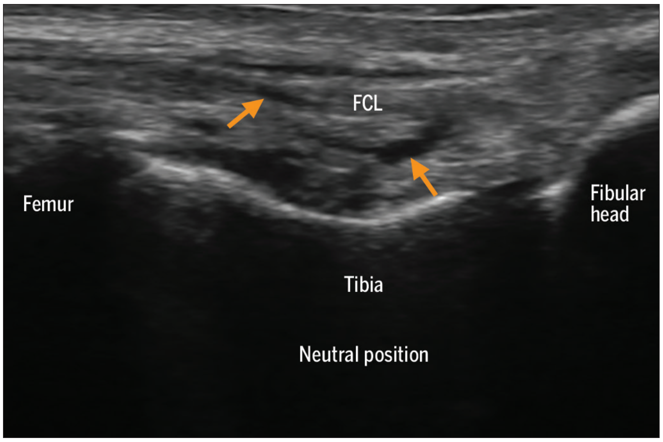

FIGURE 1. Long-axis ultrasound image of the fibular (lateral) collateral ligament (FCL) of the knee at rest in 0° of flexion. The injured ligament shows inconsistency of thickness, along with small hypoechoic foci suggestive of ligament disruption and fluid.

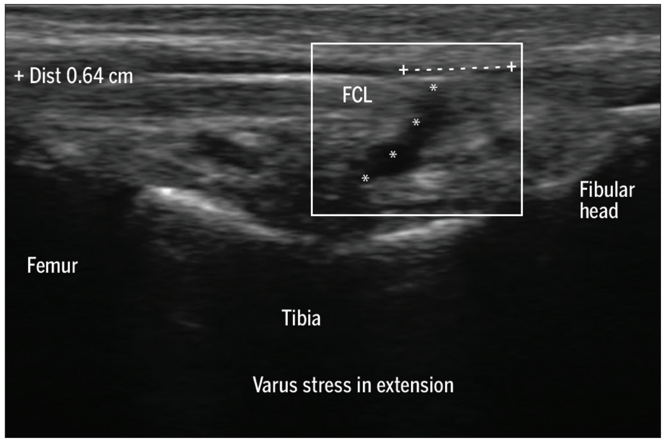

FIGURE 2. Long-axis dynamic ultrasound image of the fibular (lateral) collateral ligament (FCL), with varus stress, in 0° of flexion. Expansion of the hypoechoic area up to 0.64 cm, extending to the surface with diffuse hypoechogenicity, suggests laxity and disruption of the ligament fibers.

Use of Dynamic Ultrasound Imaging for Assessment of the Fibular Collateral Ligament of the Knee

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A 25-YEAR-OLD MALE COLLEGE STUdent reported planting and cutting with his left foot while playing recreational basketball and felt an immediate sharp pain in the lateral aspect of his left knee. Because of continued pain and intermittent buckling after 2 months of rest, ice, and anti-inflammatory drugs, he sought a direct-access consultation by a physical therapist to determine whether an orthopaedic referral was necessary.

Clinical examination revealed full knee range of motion, with tenderness of the lateral aspect of the joint. Following a positive Lachman test for the anterior cruciate ligament, examination of the fibular (lateral) collateral ligament (FCL) was performed. Varus stress testing at 0° and 30° of knee flexion was positive. Due to the superficial nature of the FCL, static (**FIGURE 1**) and dynamic (**FIGURE 2**) ultrasound imaging with a multifrequency, 5- to 12-MHz linear transducer in long axis was used to visualize the FCL. Dynamic imaging with varus stress was performed with the assistance of a second physical therapist. Small hypoechoic foci suggestive of ligament disruption and surrounding fluid were present in the static image, which markedly expanded with dynamic varus stress imaging (**ONLINE VIDEO**).

Complementing the clinical examination findings, use of dynamic imaging strengthened the differential diagnosis of multidirectional laxity and supported the clinical decision of referral. Subsequent follow-up magnetic resonance imaging confirmed tears of the anterior cruciate ligament and FCL, resulting in surgical intervention. Dynamic imaging techniques have the potential to improve ligament characterization[1] in the clinical setting, helping to guide the clinical decision-making process. *J Orthop Sports Phys Ther 2019;49(3):210. doi:10.2519/jospt.2019.8460*

Reference

1. Hodgson RJ, O'Connor PJ, Grainger AJ. Tendon and ligament imaging. *Br J Radiol*. 2012;85:1157-1172. https://doi.org/10.1259/bjr/34786470

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Knee Function, Strength, and Resumption of Preinjury Sports Participation in Young Athletes Following Anterior Cruciate Ligament Reconstruction

BACKGROUND: Following anterior cruciate ligament reconstruction (ACLR), young athletes demonstrate deficits in knee function and strength whose association with successful return to preinjury sports participation is not well understood.

