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The Effect of Strength Training on Running Kinematics: A Narrative Review

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ABSTRACT: Running kinematics have been related to injury and therefore may provide a therapeutic avenue for injury prevention and rehabilitation. The effect of strengthening exercise on running kinematics has not been systematically reviewed. The objective of this study was to determine the effect of strengthening exercise programs on 3D running kinematics in experienced runners. A systematic literature review was completed of PubMed/MEDLINE, CINAHL, and SPORTDiscus from inception to April 2020. Articles investigating strengthening exercise programs and completing 3D kinematic analysis during running on experienced runners were included. Twenty-two full text articles were reviewed. Eight met the inclusion criteria. The modified Downs and Black criteria were used to assess article quality and risk of bias. Due to the heterogeneity of methodology, data synthesis was not possible. Therefore, a narrative review is presented. There was inconsistent evidence for the role of strengthening programs on hip adduction, knee internal rotation, and metatarsophalangeal range of motion which may be influenced by the type of strengthening exercise employed or by differences in the sample populations investigated. Most variables showed no change following the completion of a strengthening program. However, some studies indicated that specific strengthening programs may increase trunk rotation excursion, decrease peak hip adduction, increase hip adduction excursion, decrease peak knee internal rotation, increase plantarflexion excursion, or decrease eversion excursion. There is inconclusive evidence for how strengthening exercise may affect running kinematics. The type, frequency, intensity, and duration of strengthening exercise and mode of feedback on movement performance needed to change running kinematics is unknown.

KEY WORDS: biomechanics, running, resistance training, rehabilitation

I. INTRODUCTION

Several kinematic variables have been associated with running-related injuries (RRI) through multiple systematic reviews and a recent meta-analysis.[1–6] The evaluation of running kinematics is also included in a recent framework for understanding the etiology of RRI.[7] Because of the role that running kinematics may play in RRI, identifying avenues that allow coaches and clinicians to modify running kinematics may provide a therapeutic avenue for the prevention and treatment of RRI.[2,8,9]

Numerous strategies have been suggested to alter running kinematics including strengthening[9–12] and movement training programs,[9,13] while some have claimed that strengthening programs alone may be insufficient to alter the motor program related to running kinematics.[14] Those claiming that strengthening alone is insufficient to alter running kinematics promote targeted gait-retraining strategies to change running kinematics. Several gait-retraining techniques are available including visual[15–18] or audio feedback[19,20] on spatiotemporal parameters, step rate modification,[21–24] postural cues,[25,26] and alterations in footstrike.[27,28] There is no consensus on the best approach.[29]

Gait-retraining strategies appear to be effective in altering multiple kinematic and kinetic variables associated with running.[29,30] But, to our knowledge, the success of gait retraining compared to strengthening programs to altering running kinematics has not been determined. Previous studies have examined the relationship between strength-related variables and running kinematics, and report inconsistent findings on its magnitude and relevance.[31–37] This inconsistency supports the notion that a runner's strength may not be a primary determinant of his or her running kinematics. An important shortcoming of this view is that the available evidence is from correlational studies that have largely examined relationships between a runner's strength and kinematics at specific points *in* time which may not inform researchers or clinicians of the effects of strengthening programs *over* time.

Since strengthening exercises can include aspects of movement specificity that mimic the task of running, there may be some potential for these movement patterns to overlap with, or carry over to, the task of running.[13] "Strengthening" exercises have also been successfully used as part of multimodal treatment programs for runners[38–40] and continues to be a suggested component of training and rehabilitation associated with running.[9,12,41–43] The degree to which strengthening affects running kinematics is uncertain since there has been no systematic investigation of the effects of strengthening programs on running kinematics.

The purpose of this study was to systematically review the current studies investigating the effects of strengthening programs on running kinematics. These results may be used to help guide clinicians toward the use of appropriate strategies to achieve desired running kinematics.

II. METHODS

A. Search Strategy

An independent search was completed in April of 2020 through PubMed/MEDLINE, CINAHL, and SPORTDiscus. Search terms included (biomechanics OR kinematics) AND (running OR runner*) AND (strength* OR resist* OR training). Reference lists from identified articles and from other systematic reviews were screened to identify potential articles not identified through this search strategy.

B. Inclusion and Exclusion Criteria

Studies investigating the role of an exercise program designed to improve strength and its effects on running kinematics were considered eligible for inclusion. Additional inclusion criteria were the use of human subjects, written in English, and participants currently running on a weekly basis. Studies were excluded if participants were novice runners, military recruits, triathletes, or ball sport athletes; if 3D kinematic variables were not included in the biomechanical assessment, biomechanical assessment was not completed pre- and postintervention, or the intervention included gait retraining, plyometrics, or were designed as a "fatigue" protocol. No restrictions were placed on the year of publication, but abstracts, study protocols, books, dissertations, and theses were excluded.

