currently used in practice, this study was conducted as observational review that included men and women who participated in a risk-reduction athlete development program from 2019 to 2023 at a University-affiliated sports medicine and performance facility. Data were retrieved from athlete charts stored on a secured online athlete management system (Kinduct Technologies Incorporated, Halifax NS, Canada). Program records captured included assessment scores for isometric quadriceps and hamstrings strength using a handheld dynamometer (MicroFet 2, Hoggan Scientific, Salt Lake City, Utah, USA) on both limbs prior to (PRE) and after (POST) the 12-session training program. Chart items captured included strength data and program attendance and all deidentified data were approved under a retrospective chart review by the University of Kansas Medical Center Institutional Review Board Human Research Protections Program; #STUDY00148827.

2.3. Subjects

Fifty-five men and women athletes (age range: 13–28 years) had previously participated in a risk-reduction athletic development program as part of sports performance programming. The data of individuals who had participated in the 6-week training program after the completion of their rehabilitation was extracted from the athlete database and assessed for eligibility (Fig. 1).

Data eligibility included athletes that completed at least two-thirds (8 sessions) of the program's training sessions, completed assessments at PRE and POST with the facility staff, and had undergone a knee related surgery or completed the program as a healthy athlete with no previous documented knee injuries, with no additional previous surgeries. There were no restrictions placed on specific knee surgery procedures (e.g., meniscal repair status for patients undergoing anterior cruciate ligament reconstruction) for the post-rehabilitative athletes.

2.4. Strength assessments

At PRE and POST, participants underwent assessments for maximal quadriceps and hamstrings isometric strength of both limbs. For the post-rehabilitative athletes, the non-operative limb (NOP) was tested prior to the operative (OP) limb. All testing was conducted by a certified athletic trainer or corrective exercise specialist. Maximal voluntary isometric contractions (MVICs) of the quadriceps and hamstrings were performed in an upright seated position with the knee angle at 90° flexion. Peak force (kg) was recorded from a belt-stabilized[24] hand-held dynamometer (HHD). For the quadriceps, the HHD was placed on the distal portion of the anterior shin above the malleoli. While for the hamstrings, it was placed on the distal portion of the posterior lower limb, above the Achilles tendon.

2.5. Training protocol

After PRE testing, athletes engaged in a 6-week training program, two nonconsecutive days per week. Each session lasted approximately 45–60

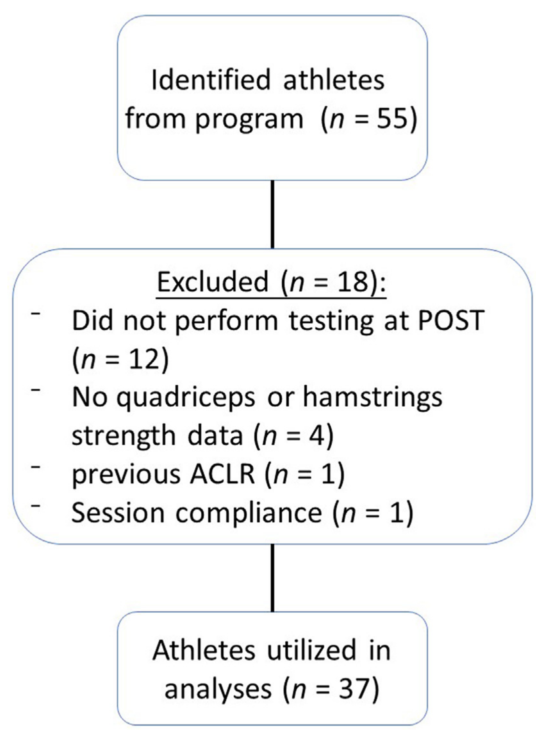

Fig. 1. Flow chart of the identified and included athletes for analyses. ACLR: anterior cruciate ligament reconstruction; POST: post-training.

minutes (min) and began with a dynamic warm-up as well as low-intensity plyometric, jumps and landing movements. Briefly, the training program (Table 1) was designed by the athletic training staff to be focused primarily on lower body and anatomical core exercises. Lower body strength training exercises included bilateral (e.g., barbell squat, deadlifts, hip thrust, good-mornings, calf raises) and unilateral movements (e.g., lunges, split squats, single-leg deadlifts, single-leg squats to a box, single-leg step-downs). Anatomical core exercises included isometric movements (e.g., planks) along with dynamic stability movements (e.g., dead-bugs, bird-dogs). All exercises were performed for 2–3 sets and load was progressed on an individualized basis per session.