OBJECTIVES: To examine differences in knee function and strength at the time of return-to-sport clearance between young athletes who successfully resumed preinjury sports participation, those who did not resume preinjury sports participation, and those who sustained a second anterior cruciate ligament (ACL) injury by 1 year following return-to-sport clearance.

METHODS: This prospective cohort study collected data in 124 young athletes (mean $\pm$ SD age, 17.1 $\pm$ 2.4 years) at the time of return-to-sport clearance post ACLR. Measures included the Knee injury and Osteoarthritis Outcome Score (KOOS), single-leg hop tests, isokinetic quadriceps and hamstring strength, and limb symmetry during hop tests and strength tests. Participants were allocated to 3 groups: resumed preinjury sports participation (Tegner score), did not resume preinjury sports participation, or sustained a second ACL injury. Group differences were compared using Kruskal-Wallis tests and Mann-Whitney *U* post hoc tests.

RESULTS: Seventy (56%) participants successfully resumed preinjury sports participation and 26 (21%) sustained a second ACL injury by 1 year post return-to-sport clearance. Participants who successfully resumed preinjury sports participation demonstrated greater absolute performance at return-to-sport clearance in the involved and uninvolved limbs on the triple hop (P = .007 and P = .004, respectively) and the crossover hop (P = .033 and P = .037, respectively), and in the involved limb on the single hop (P = .043), compared to those who did not (n = 28). Participants who sustained a second ACL injury demonstrated greater absolute performance at return-to-sport clearance in the involved and uninvolved limbs on the triple hop (P = .034 and P = .027, respectively) compared to those who did not resume preinjury sports participation. There were no group differences between those who successfully resumed preinjury levels of sports participation and those who sustained a second ACL injury.

CONCLUSION: Following ACLR, the small proportion of young athletes who successfully resumed preinjury levels of sports participation 1 year after return to sport demonstrated greater absolute functional performance at the time of return-to-sport clearance. No differences were identified between those who successfully resumed preinjury sports participation and those who sustained a second ACL injury. Measures of limb symmetry did not differ among any of the groups.

LEVEL OF EVIDENCE: Prognosis, level 2b.
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KEY WORDS: *ACL reconstruction, knee function, sports participation*

Young athletes commonly sustain anterior cruciate ligament (ACL) injury, and anterior cruciate ligament reconstruction (ACLR) is usually performed to restore functional joint stability and enable return to sports participation.[9,10] However, a large body of evidence demonstrates that many active individuals after ACLR are unable to return to participating in sports at their preinjury level.[1-4,6] Previous studies found that, when examining return to preinjury sports at all competition levels, only 31% had returned at 1 year,[3] only 41% had returned at 2 years,[4] and only 63% had returned at any time after ACLR.[7] Additionally, examining return to competitive-level sports, only 33% to 55% of athletes were able to return to sport after ACLR.[1,6,7] Several factors associated with successful return to sport after ACLR have been reported, including higher confidence and less fear of reinjury,[3,4,17] higher knee function and strength,[4,6,29] and less knee pain, symptoms, and instability.[17,29] Importantly, in

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young athletes who are able to return to sport after ACLR, the risk of sustaining additional knee injury, including a second ACL injury, is high.[19,36,37,48]

In line with the suboptimal return-to-sport and second-injury outcomes after ACLR, deficits in knee function and strength are also commonly reported at the time of, and following, return-to-sport clearance.[8,20,22,31,35,42,43] At the time of return to sport, individuals who have undergone ACLR report deficits in function on the Knee injury and Osteoarthritis Outcome Score (KOOS),[22] and demonstrate deficits in knee-related functional performance on single-leg hop tests.[31,35,43,45] In addition, following ACLR, deficits in KOOS scores may persist for up to 2 years or more.[8,20] Examining muscle strength, individuals after ACLR demonstrate persistent deficits in both quadriceps femoris and hamstring strength over time following ACLR.[5,22,27,43,45]

While previous studies have examined the association between knee-related function and strength and the ability to return to sport after ACLR,[4,6,17,29] these associations have not been examined in a specific cohort of young, high school–aged athletes planning to return to high-level cutting and pivoting sports. In light of the low proportion of young athletes who return to sports participation and the high risk of second injury after ACLR, a better understanding of clinical factors at the time of the important decision to clear athletes for return to sport and their association with successful return to, and maintenance of, preinjury levels of sports participation is needed. The purpose of this study was to examine differences in knee function and strength at return-to-sport clearance between young athletes who successfully resumed preinjury levels of sports participation following ACLR, those who did not resume preinjury sports participation following ACLR, and those who sustained a second ACL injury over the year following return-to-sport clearance. The hypothesis tested was that young athletes after ACLR who successfully resumed preinjury sports participation 1 year post return-to-sport clearance would demonstrate greater self-reported knee function, greater knee-related functional performance, and greater muscle strength at the time of return to sport than those who did not resume sports and those who sustained a second ACL injury.