C. Review Process

Titles and abstracts were screened and reviewed for inclusion and exclusion criteria. If insufficient information was available to determine appropriateness for inclusion, the full text was obtained and reviewed. Full-text articles were independently reviewed by two authors. Discrepancies in articles identified for inclusion were resolved with a consensus meeting.

D. Methodological Quality and Risk of Bias Assessment

The methodological quality of each article retained for final review was rated by two authors. A modified form of the Downs and Black checklist was used as performed in previous studies investigating running injuries.[44,45] Differences in quality assessment between the two raters were resolved with a consensus meeting.

E. Data Extraction

Participant characteristics for each study were recorded. The body region targeted by the strengthening intervention, exercises completed, frequency of intervention, duration of intervention, volume of exercise, resistance parameters, and level of supervision were compared among studies. Biomechanical measures reported in each study were extracted and catalogued independently.

F. Data Synthesis

If two or more studies reported on the same variable, were completed in a similar sample of runners, were of the same sex (males only, females only, or a combined sample of males and females), and used a similar exercise protocol, a meta-analysis was planned. If criteria for a meta-analysis were not met, a qualitative level of evidence was planned to assign categories of evidence as described previously.[1]

III. RESULTS

A. Search Results

The initial search revealed 2,821 potential articles for review. Following the inclusion/exclusion process, only eight studies were considered eligible (Fig. 1). Three studies[46–48] investigated the effects of foot-strengthening programs. Two studies[10,49] investigated the effects of hip-strengthening programs. Two studies[50,51] investigated generalized lower extremity–strengthening programs. And, one study[52] investigated the combined effects of a core conditioning and lower extremity–strengthening program.

B. Article Quality Assessment

Six[10,46,47,50–52] of the eight studies were rated as moderate quality and two[48,49] were rated as high quality (Table 1). Quality ratings ranged from 7 to 11. Only one study blinded the individual performing the outcome measurements.[48] All studies imposed some degree of restriction on participant recruitment and selection that may have limited their generalizability to all runners.

C. Participants

Across all included studies, 133 participants (49 males; 48 females; 36 unreported) underwent strengthening interventions (52 foot; 23 hip; 52 lower extremity; 6 core and lower extremity; Table 2). Five studies were completed on mixed-sex samples,[46–48,50,52] while two studies were completed on females only[10,49] and one study was completed on

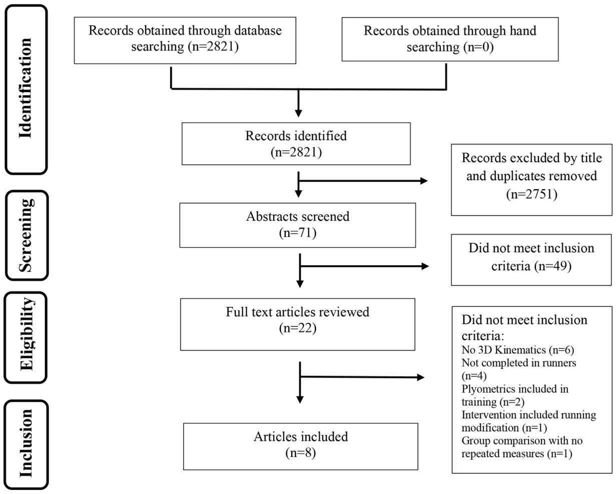

FIG. 1: Flow diagram of literature search

TABLE 1: Article quality assessment

Modified Downs and Black criteria	**Day, 2019**	**Fukuchi, 2016**	**Gottschall, 2019**	**Letafatkar, 2019**	**Snyder, 2009**	**Taddei, 2018**	**Taddei, 2020**	**Willy, 2011**
Clear aim/hypothesis	1	1	1	1	1	1	1	1
Outcome measures clearly described	0	2	1	1	1	1	1	1
Participant characteristics clearly described	1	2	1	1	2	1	1	1
Confounding variables described	1	2	2	2	2	1	1	1
Main findings clearly described	1	1	1	0	1	0	1	1
Measures of random variability provided	1	0	2	1	1	2	1	1
Actual probability values reported	1	1	0	1	1	2	1	1
Participants representative of entire population	2	0	U	0	2	2	2	2
Participants representative of entire population	2	0	0	0	0	2	2	2
Blinding of outcome measurer	0	0	0	0	0	0	1	0
Analysis completed was planned	1	1	1	1	1	1	1	1
Appropriate statistics	1	1	1	1	1	1	1	1
Valid and reliable outcome measure	1	1	1	1	1	1	2	1
Appropriate case control matching	0	0	0	0	0	0	0	0
Adjustment made for confounding variables	2	1	U	1	1	1	1	1
Total score	**9**	**7**	**7**	**9**	**9**	**8**	**11**	11

0, no; 1, yes; 2, partially; U, unable to determine; > 10, high quality; 6–10, moderate quality; < 6, low quality.