2.6. Statistical analyses

Due to the limited number of healthy athletes that participated in the scheduled programming, no direct comparison between the two cohorts was completed. For the post-rehabilitative athletes, separate 2 × 2 [leg (OP vs. NOP) × time (PRE vs. POST)] repeated measures analyses of variance (ANOVAs) assessed differences in quadriceps and hamstrings MVIC. For the healthy athletes, separate 2 × 2 [leg (left vs. right) × time (PRE vs. POST)] repeated measures ANOVAs assessed differences in quadriceps and hamstrings MVIC. In the case of a significant 2-way interaction, ANOVAs were decomposed with 1-way ANOVAs. Main effects were analyzed via paired samples or independent samples *t*-tests as post-hoc comparisons. Partial eta square (η_p^2) effect sizes were generated for the 2-way interactions and interpreted as trivial (< 0.01), small (0.01–0.06), moderate (0.06–0.14), or large (> 0.14).[25] Cohen's *d* effect sizes were generated for the main effects and post-hoc pairwise comparisons[26] and interpreted as small ($d < 0.2$), medium ($d = 0.5$), or large ($d > 0.8$).[27] All data are presented as mean ± standard deviation (*SD*) with mean differences presented as mean ± standard error (*SE*) with 95% confidence intervals (*CI*). All analyses were performed in R Statistical Software (v4.3.0, R Core Team, Vienna, Austria) through RStudio (RStudio, Posit Software, PBC, Boston MA, USA). Data were considered significant at $p \leq 0.05$.

3. Results

3.1. Athlete characteristics

Upon evaluation of inclusion and exclusion criteria, a total of 37 athletes were included in analyses (59.5% women), 31 of which completed the training program following post-surgery rehabilitation (20 women) and 6 of which were healthy with no previous surgeries (2 women). The post-rehabilitative athletes were (196.4 ± 41.9) days post-surgery (range: 112–326 days), attended (11.1 ± 1.2) training sessions out of the 12 total sessions, and were (17.4 ± 3.2) years old. The healthy athletes attended (11.5 ± 0.8) of the total training sessions and were (15.2 ± 1.9) years old.

3.2. Quadriceps MVIC

For the post-rehabilitative athletes' quadriceps strength (Table 2), there was no significant leg × time interaction ($p = 0.55$, $\eta_p^2 = 0.012$). However, there were main effects for leg ($p < 0.01$) and time ($p < 0.01$). Collapsed across time, post-hoc analyses indicated that the NOP leg was stronger than OP (mean difference: (2.85 ± 0.7) kg; 95% *CI*: 4.2 to −1.5 kg; $p < 0.01$, $d = 0.77$). While collapsed across leg, MVIC strength improved from PRE to POST ([4.20 ± 0.7] kg; 95% *CI*: 5.7 to −2.7 kg; $p < 0.01$, $d = 1.1$). In contrast, for the athletes that did not undergo knee surgery, there was not a leg × time interaction ($p = 0.73$, $\eta_p^2 = 0.02$) for MVIC strength. Further, there were no main effects for leg ([0.71 ± 1.2] kg; 95% *CI*: 2.5 to 3.9 kg; $p = 0.62$, $d = 0.22$) or time ([−1.38 ± 0.6] kg; 95% *CI*: 3.0 to 0.2 kg; $p = 0.07$, $d = 0.92$).

3.3. Hamstrings MVIC

For the post-rehabilitative athletes hamstring strength (Table 2), there was no significant leg × time interaction ($p = 0.59$, $\eta_p^2 = 0.01$), nor was there a main effect for leg (mean difference: [0.53 ± 0.4] kg; 95% *CI*: 1.4 to 0.3 kg; $p = 0.20$, $d = 0.23$). However, there was a main effect for time as hamstrings MVIC increased, collapsed across legs, from PRE to POST ([4.53 ± 0.9] kg; 95% *CI*: 2.7–6.4 kg; $p < 0.01$, $d = 0.92$). Similarly, for the healthy athletes, there was not a leg × time interaction ($p = 0.20$, $\eta_p^2 = 0.30$). There was also not a main effect for leg ([−0.61 ± 1.3] kg; 95% *CI*: 3.9 to 2.7 kg; $p = 0.66$, $d = 0.19$). However, there was a main effect for time as hamstrings MVIC improved from PRE to POST collapsed across legs for the healthy athletes ([5.33 ± 1.4] kg; 95% *CI*: 1.8–8.9 kg; $p = 0.01$, $d = 1.6$).