METHODS

Participants

The current work included participants from a previous study (ACL REconstruction Long-term outcomes in Adolescents and Young adults [ACL-RELAY])[21,22,37,43,46] enrolled from 2007 to 2017. The ACL-RELAY study is an ongoing, prospective study evaluating outcomes in young athletes after ACLR at Cincinnati Children's Hospital Medical Center. Participants in the ACL-RELAY study were recruited from orthopaedic surgeon practices and physical therapy clinics in the greater Cincinnati and northern Kentucky areas at the time of return-to-sport clearance after primary, unilateral ACLR. To be enrolled, participants had to have been previously cleared to return to sport by their orthopaedic surgeon and rehabilitation specialist, and to have planned to return to regular participation in cutting and pivoting sports (greater than 50 hours per year). The ACL-RELAY study did not control rehabilitation or the decision of return-to-sport clearance, and baseline testing took place within 4 weeks after each participant's return-to-sport clearance. Potential participants were excluded for the following reasons: (1) a history of low back pain or lower extremity injury or surgery in either limb (other than their primary ACL injury) requiring the care of a physician in the past year, or (2) sustaining a concomitant knee ligament injury (beyond grade 1 medial collateral ligament injury) with their primary ACL injury. The ACL-RELAY study included participants with a variety of graft types, including hamstring tendon autograft, bone-patellar tendon-bone autograft, and allograft. Additionally, it included participants with and without meniscus repair or partial meniscectomy at the time of ACLR. The current analysis excluded participants with a modified ACLR procedure due to open epiphyseal plates in the tibia and/or femur and those with a history of bilateral or multiple ACL injuries. Additionally, the present analysis included participants who completed baseline testing at the time of return-to-sport clearance to evaluate knee function, strength, and sports participation, as well as testing at a visit 1 year post return-to-sport clearance to re-evaluate sports participation (**FIGURE 1**). Twenty-four participants (16%) who completed baseline testing at the time of return-to-sport clearance were lost to follow-up prior to the visit 1 year post return to sport (**FIGURE 1**). All participants provided informed consent or parental permission/assent (when younger than 18 years of age) prior to participating in the ACL-RELAY study. All study procedures were approved by the Cincinnati Children's Hospital Medical Center Institutional Review Board.

Measurement of Knee-Related Function at Return-to-Sport Clearance

Self-reported Function Self-reported knee function was assessed using the KOOS. The KOOS is made up of 5 subscales evaluating different constructs of knee-related function, including pain, other symptoms, function in daily living, function in sport and recreation, and knee-related quality of life.[39-41] Total scores for each subscale range from 0 (worst knee function) to 100 (no knee-related problems).[39,40] The KOOS is a valid and reliable measure in individuals after ACLR,[39-41] with a minimal detectable change of 6.1 to 8.5 points, depending on the subscale.[39-41]

Knee-Related Functional Performance Knee-related functional performance was evaluated using single-leg hop tests. Three single-leg hop tests for maximum distance were performed on both the involved and uninvolved limbs in the following order: the single hop (centimeters), the triple hop (centimeters), and the crossover hop (centimeters). The single hop involves 1 maximal-distance jump forward, the triple hop involves 3 consecutive maximal-distance jumps forward, and the crossover hop involves 3 consecutive maximal-distance jumps forward while simultaneously crossing horizontally over a line. For a trial to be considered valid, the participant had to control the landing. The average hop distance from 2 trials on each limb was normalized to height (centimeters) and used to calculate the limb symmetry index (LSI): (involved value/uninvolved value) × 100%.

The single-leg distance hop test has been shown to be a valid and reliable measure of knee-related functional performance after ACLR,[11,13,38] with minimal detectable change values on the LSI of 8% to 13%.[38]

Quadriceps Femoris and Hamstring Strength Assessment at Return-to-Sport Clearance

Quadriceps femoris and hamstring muscle strength were measured using an isokinetic dynamometer (Biodex Medical Systems, Shirley, NY), with the participant positioned as previously described.[22,42,43] Isokinetic strength testing of the quadriceps femoris and hamstring muscles was performed at 180°/s and 300°/s, from 90° of knee flexion to full extension.[14,25] Participants performed 5 trials at 180°/s and 10 trials at 300°/s on each limb. The peak torque values from these trials were calculated for each condition for both limbs and normalized to each participant's body mass (Newton meters per kilogram). Quadriceps femoris and hamstring strength LSIs were calculated with the same equation used for the hop tests. Isokinetic quadriceps femoris and hamstring strength testing has been able to detect limb strength asymmetries and has demonstrated good reliability in individuals after ACLR.[13,15,16,23,24,34] Additionally, performing isokinetic strength testing at varying speeds is recommended after ACLR to assess different muscle performance characteristics of the quadriceps femoris and hamstring musculature.[14,25]