TABLE 2: Participant demographics

Author, Year	**Male/ female**[a]	**Age (years)**	**Height (m)**	**Weight (kg)**	**BMI (kg/m^2)**	**Running level**	**Running volume**	**Running experience (years)**
Day, 2019	15/8	24 (6)	1.73 (0.10)	60 (8)	NR	Competitive	90 (21) km/week	NR
Fukuchi, 2016	N = 36 (M/F = NR)	59.8 (4.7)	1.723 (0.10)	72.7 (13.4)	24.4 (3.1)	Recreational	3.7 (1.8) hours/week	18.9 (15.2)
Gottshall, 2019	2/4	33.2 (9.36)	1.692 (0.527)	65.82 (6.83)	NR	Recreational	> 20 km (120 min)/week	NR
Letafatkar, 2019	16/0	33.4 (6.25)	1.72 (.394)	60.4 (4.42)	22.4 (1.29)	Recreational	> 8 km/week	1.3 (1.05)
Snyder, 2009	0/13	21.9 (1.2)	1.54 (0.05)	63.6 (6.4)	NR	Recreational	NR	NR
Taddei, 2018	7/8	44.8 (8.7)	1.687 (0.088)	67.8 (12.7)	NR	Recreational	34.07 (13.58) km/week	NR
Taddei, 2020	9/5	41.6 (6.0)	1.694 (9.18)	75.1 (13.9)	NR	Recreational	30.8 (13.4) km/week	10.9 (7.9)
Willy, 2011	0/10	22.7 (3.5)	NR	NR	22.3 (2.3)	Recreational	21.7 (8.5) km/week	NR

Note: Values reported as means with standard deviations in parentheses.

NR, not reported; M, male; F, female.

[a] Male and female participants indicate number who underwent strength training and do not reflect the entire sample when comparison groups were used.

males only.[51] One study included only competitive runners,[46] while the remaining studies included recreational runners. The average age of participants was 22–60 years. One study focused specifically on "older runners" (55–75 years of age).[50] Weekly running volume was reported in all but one study[10] with volumes of 8–90 km/week. Running experience was reported in only three studies.[47,50,51]

D. Study Characteristics

Seven[46–52] of the eight included studies used a comparison group to examine changes in running kinematics (Table 3). Six[46–48,50–52] studies used a randomized control design. In these studies, only the intervention group undergoing a strengthening intervention was included in this analysis. Six[10,46–50] studies included a measure of strength to assess the effectiveness of the strengthening intervention. Two studies had all strength-training exercise sessions supervised,[10,52] four studies[47–50] had one weekly supervised session with the remaining sessions being completed independently. One study had one supervised strength-training session for guided exercise instruction, with the remainder completed independently. Compliance was monitored using a self-reported training log.[46] One study did not report on the level of supervision used during the intervention.[51]

E. Intervention Characteristics

Seven different exercise protocols were used (Table 3). Two studies used the same protocol for foot-strengthening and were subanalyses registered to the same randomized control trial.[47,48] The range in duration of interventions was 6–10 weeks. Session frequency ranged from twice to six times weekly. Three studies completed the same exercises throughout the intervention period with no description of exercise progression or changes to resistance.[46,51,52] Three studies had participants complete the same group of exercises for the duration of the intervention but altered either the resistance or the position of the exercise to progress the exercise.[10,47,48] One study progressed exercise based on a predetermined schedule of increasing challenge.[50] And one study progressed exercise through a combination of a predetermined schedule of exercises and adjusting resistance.[49] Only three studies adjusted resistance in an individualized manner.[10,49,50]

F. Kinematic Changes

Due to study heterogeneity, a meta-analysis was not completed. Further, as no two studies were reported on the same sample of runners, strengthening programs varied across studies, and studies did not report the same variables, it was not possible to complete qualitative synthesis for a cumulative rating of evidence. Therefore, the effects of specific strengthening programs are presented as the results of single studies and a narrative review is provided. Effect sizes were calculated using Hedge's *g* to indicate the size of the effect when possible to aid in the interpretation of results in the absence of pooled findings. Effect sizes were classified as described in previous reviews[6,53] (very small:

TABLE 3: Intervention characteristics

Author, Year	Body area targeted	Strengthening exercises completed	Frequency	Volume	Resistance/ intensity	Duration	Supervision	Control group	Strength change
Day, 2019	Foot	foot curl, eccentric band curl, short foot, concentric band curl	3× week	30 reps/ exercise	NR	10 weeks	In-person instruction; independent completion; exercise log reported weekly	Y	↑ 27% toe flexors
Fukuchi, 2016	Lower extremity	Weeks 1-2: Side-lying hip abduction, calf raises, squats, half-lunges, seated IR/ER, lying hip extension Weeks 3–4: hip hike, calf raises (on step), single-leg half squat, standing hip IR/ER, lateral step down, half-lunges Weeks 5–6: standing hip abduction, single-leg calf raise, single-leg half squat, standing hip IR/ER, full lunges Weeks 7–8: hip extension at 45 degrees, single-leg calf raise, single-leg full squat, standing hip IR/ER, full lunges (single leg)	6× week	45 reps/ exercise	Resistance Bands RPE: 5–8/10	8 weeks	In-person instruction and weekly visit; independent completion; exercise log provided	Y	↔ hip abductors ↓ 10.5% hip extensors ↑ 10.3% ankle plantarflexors
Gottshall, 2019	Core and lower extremity	3 minutes: abdominal and oblique crunches, bridges 7 minutes: integrated core exercises (planks and hovers) 4 minutes: lower body strength (squats and lunges) 5 minutes: hip strength (adduction and abduction) 6 minutes: obliques (cross crawls and mountain climbers) 5 minutes: back (pointers and extension)	3× week	Defined by duration of exercise	NR	6 weeks	Supervised group classes	Y	NR

TABLE 3: (*continued*)

Letafatkar, 2019	Lower extremity	squats, lunges, hip abduction/extension rotation with elastic band, proprioception and foot coordination (standing on Busso ball, flex knees and lift heels; extend and then flex knees; lower heels)	3× week	30–45 reps/exercise	NR	8 weeks	NR	Y	NR
Snyder, 2009	Hip	Cable column “TOWARD” and “AWAY” exercises of a closed kinetic chain hip rotation; hip hike	3× week	1 set to failure	60% 1RM; increased by 1.13 kg if able to complete 12 reps and 2.27 kg if able to complete 30 reps	6 weeks	Supervised sessions	N	↑ 12.8% hip abductors ↑ 25.0% hip external rotators
Taddei, 2018	Foot/ankle	Heel raises, grasping cotton ball, rubber ball, and pen with toes, arch raises, short foot exercises, gait while grasping toes and with toes abducted	2–3× week	1–3 sets of 10–40 repetitions	Sitting, standing, and single-leg stance positions used as progression	8 weeks	Weekly supervised sessions; 2 independent sessions/week On-line training log completed	Y	↑ 12.1%–36.0% in hallux and toe flexor strength
Taddei, 2020	Foot/ankle	Heel raises, grasping cotton ball, rubber ball, and pen with toes, arch raises, short foot exercises, gait while grasping toes and with toes abducted	3× week	1–3 sets of 10–40 repetitions	Sitting, standing, and single-leg stance positions used as progression	8 weeks	Weekly supervised session; 3 independent sessions/week On-line training log completed	Y	↑ 9.6% toe flexor strength ↑ 8.8%–22.3% foot muscle CSA

TABLE 3: (*continued*)

Author, Year	**Body area targeted**	**Strengthening exercises completed**	**Frequency**	**Volume**	**Resistance/ intensity**	**Duration**	**Supervision**	**Control group**	**Strength change**
Willy, 2011	Hip	Week 1: side-lying hip ER/extension; hip abduction at wall Week 2: Clamshell; hip abduction at wall Week 3: squat with resistance band targeting ER; hip hike at wall Week 4: side-stepping with resistance band; single-leg squat with UE support Week 5: standing isometric hip abduction, ER, and pelvic hike at wall; single-leg squat with UE support Week 6: standing isometric hip abduction, ER, and pelvic hike at wall; single-leg squat with resistance band targeting hip abduction	3× week	2 sets of 10 reps/ exercise	Resistance bands with tension such that final repetitions could not be completed	6 weeks	1 supervised session/week; 2 independent sessions/week	Y	↑ 41.6% hip abductors ↑ 40.0% hip external rotators

CSA, cross-sectional area; ER, external rotation; NR, not reported; RPE, rating of perceived exertion; Y, yes; ↔, no change in pre- and posttest measures of strength; ↑, increased from pretest; ↓, decreased from pretest.

< 0.2, small: 0.2–0.49, medium: 0.5–0.79, large: 0.8–1.19, very large: 1.2–1.99, and huge: ≥ 2). Three studies did not provide enough statistical information to calculate effect sizes. Two of those studies[50,52] only reported graphical results and did not provide means or standard deviations to enable effect size to be calculated, while another study[48] reported only means with no standard deviations.