4. Discussion

The aim of this study was to observe changes in lower-body isometric strength following a 6-week risk-reduction athletic development training

Table 2
MVIC values of both post-rehabilitative and healthy athletes across legs and time.

		Post-rehabilitative		Healthy	
		OP	NOP	Right	Left
Quadriceps	**PRE (kg)**	25.4 ± 1.8[a]	28.4 ± 1.9	24.7 ± 3.2	23.7 ± 2.8
	POST (kg)	29.8 ± 1.9[a,b]	32.4 ± 2.1[b]	25.8 ± 2.8	25.4 ± 2.8
Hamstrings	**PRE (kg)**	21.2 ± 1.3	21.8 ± 1.4	18.0 ± 1.9	17.7 ± 3.0
	POST (kg)	25.8 ± 1.7[b]	26.2 ± 1.6[b]	22.4 ± 2.3[b]	24.0 ± 2.7[b]

Values are presented as mean ± standard error (*SE*). PRE: pre-training; POST: post-training; OP: operative leg; NOP: non-operative leg.
[a] Indicates difference ($p < 0.05$) between limbs.
[b] Indicates difference ($p < 0.05$) from PRE.

Table 1
Four example training sessions for a post-rehabilitative athlete.

Session 1		Session 6		Session 9		Session 12	
Exercise	*Load (pounds)*	*Exercise*	*Load (pounds)*	*Exercise*	*Load (pounds)*	*Exercise*	*Load (pounds)*
Banded Box Squats	BW	**Bulgarian Split Squats**	5	**Banded Goodmornings**	BW	**Barbell Back Squat**	65
Cross-arm RDL	BW	**Cross-arm RDL**	15	**DB Split Squats**	45	**Bulgarian Split Squats**	BW
Step-ups	BW	**Hip Thrusts**	BW	**Banded Side Lying Hip Abductions**	BW	**Hyperextensions**	BW
		Side Planks	BW	**SL Glute Bridge**	BW	**Hand-Supported Pistol Squats**	BW
		SL Glute Bridge	BW	**SL RDL**	20		
		Slider Lunges	BW				
		Banded Clam Shells	BW				

BW: bodyweight; RDL: Romanian deadlift; SL: single-leg, DB: dumbbell.

program in men and women athletes. The main findings indicated improvements in hamstring and quadriceps strength in the post-rehabilitative athlete's OP and NOP limbs. However, despite the additional 6-week program following 6–7 months of physical therapy, large between-limb differences for quadriceps MVIC strength persisted. For the healthy athletes, the only significant change was improved hamstrings MVIC strength over time.

Persistent quadriceps weakness of the OP leg has been extensively reported after orthopedic knee surgeries, particularly ACLR.[21,28,29] The present athletes were approximately 204.6 days (6.7 months) post-rehabilitative and both limbs demonstrated an average increase of (4.20 ± 0.7) kg (15.6%) over time. For the post-rehabilitative athletes, there was a between-limb difference of approximately 8.9% for quadriceps strength at POST, however, this was an improvement from the 12.0% difference observed at PRE. Further, these differences do not align with those reported in previous cross-sectional studies investigating isometric quadriceps strength changes after ACLR as there appear to be inconsistent deficits reported across the literature, especially dependent on the post-surgical timepoint. For example, our overall 10.3% between-limb deficit is greater than the 5.8% difference reported in participants an average of 5.7 years post-ACLR,[18] less than the 39% deficit in patients an average of 8-months post-ACLR,[30] yet comparable to the difference of 7.9% in isometric strength expressed normalized to body mass in patients 28 weeks (~6.4 months) after ACLR. Nevertheless, these all indicate quadriceps weakness of the OP limb continually persists to some extent for an extensive duration after surgery and post-surgical rehabilitation.