Tegner Activity Scale Scores and Maintenance of Preinjury Sports Participation

Sports participation was assessed using the Tegner activity scale.[44] The Tegner activity scale is a numeric scale scored from 0 to 10.[44] Each value on the Tegner scale indicates the ability to perform at a specific sport-related level of activity (10, participation in competitive sports at a national level; 6, participation in recreational sports; 0, on sick leave or disability due to knee problems).[44] The Tegner activity scale is reliable and valid in individuals with ACL injury and other knee injuries.[12,44] The Tegner activity scale was completed regarding preinjury activity level at the time of return-to-sport clearance, and again at 1 year post return-to-sport clearance regarding participants' activity level at that time. Successful resumption of preinjury sports participation at 1 year post return-to-sport clearance was defined as reporting the same or higher Tegner score at 1 year post return-to-sport clearance compared with the preinjury score. Participants who sustained a second ACL injury prior to 1 year post return-to-sport clearance were included as a third group for comparison (**FIGURE 1**).

Statistical Analysis

Prior to performing statistical analyses, data normality was examined across the entire cohort as well as within the 3 groups (successfully resumed preinjury sports participation, did not resume preinjury sports participation, second ACL injury) using histograms and quantile-quantile plots. Equal group variance was confirmed between the groups using Levene's tests. All KOOS data were found to be nonnormal and could not be successfully transformed with natural log and square-root transformations to meet the normality assumption. Due to nonnormality, Kruskal-Wallis tests and chi-square tests (continuous and categorical data, respectively) were used to compare demographic data, KOOS scores, single-leg hop performance, and quadriceps femoris and hamstring strength at return-to-sport clearance among the groups (successfully resumed, did not resume, second ACL injury), using an alpha level of .05. When significant group differences were identified, post hoc testing was performed using Mann-Whitney *U* tests between individual groups. All statistical analyses were performed using SPSS Version 24.0 (IBM Corporation, Armonk, NY).

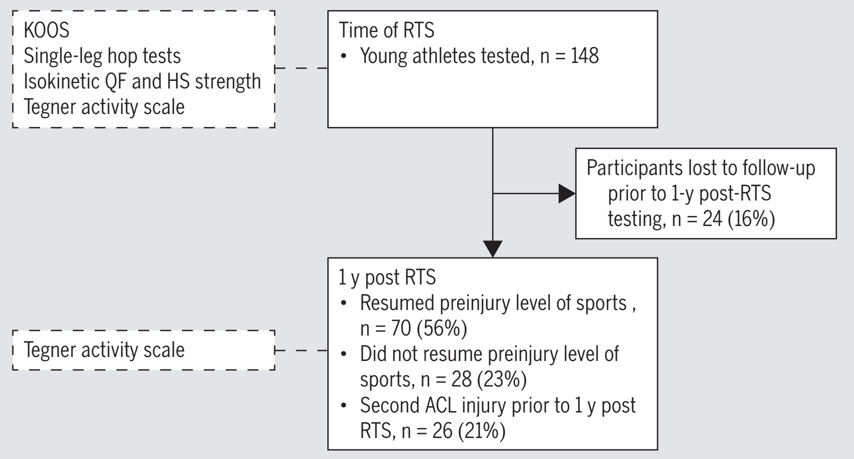

FIGURE 1. Cohort flow chart and testing time points. Abbreviations: ACL, anterior cruciate ligament; HS, hamstrings; KOOS, Knee injury and Osteoarthritis Outcome Score; QF, quadriceps femoris; RTS, return-to-sport clearance.

RESULTS

OF THE PARTICIPANTS WHO COMPLETED testing at the time of return-to-sport clearance and were not lost to follow-up, 70 (56%) successfully resumed and 28 (23%) did not resume their preinjury level of sports participation 1 year later (**FIGURE 1**). Twenty-six participants (21%) sustained a second ACL injury prior to 1 year post return-to-sport clearance (**FIGURE 1**). The groups did not differ by sex, graft type distribution, meniscus injury proportions, time from surgery to return-to-sport clearance, or preinjury Tegner activity scale scores (**TABLE 1**). The individuals who sustained a second ACL injury were younger than those who successfully resumed sports (post hoc *P* = .024) and those who did not resume sports (post hoc *P* = .028) (**TABLE 1**).