Two studies[49,50] examined kinematics of the trunk and/or pelvis (Table 4). One study suggested that a generalized lower extremity–strengthening program has no impact on sagittal plane trunk excursion, but may increase transverse plane trunk excursion[50] in older runners (55–75 years of age). Another study suggested that a hip-strengthening program does not alter pelvic drop in female runners ($g = 0.04$).[49]

Four studies[10,49,50,52] examined hip kinematics (Table 4). The results across studies were inconsistent for the effects of strengthening programs on peak hip adduction. A progressive hip-strengthening program resulted in no statistical change and small effect in peak hip adduction in female runners ($g = 0.37$),[49] while a generalized lower extremity–strengthening program resulted in an increase in peak hip adduction in male runners with a large effect size ($g = 0.93$).[51] Another study reported that a hip-strengthening program does not change peak hip internal rotation in female runners, despite a moderate effect size ($g = 0.55$).[49] Two studies had different findings on the effects of strengthening programs on frontal plane hip excursion.[10,50] In younger females, a closed kinetic chain hip-strengthening program resulted in an increase in frontal plane hip excursion, but the effect size was small ($g = 0.31$),[10] while a generalized lower extremity–strengthening program had no effect on frontal plane hip excursion in runners aged 55–75 years.[50] In young female runners, a closed kinetic chain hip-strengthening program did not lead to significant changes in transverse plane hip excursion and the effect size was small ($g = 0.47$).[10] One study[52] examined kinematic symmetry at the hip to report that a combined core- and lower extremity–strengthening program improved symmetry in sagittal plane hip excursion but had no effect on the symmetry of frontal plane hip excursion in recreational runners.

Four studies[10,49,51,52] examined knee kinematics (Table 4). Two studies[49,51] examined peak knee internal rotation yielding inconsistent results. Willy and Davis[49] reported no changes in peak knee internal rotation following a progressive hip-strengthening program in female recreational runners ($g = 0.42$), while Letafatkar et al.[51] showed that a generalized lower extremity–strengthening program decreased peak knee internal rotation in male recreational runners ($g = 0.21$). Each of these studies demonstrated small effect sizes. One study examined frontal plane knee excursion and reported that a closed kinetic chain hip-strengthening program does not affect frontal plane motion of the knee ($g = 0.19$).[10] One study examined kinematic symmetry at the knee and reported that a combined core- and lower extremity–strengthening program may improve sagittal plane knee symmetry but not frontal plane knee symmetry in recreational runners.[52]

Four studies[10,46,50,52] examined changes in ankle kinematics (Table 4). One study examined sagittal plane ankle excursion and reported that a generalized lower extremity–strengthening program increased ankle motion in runners aged 55–75 years.[50] One study reported that a foot-strengthening program may not affect plantarflexion velocity in

TABLE 4: Summary of results across all kinematic variables examined across studies

Author, year	Trunk Flex-Ext ROM	Trunk rotation ROM	Peak pelvic drop	Peak hip Abd	Peak hip IR	Hip Abd-Add ROM	Hip IR ROM	Peak knee IR	Knee Abd ROM	PF-DF ROM	PF velocity	Eversion at IC	Eversion ROM	Eversion velocity	MLA ROM	MTPJ ROM
Foot-strengthening programs																
Day, 2019											↔					↔
Taddei, 2018																↕
Taddei, 2020															↔	
Hip-strengthening programs																
Snyder, 2009						↑	↔		↔			↔	↓	↔		
Willy, 2011			↔	↔	↔*			↔								
Generalized lower extremity–strengthening																
Fukuchi, 2016	↔	↑				↔				↑						
Letafatkar, 2020				↓**				↓								
Gottschall, 2019[a]																

Abd, abduction; Abd-Add, abduction-adduction; Add, adduction; Flex-Ext, flexion-extension; IC, initial contact; IR, internal rotation; MLA, medial longitudinal arch; MTPJ, metatarsophalangeal joint; PF, plantarflexion; PF-DF, plantarflexion-dorsiflexion; ↕, variable effect after strengthening; ↔, no change after strengthening; ↑, increased after strengthening; ↓, decreased after strengthening.

*, moderate effect size (Hedge's *g*).

**, large effect size (Hedge's *g*).

[a] Reported on motion symmetry finding improved symmetry for sagittal plane motion at the ankle, knee, and hip.

Empty cells indicate the study did not investigate the variable in the respective column.

competitive runners ($g = 0.13$).[46] Another investigated the effect of a closed kinetic chain hip-strengthening program on ankle motion in female runners and reported no changes in eversion angle at initial contact ($g = 0.11$) or eversion velocity ($g = 0.24$), but eversion range of motion was decreased ($g = 0.46$).[10] Lastly, a combined core- and lower extremity–strengthening program may improve sagittal plane ankle range of motion symmetry, but not frontal plane ankle range of motion symmetry in recreational runners.[52]

Three studies[46–48] examined changes in foot kinematics (Table 4). One study reported that a foot-strengthening program may not alter medial longitudinal arch range of motion in recreational runners ($g = 0.25$),[47] while another study provided very limited evidence that a different foot-strengthening program has no effect on metatarsophalangeal joint range of motion in competitive runners ($g = 0.15$).[46] One study did provide very limited evidence that a foot-strengthening program may have variable effects on metatarsophalangeal joint motion in recreational runners.[48] However, no systematic or statistical change was noted, and means and standard deviations were not reported, precluding any effect size calculations.