Prior to and following training, there were no between-leg differences in hamstrings MVIC in the present study. The additional 6-weeks of training resulted in an overall improvement of ~21.1% for the post-rehabilitative patients and 29.9% for the healthy athletes' hamstring MVIC strength. These results are similar to changes reported by Huang et al. who found that 6-weeks of suspension based training or traditional rehabilitation improved OP hamstrings concentric peak torque by ~31.5% and 15.6%, respectively, in participants who were at least 6-months post-ACLR.[16] Further, Huang et al. demonstrated that hamstrings symmetry indices, expressed as the OP leg's values relative to the NOP, improved significantly in the suspension training group only.[16] Lastly, a progressive strength training program initiated 3-months after ACLR, increased OP hamstrings isokinetic strength by 12.3% after 6-months of rehabilitation and 16.8% after 9-months of rehabilitation compared to the initial values.[31] Overall, similar training protocols to the present study and progressive strength training protocols utilized by Welling et al.[31] can increase hamstring strength across time in athletes. The only significant finding for the present study's healthy athletes was a 29.9% improvement in hamstrings MVIC PRE to POST. Quadriceps MVIC also tended to improve (5.7%) for this limited sample of healthy athletes (Table 2), although not significant. These findings demonstrate the efficacy of the training program for improving strength in not only the post-rehabilitative athletes, but also for the healthy athletes. The premise of this 6-week program is to provide any athlete with a risk-reduction to ACL and other sport-related injuries through education and individualized programming in only 12 sessions. Increases in both quadriceps and hamstrings isometric strength have been reported following a longer training period (24 sessions) in healthy young athletes in response to common injury prevention programs.[32] Further, improvements in quadriceps MVIC strength have been reported to be observed as early as 4-weeks after commencement of resistance training.[33]

The lack of recovery for the post-rehabilitative athletes could be due to a myriad of physiological factors associated with persistent lower-limb weakness after lower-limb injuries and surgeries.[18,34,35] Although not investigated in the present study, these factors could include, but may not be limited to, muscle atrophy[29,35] or altered neuromuscular properties.[19,34] Therefore, the associations between these properties and muscle strength should be investigated to further isolate what exact physiological characteristics need to be targeted in training programs. With the large between-limb differences observed after knee surgeries, training protocols like the one utilized in the present study need to be continually evaluated to attenuate these differences. The training program of the present study was unique compared to previous research in that it integrated basic, recommended fundamental strength training principles and education on adequate warm-up.[22] Limitations to consider that were not collected from the program facilitator include other quantitative measurements such as dynamic strength or rate of force development,[36] kinematic or kinetic measurements during jumping-related tasks,[11] and neuromuscular or muscle morphological[19,37] outcomes that may have provided insight into what exact factors are driving the strength deficits in the post-rehabilitative athletes. Additionally, limb dominance was not recorded for the healthy athletes to directly compare the post-surgical involved and intact limbs between these distinct groups. These variables should be included in future studies to provide evidence on what should be emphasized after surgery and rehabilitation from knee surgeries, as well as in strategic injury mitigation efforts in healthy athletes. Further, this study was retrospective, and the training program was individualized to each athlete based on the experience of the coaches who implemented the program. Lastly, a larger sample of healthy athletes would have provided further information on the exercise program's efficacy in an uninjured population, yet the description of the evaluated risk-reduction programming was "to help athletes develop proper skills for reducing their risk of ACL and other sport-related injuries", which may not attract healthy athletes. However, the healthy athletes were included in the present study to illustrate the training program's efficacy. The increase in the hamstrings strength for the healthy athletes but not the post-rehabilitative athletes highlights the potential need for specialized training programs in athletes post-rehabilitation completion.

5. Conclusions

To conclude, effective creation of similar risk-reduction programs should be implemented and documented to potentially limit primary injuries in athletes and to attenuate secondary injuries and complications associated with knee surgeries. Strength training integration after knee surgery such as ACLR should be continually evaluated for outcome variables (e.g., strength) and factors affecting these outcomes (e.g., neuromuscular activity and muscle morphology). To overcome these deficits, exercise modifications that focus on muscle hypertrophy or more so on muscle strength should be implemented. Further, the fundamental strength training principles of specificity, overload, and progression should be integrated into the post-knee surgery and rehabilitation training programs in research, to best reflect the methods that are utilized in practice. Collectively, all members of a high-performance athletic development unit should be engaged in identifying strategies to reduce the high rates of knee-related functional deficits after surgery.

Conflict of interest

Dr. Bryan G. Vopat reports stock or stock options for Altior, Carbon 22, and Spinal Simplicity, is a paid consultant for Artelon and is a board/committee member of the American Orthopedic Foot and Ankle Society.

Ethics approval statement

The study was reviewed and approved as a retrospective chart review by the University of Kansas Medical Center Human Research Protections Program (STUDY00148827) in accordance with the Declaration of Helsinki. The review board determined that informed consent was not required from participants due to the retrospective design.

Data sharing statement

Data are available from the corresponding author upon reasonable request.

CRediT authorship contribution statement

Christopher J. Cleary: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Krisha Crane:** Writing – review & editing, Data curation. **Lisa M. Vopat:** Writing – review & editing, Conceptualization. **Bryan G. Vopat:** Writing – review & editing, Conceptualization. **Ashley A. Herda:** Writing – review & editing, Supervision, Formal analysis, Conceptualization.

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