The groups did not differ in their scores on the KOOS subscales of pain (*P* = .689), other symptoms (*P* = .635), function in daily living (*P* = .413), function in sport and recreation (*P* = .515), or knee-related quality of life (*P* = .439) (**FIGURE 2**). Regarding the single hop, participants who successfully resumed sports demonstrated greater absolute involved-limb performance (normalized to height) compared to those who did not resume sports (*P* = .043) (**FIGURE 3**). There were no differences in absolute involved-limb single hop performance between those who sustained a second ACL injury and those who successfully resumed sports (*P* = .982) and did not resume sports (*P* = .094) (**FIGURE 3**). Additionally, there were no differences among the groups in absolute uninvolved-limb single hop performance (*P* = .133). Regarding the triple hop, participants who successfully resumed sports and those who sustained a second ACL injury demonstrated greater absolute involved-limb performance compared to those who did not resume sports (*P* = .007 and *P* = .034, respectively) (**FIGURE 3**). Similarly, those who successfully resumed sports and those who sustained a second ACL injury demonstrated greater absolute uninvolved-limb performance compared to those who did not resume sports (*P* = .004 and *P* = .027, respectively) (**FIGURE 3**). Regarding the crossover hop, participants who successfully resumed sports demonstrated greater absolute performance compared to those who did not resume sports for the involved limb (*P* = .033) and the un-

TABLE 1 PARTICIPANT DEMOGRAPHIC DATA

	Successfully Resumed (n = 70)	Did Not Resume (n = 28)	Second Injury (n = 26)	*P* Value
Sex, n (%)				.729
Male	19 (27)	7 (25)	5 (19)	
Female	51 (73)	21 (75)	21 (81)	
Graft type, n (%)				.704
Hamstring autograft	32 (46)	17 (61)	14 (54)	
BPTB autograft	33 (47)	10 (36)	10 (38)	
Allograft	5 (7)	1 (3)	2 (8)	
Meniscus injury, n (%)				.784
Yes	35 (50)	14 (50)	11 (42)	
No	35 (50)	14 (50)	15 (58)	
Age at RTS clearance, y*	17.3 ± 2.7	17.6 ± 2.5	16.1 ± 1.2	.044†
Time from surgery to RTS clearance, mo*	8.2 ± 2.6	8.3 ± 2.3	8.1 ± 1.8	.958
Preinjury Tegner score*	8.9 ± 0.7	8.9 ± 0.8	8.7 ± 0.8	.391

Abbreviations: BPTB, bone-patellar tendon-bone; RTS, return to sport.
**Values are mean ± SD.*
†Participants in the second injury group were significantly younger than those who successfully resumed and did not resume sport.

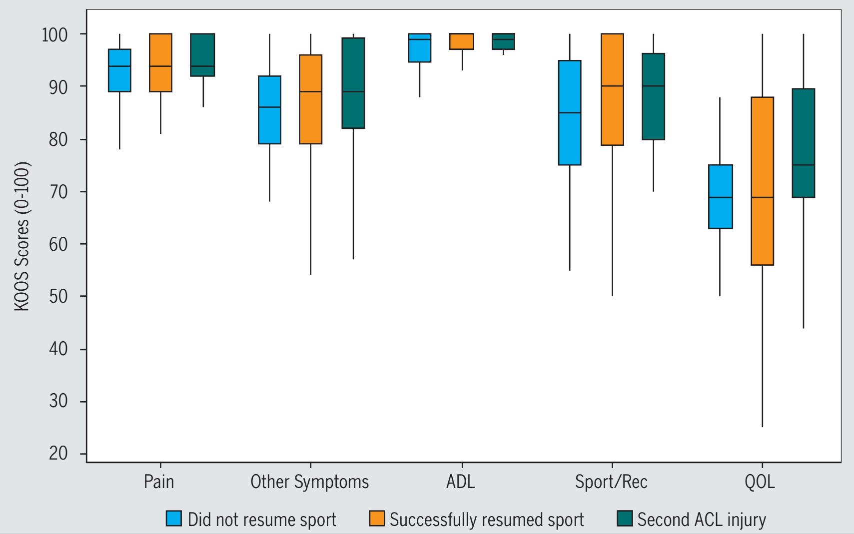

FIGURE 2. Return-to-sport KOOS score comparison between groups. Data are presented as box plots for the group of participants who did not resume (n = 28), successfully resumed (n = 70), and sustained a second injury (n = 26). The bars represent the highest and lowest values for each measure within each group, the middle line represents the median value, the top of the box represents the first quartile, and the bottom of the box represents the third quartile. Abbreviations: ADL, function in daily living; KOOS, Knee injury and Osteoarthritis Outcome Score; QOL, knee-related quality of life; Sport/Rec, function in sport and recreation.

involved limb (*P* = .037) (**FIGURE 3**). There were no differences in absolute involved-limb or uninvolved-limb crossover hop performance between those who sustained a second ACL injury and those who successfully resumed sports (*P* = .569 and *P* = .551, respectively and those who did not resume sports (*P* = .149 and *P* = .109, respectively) (**FIGURE 3**).

The groups did not differ in involved-limb or uninvolved-limb isokinetic peak torque (Newton meters per kilogram) for the quadriceps femoris muscles at 180°/s (*P* = .665 and *P* = .892, respectively), quadriceps femoris muscles at 300°/s (*P* = .481 and *P* = .533, respectively), hamstring muscles at 180°/s (*P* = .163 and *P* = .755, respectively), or hamstring muscles at 300°/s (*P* = .341 and *P* = .229, respectively) (**FIGURE 4**). Regarding limb symmetry values, the groups did not differ in LSI for all single leg hop tests and all measures of quadriceps femoris and hamstring strength (all, *P*>.05) (**TABLE 2**).