G. Strengthening Programs

All three[46–48] foot-strengthening programs demonstrated improvements in toe flexor strength, and one study showed concomitant increases in foot muscle cross-sectional area.[47] These combined results were inconsistent on the effectiveness of foot strengthening in altering metatarsophalangeal joint range of motion, and one study provided evidence that foot-strengthening programs had no effect on medial longitudinal arch range of motion and plantarflexion velocity during running (Table 4).

The two studies investigating hip-strengthening programs each demonstrated improved hip abduction and external rotation strength.[10,49] These studies[10,49] indicated that hip-strengthening programs may increase frontal plane hip excursion during running and decrease eversion range of motion, but may not affect peak pelvic drop, peak hip adduction angle, peak hip internal rotation, hip internal rotation range of motion, peak knee internal range of motion, knee abduction range of motion, eversion angle at initial contact, or eversion velocity (Table 4).

One generalized lower extremity–strengthening program demonstrated no change in hip abductor strength, reduced hip extensor strength, and increased plantar flexion strength, while the other study did not report changes in strength.[50,51] These studies[50,51] indicated that generalized lower-extremity strengthening may increase trunk rotation excursion and ankle sagittal plane excursion, decrease peak hip adduction and peak knee internal rotation, and may not affect trunk flexion/extension excursion and frontal plane hip excursion during running (Table 4).

One study[52] examining a combined core- and lower extremity–strengthening program did not report on the changes in strength achieved, yet provided some evidence that this program may improve sagittal plane range of motion symmetry of the hip, knee, and ankle during running. The same study indicated that this program may not affect frontal plane range of motion symmetry of the hip, knee, or ankle (Table 4).

IV. DISCUSSION

The purpose of this review was to systematically review the effects of strengthening exercise programs on running kinematics. The review indicated that the overall body of evidence investigating this topic was limited, the methodologies employed differed, the strengthening programs described varied, and the sample sizes were generally small. Therefore, the current literature on this research question largely prohibits any synthesis across studies and therefore limits any definitive conclusions. As strengthening programs remain an important part of training and rehabilitation,[12] this review highlights the need for further work in understanding the role of strength and strength training on running kinematics and its potential use in injury risk reduction and rehabilitation.

A. Effects of Strengthening Programs on Running Kinematics

In summarizing the overall effect of strengthening programs on running kinematics, there was largely inconclusive evidence for the use of strengthening exercise to alter running kinematics. The changes that were reported appear to vary with the program used, and kinematics may not change in the manner anticipated. Most kinematic variables investigated showed no change following 6–10 weeks of strengthening exercise. However, it cannot be ignored that certain running kinematics did change following the completion of some strengthening programs.

From the review of available literature on muscle strength and running kinematics, it seems reasonable to conclude that simply strengthening muscles involved in a particular motion during running may not alter that motion. For example, increasing hip abductor muscle strength may not lead to reduced hip adduction during the stance phase of running. Willy and Davis[49] investigated a progressive strengthening program including both open and closed kinetic chain exercises in a group of female runners demonstrating increased hip adduction during stance. Despite the runners completing a six-week program and demonstrating an increase in isometric hip strength, running kinematics about the hip remained unchanged. However, this is not to say that completing any type of hip-strengthening (or generalized lower extremity–strengthening) program will not affect a runner's kinematics at all. Snyder et al.[10] reported that a closed kinetic chain hip-strengthening program may lead to changes in running kinematics. Interestingly, however, they showed that hip adduction excursion *increased* despite a concomitant increase in hip abductor strength. These authors did not report peak hip adduction, so it is impossible to determine if this variable changed in a similar manner. Snyder et al.[10] also noted a trend toward a reduction in hip internal rotation excursion ($p = 0.08$, $g = 0.47$) and, although these findings were not statistically different, peak internal rotation was reduced in the study by Willy and Davis[49] with a moderate effect size ($g = 0.55$). In addition, Snyder et al.[10] reported a reduction in eversion range of motion indicating the possibility that kinematic changes may be present at joints distal to the area targeted with strengthening exercise. Since the lower extremity functions as a linked system during the stance phase of running, it is conceivable that either proximal or distal changes in kinematics may occur following the completion of a strengthening program.

Similar results were observed in foot-strengthening programs. Despite there being no definite effect of foot-strengthening programs on foot kinematics, one study[48] noted that there was a "high degree of inter-subject variability" in kinematic measures following an eight-week program, allowing the potential for some change to be present but not detected. Additionally, none of the three studies[46–48] investigating foot-strengthening programs reported any potential changes in kinematic measures proximal to the ankle. Therefore, any changes that could have occurred at the knee or hip may have gone undetected.