DISCUSSION

The purpose of the current study was to examine differences in knee function and strength at the time of return-to-sport clearance between young athletes after ACLR who successfully resumed preinjury sports participation, those who did not resume preinjury sports participation, and those who sustained a second ACL injury over the following year. A key finding from the current study was that a low proportion of young athletes recently cleared to return to sport after ACLR successfully resumed their preinjury level of sports participation at 1 year post return-to-sport clearance (56%). Twenty-three percent of participants demonstrated a decline in activity level compared to their preinjury status, and 21% sustained a second ACL injury over the year following return-to-sport clearance. A second key finding from the current study was that young athletes who successfully resumed preinjury sports participation demonstrated greater absolute involved- and uninvolved-limb performance on several single-leg hop tests for distance at the time of return-to-sport clearance compared to those who did not resume preinjury sports participation. In addition, young athletes who sustained a second ACL injury also demonstrated greater absolute involved- and uninvolved-limb single-leg triple-hop test performance

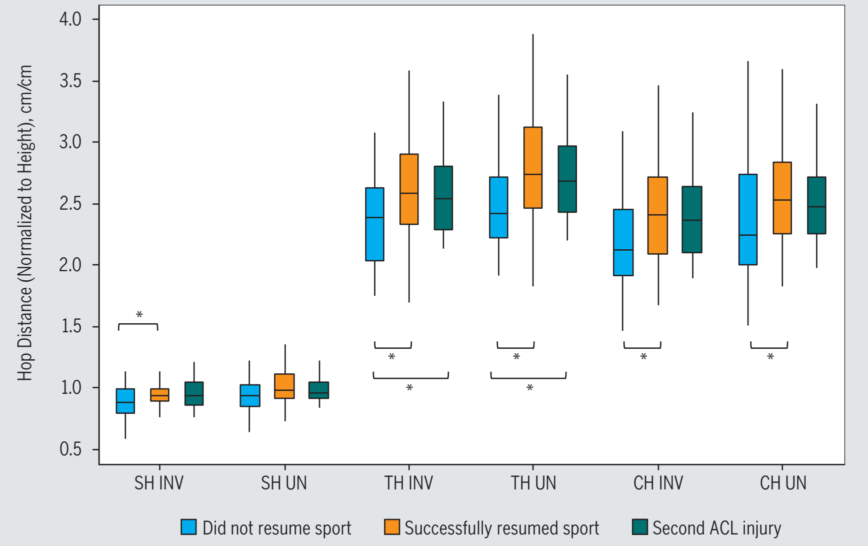

FIGURE 3. Return-to-sport hop test comparison between groups. Data are presented as box plots for the did not resume group (n = 28), the successfully resumed group (n = 70), and the second injury group (n = 26). The bars represent the highest and lowest values for each measure within each group, the middle line represents the median value, the top of the box represents the first quartile, and the bottom of the box represents the third quartile. *Group difference via Mann-Whitney *U* post hoc tests (*P*<.05). Abbreviations: CH, crossover hop; INV, involved limb; SH, single hop; TH, triple hop; UN, uninvolved limb.

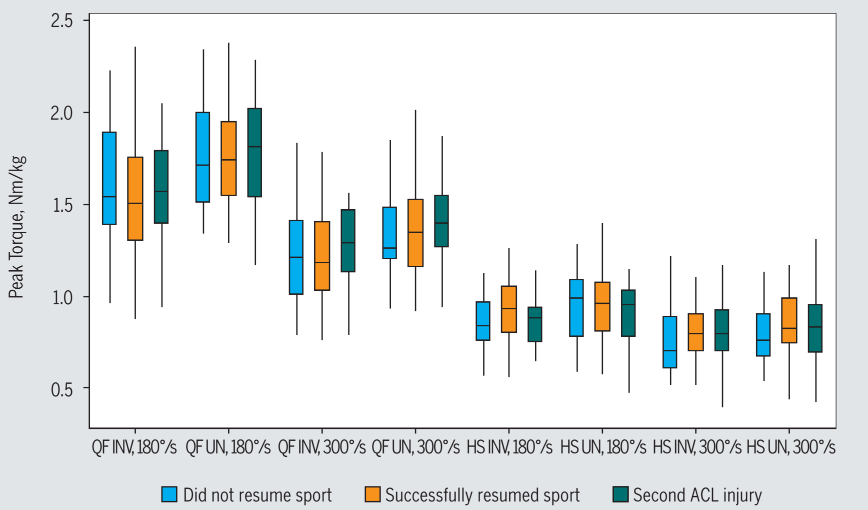

FIGURE 4. Return-to-sport strength comparison between groups. Data are presented as box plots for the did not resume group (n = 28), the successfully resumed group (n = 70), and the second injury group (n = 26). The bars represent the highest and lowest values for each measure within each group, the middle line represents the median value, the top of the box represents the first quartile, and the bottom of the box represents the third quartile. Abbreviations: HS, hamstrings; INV, involved limb; QF, quadriceps femoris; UN, uninvolved limb.