When considering the results of generalized lower extremity programs, as opposed to those targeting a specific body region, it appears that more changes were detected. Fukuchi et al.[50] reported increased trunk rotation and increased plantarflexion following completion of their program in older runners, and Letafatkar et al.[51] reported reductions in both peak hip adduction and knee internal rotation in male runners after completing their strengthening program. Given the associations of these kinematic variables to RRI in female runners,[1,6] it would seem that investigating a similar effect in female runners would be an important area for further research. Further, a combined core- and lower extremity–strengthening program showed improved sagittal plane symmetry during running, although frontal plane symmetry was not affected.[52] The combined results of these studies seem to indicate that more generalized lower extremity strengthening may yield more consistent changes in running kinematics as opposed to regional specific strengthening. However, this needs further confirmation from additional studies.

Nonetheless, the overall effect of strengthening programs is unclear. One may hypothesize individual responses to strengthening programs that depend on each person's prior level of experience with strengthening,[54,55] their initial fitness level and capacity for strength increases,[55,56] their individual kinematic profile during running,[57,58] and how the specific exercises selected are incorporated into their unique motor program/movement signature[59,60] may be contributing to the inconsistency of results.

Further, when to consider a runner "weak" is unknown. We are aware of only one study[61] that investigated normative values for hip abduction strength in recreational runners to assist in making this determination. Yet in the studies included in this review, only one specified that participants were *not* to have had any previous strengthening experience[52] but no qualifications that participants were to be considered "weak" was made in any of the included studies. Thus, it is possible that if runners demonstrate a certain amount of "weakness" they may respond more favorably to efforts from strengthening programs to alter their running kinematics. However, this is a question that has yet to be investigated and requires further research to elucidate. In light of these questions, it is clear that there are several methodological limitations within the studies reviewed that also hinder formulating a clear conclusion on this topic.

B. Methodological Limitations

Several important differences in methodology across studies should be noted. First, there was very little overlap in the running kinematics reported across studies. For example, only four variables were consistently reported by more than one study and no more than two studies reported on the same kinematic variable (Table 4). These factors precluded examination of any pooled effects of strengthening exercise on running kinematics. Further, no study included a comprehensive kinematic analysis of the lower extremity, making it possible that kinematic changes may have occurred but were undetected. The effect of strengthening exercise on running kinematics is an area needing further investigation. This would seem critical to understanding how strengthening programs could be used to address aberrant running kinematics that may be associated with injury risk.

Discrepancies in results across studies may also be due to the differing manner in which exercises were employed within each strengthening program (Table 3). Willy and Davis[49] used a predetermined exercise progression, moving from only open kinetic chain exercises to a combination of open and closed kinetic chain exercises with increased resistance. Exercises were progressed in all participants on a weekly basis. Snyder et al.,[10] on the other hand, used only three strengthening exercises throughout their program and increased resistance in an individualized manner. Fukuchi et al.[50] used a program for the entire lower extremity that progressed both open and closed kinetic chain exercises every other week. Letafatkar et al.[51] used a consistent program for eight weeks that consisted of a combination of open and closed kinetic chain exercises. These differences make it difficult to compare results across studies and hence difficult to draw any conclusion beyond the specific strategy employed within each study.

Another consideration is the variability in running population studied (Table 2). Four of the eight studies included a mixed-sex sample[46–48,52]; one did not report the sex of participants,[50] two included only females,[10,49] and one only males.[51] As a runner's sex appears to impact elements related to running kinematics,[62,63] it would seem important to consider how mixed-sex samples may influence the findings of a study and whether or not results from a male population are generalizable to a female population. The age of study populations is another factor which may influence the interpretation of results. There was a considerable range in the average age reported in the studies (22–60 years). One study specifically targeted an older population where included runners were between the ages of 55 and 75.[50] As running biomechanics appear to change with age,[64] it is questionable to what extent findings in older populations may be applicable to those of younger ages.

Lastly, the sample sizes in these studies ranged from 6 to 36 participants (Table 2). Only four studies reported an *a priori* sample size calculation,[10,48–50] which raises the question of how many of these studies were powered sufficiently to confidently conclude that no changes occurred in the variables investigated. For example, Snyder et al.[10] reported results for internal rotation excursion approaching significance ($p = 0.08$) and effect size near moderate ($g = 0.47$). This raises the question of whether this change would have been detected if there had been more participants. Similarly, Willy et al.[49] reported no change in peak hip internal rotation, but the 2° reduction in the training group did have a moderate effect size. Had more participants been included would this effect have reached significance? Also, if one considers that the reliability of hip and knee rotation is less than that of other joints and the standard error of measure is estimated as greater than 5° for these motions,[65] it seems important to consider whether the lack of differences found for transverse plane motions of the hip and knee is truly due to no differences being present or due to the greater measurement error which can occur during these motions. Continued work appears necessary in this area of research.