at the time of return-to-sport clearance compared to those who did not resume preinjury sports participation. These results partially confirmed the hypothesis that those who successfully resumed preinjury sports participation would demonstrate greater function, performance, and strength at return-to-sport clearance compared to those who did not. However, young athletes who sustained a second ACL injury after return to sport did not differ from those who successfully resumed preinjury sports participation at 1 year post return to sport. In addition, all 3 groups did not differ in self-reported function, strength, or LSI for all measures, which was contrary to the hypothesis.

It is well established that following ACLR, a small proportion of individuals return to their preinjury level of sports participation.[1-4,6] Specifically, data from Ardern and colleagues[3,4] demonstrated that 31% of athletes returned to their preinjury level of sports participation at 1 year post ACLR[3] and 41% of athletes returned to their preinjury level of sports participation at 2 years post ACLR.[4] The current study found that 56% of young athletes at 1 year post return to sport (approximately 1 year and 8 months post ACLR, on average) were participating at their preinjury level (or higher) of sports participation. While this proportion is higher than those reported by previous longitudinal studies,[3,4] these results are concerning, as this cohort is unique from previous work in its young age (high school aged at injury), history of participating in cutting and pivoting sports (preinjury Tegner scores indicating competitive level), and self-reported plan of returning to consistent participation in cutting and pivoting sports. Additionally, due to the age of the cohort in the current study, participants might have been less likely to encounter certain life-related reasons for a decline in level of sports participation (job requirements, family commitments, other health issues).[17] In this study cohort, a large proportion of participants (21%) sustained a second ACL injury prior to 1 year post return to sport. This is consistent with previous studies, including a recent meta-analysis that reported that 23% of athletes younger than 25 years and returning to sports participation after ACLR sustained a second ACL injury.[48] However, of note is that participants who sustained a second ACL injury did not differ in function, strength, or performance when compared with those who successfully resumed their preinjury level of sports participation. Previous work has identified that higher quadriceps femoris strength symmetry[19] and passing return-to-sport criteria cutoffs[26] were associated with lower risk of subsequent knee injury after ACLR. However, the individuals in these previous studies were generally older[19,26] and participating in professional-level sports,[26] differing from the high school–aged athletes in the current cohort. Taken together, the results from the current study and previous work demonstrate the continued need to develop, validate, and implement effective rehabilitation strategies and return-to-sport decision-making paradigms in young, active individuals after ACLR to potentially mitigate the risk of suboptimal outcomes.

Previous studies in individuals after ACLR have established a relationship between lower extremity performance measures and successful return to sport.[3,4,6] Ardern and colleagues[3,4,6] found that athletes who successfully returned to their preinjury level of sport following ACLR demonstrated higher single hop symmetry when examining return-to-sport status at 1 year after surgery[3,6] and 2 years after surgery.[4] However, in the current study, limb symmetry values for all single-leg hop tests evaluated did not differ between young athletes who did and did not successfully resume preinjury levels of sports participation. Instead, young athletes who successfully resumed preinjury sports participation jumped farther (normalized to height) on both the involved limb and the uninvolved limb for several single-leg hop tests compared to those who did not resume preinjury sports participation. Regarding the use of symmetry values for return-to-sport decision making, previous studies have illustrated that using an LSI to evaluate involved-limb recovery after ACLR may require caution, given the possibility for uninvolved-limb detraining and detrimental neuromuscular injury effects bilaterally.[18,30,33,47] Specifically, the use of LSIs may overestimate involved-knee function, due to a decline in uninvolved-limb function over time in

TABLE 2 RETURN-TO-SPORT LIMB SYMMETRY DATA COMPARISON*

LSI	Successfully Resumed	Did Not Resume	Second Injury	*P* Value†
Single-leg hop test symmetry, %				
Single hop	94.1 ± 6.4	93.8 ± 6.0	96.0 ± 7.0	.475
Triple hop	95.4 ± 6.3	95.1 ± 7.3	95.2 ± 6.4	.868
Crossover hop	95.3 ± 7.6	93.5 ± 13.2	95.5 ± 5.3	.934
QF strength symmetry, %				
180°/s	87.8 ± 13.5	90.4 ± 10.8	89.1 ± 9.3	.542
300°/s	90.2 ± 11.3	91.0 ± 11.6	90.8 ± 7.5	.853
HS strength symmetry, %				
180°/s	99.0 ± 17.5	92.3 ± 13.4	95.2 ± 23.5	.185
300°/s	96.4 ± 15.8	96.3 ± 13.7	97.2 ± 12.6	.969