C. Suggestions for Clinical Integration

As the current evidence informing how strengthening programs may affect running kinematics is inconclusive, it is important that clinicians neither oversell nor underappreciate the potential benefits of strength training and how it may affect running kinematics. This is a challenging area to navigate in the presence of limited evidence. Thus, it may be important to distinguish between the *presence* of strength, how strengthening *exercise* is performed to address deficits, and the *transfer* of neuromuscular characteristics from strengthening exercise to the skilled performance of running.

Six[10,46–50] of the eight studies included in this review also reported changes in strength of the hip or foot based on force output, while only two[10,50] of those studies also documented systematic changes in running kinematics. This would seem to indicate that the mere increase in capacity of the hip or foot musculature to produce force may not result in a change in running kinematics. Similarly, a reduction in strength may not lead to systematic changes in kinematics. Bazett-Jones et al.[66] reported a significant reduction in hip abductor strength after an exhaustive run with no associated increase in hip adduction. This is also seen in the multitude of studies that have not found a consistent relationship between lower-extremity strength and running kinematics.[31–37] Thus, it seems reasonable to conclude that simply increasing the *presence* of strength in the lower-extremity muscles may not be a primary determinant of running kinematics.

How strengthening *exercise* is performed, however, may be an important factor in determining its effects on running kinematics. The four studies[10,50–52] in this review that reported consistent changes in running kinematics all used strengthening programs that included closed kinetic chain exercises which remained consistent throughout the study period. The other strengthening programs included non-weight-bearing foot exercises or a predetermined progression through a series of open and closed kinetic chain exercises. The use of closed kinetic chain exercises that place the performer in positions required during running may promote greater transfer to the task of running. Indeed, Wouters et al.[13] investigated the effectiveness of a movement retraining program aimed at altering frontal plane running mechanics and reported that runners showed less knee abduction following four weeks of training. This program used structured feedback on participants' form during exercise and focused on neuromuscular control aspects of training while utilizing a common array of "strengthening" exercises. Thus, the type and structure of feedback on movement performance may also influence how strengthening exercise affects running kinematics.

The *transfer* of neuromuscular characteristics from strengthening exercise to skilled performance is another factor to consider. Although strength is viewed as a vital component of athletic performance, strengthening through traditional exercise is still believed among coaches and elite athletes to have limited carryover to skilled performance.[41] Running is a skilled and repetitive task that requires the coordination of many muscles crossing multiple joints to achieve a specific outcome. The coordination strategy developed in runners is likely the product of thousands of strides that have led to a habitual pattern[58] within a preferred pathway determined by the runner's unique anatomical, physiological, and behavioral constraints.[7,57,67,68] Changing this pattern may take dedicated effort on the part of both the clinician and the runner. This is evidenced by many gait-retraining strategies often using up to four sessions per week over a period of two to six weeks.[14,69] Yet the retention of kinematic changes from such gait-retraining interventions beyond the initial instruction period is largely unknown.[14,30] Thus, a runners "preferred" kinematics appear to be relatively robust to changes imposed upon it.

Consequently, the selection of exercises used for strengthening may be more important than the amount of resistance used or the amount of strength gained. This may explain why some studies[10,48,50–52] have reported changes in running kinematics while others[46,47,49] have not. It may also provide insight into why some movement-training programs have been effective.[13,40,55] If this premise is true, it may prove useful in situations where symptoms or pathology are severe enough to preclude an athlete's participation in running (i.e., following ACL reconstruction or stress fracture). The potential for strengthening to develop the muscular capacity to accommodate and tolerate increased loads during running may be another important factor in running rehabilitation and training.[12,14]

D. Future Directions

There is a clear need for further research on the role of strengthening programs and the use of resistance exercises to alter running kinematics. Distinguishing between the type of exercise, the amount of resistance and/or intensity of exercise, the feedback provided while training, the duration of exercise required, and the transfer of exercises across tasks are areas where knowledge gaps exist. Further, studies in homogenous populations that give consideration to age and sex with adequate sample sizes will be important in the future. These continue to be important areas of research to help identify optimal ways to rehabilitate, as well as reduce the risk of RRI.

V. CONCLUSION

There is a limited body of evidence on the role of strengthening exercise and its effects on running kinematics. No definitive conclusions can be drawn from the results of the reviewed studies, which highlights the need for further research. The type and intensity of strengthening exercises used and the population of runners investigated may be factors in the inconsistency of findings. The current literature on the efficacy of strengthening programs in changing running kinematics is uncertain. Caution is warranted when attempting to implement strengthening exercises to alter running kinematics, but their efficacy in changing running kinematics cannot be ruled out. Further research is needed to inform clinical implementation of the role of strengthening programs in altering running kinematics.

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