Abbreviations: HS, hamstrings; QF, quadriceps femoris.
**Values are mean ± SD.*
†Obtained via the Kruskal-Wallis test.

rehabilitation after ACLR or to deficits in comparison with age- and sex-matched normative data.[18,47] Based on the results of the current study, it is possible that the young athletes who demonstrated higher absolute single-leg hop performance bilaterally had better overall underlying athleticism, enabling a successful resumption of preinjury sports participation over the year following return-to-sport clearance. However, evaluated alongside previous studies highlighting concerns with LSIs and uninvolved-limb detraining post injury, this may suggest the importance of a specific focus on bilateral absolute lower-limb performance during rehabilitation. In addition, despite modest correlations among measures of strength, hop performance, and patient-reported function in individuals after ACLR,[32,43,49] KOOS scores and strength (quadriceps femoris and hamstring, absolute and LSI) did not differ among the participants who successfully resumed sport participation and those who sustained second ACL injury. This suggests the importance of a multifactorial assessment of function and recovery after ACLR, and that performance on one return-to-sport measure does not necessarily reflect similar performance on other common return-to-sport measures.

There are several important considerations to take into account when interpreting the results of this study. First, the young, active nature of the cohort in this study may limit the generalizability of this study's findings to all individuals after ACLR. However, given this cohort's self-reported plan to return to regular participation in cutting and pivoting sports, it was important to understand factors associated with their ability to successfully do so. Second, the current study did not collect self-reported data regarding the participants' interpretation of why their Tegner scores decreased compared to preinjury levels (beyond sustaining a second ACL injury within the year following return-to-sport clearance). Flanigan and colleagues[17] performed telephone interviews with individuals who previously underwent ACLR 12 to 25 months prior, to determine who had and had not returned to their preinjury level of sport participation. Those authors[17] found that fear of reinjury was one of the most common reasons reported by nonreturners in their cohort. Additionally, Lentz and colleagues[29] found that the primary self-reported reasons for not returning to preinjury levels of sports participation were fear of injury and lack of confidence. Supporting this, other studies have consistently identified a difference in fear of reinjury between individuals who do and do not successfully return to sport after ACLR, when assessed with both the Tampa Scale of Kinesiophobia[28,29] and the Anterior Cruciate Ligament-Return to Sport after Injury scale.[3,4] Although the second ACL injury group and those who successfully resumed preinjury sports participation did not differ in the return-to-sport measures evaluated in the current study, other factors, including psychological measures like confidence, may have differentiated these groups. The current study did not evaluate these measures. Importantly, in all of these previous studies,[3,4,17,28,29] the average age of the participants was older than 20 years (mean age range, 20.9-30.9 years). Thus, understanding the role of fear of reinjury, alongside other factors, in the ability to successfully return to sport in young, high school–aged athletes is a critical need.

CONCLUSION

A low proportion of young athletes successfully resumed preinjury sports participation 1 year post return-to-sport clearance after ACLR. Those who successfully resumed preinjury sports participation and those who sustained a second ACL injury demonstrated greater absolute involved- and uninvolved-limb functional performance at the time of return-to-sport clearance. However, the groups did not differ in LSIs for all return-to-sport measures. Further study of the interactions among measures of patient-reported function, performance, strength, second ACL injury risk, and sports participation after ACLR is warranted in this young, active population. ◉

KEY POINTS

FINDINGS: Even in young athletes planning to return to cutting and pivoting sports, few successfully resumed their preinjury level of activity at 1 year post return-to-sport clearance. Those who successfully resumed their preinjury level of activity jumped farther on single-leg hop tests on both the involved and uninvolved limbs compared to those who did not resume their preinjury level of activity. However, no differences were identified between those who successfully resumed preinjury sports participation and those who sustained a second anterior cruciate ligament (ACL) injury over the year following return-to-sport clearance. Additionally, the groups did not differ in strength or limb symmetry indices for all measures.

IMPLICATIONS: Focusing on improving absolute, bilateral performance after ACL reconstruction may be warranted in promoting more successful resumption of sports participation, but does not appear to mitigate second ACL injury risk. Future work is needed to develop or identify measures that differentiate young athletes with successful resumption of preinjury sports participation from those who sustain a second ACL injury after return to sport.

CAUTION: The observational design of the current study limits any conclusions regarding causation. Additionally, the young, active nature of the cohort in this study may limit the generalizability of this study's findings to all individuals after ACL reconstruction.

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[VIEWPOINT]

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Mobile Technology in Running Science and Medicine: Are We Ready?

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Since the running revolution of the 1970s, there has been a steady rise in recreational running participation internationally, with a 13% increase in marathon finishers between 2009 and 2014 alone.[10] One of the major challenges is the burden of running-related injuries (RRIs), with long-distance track-and-field athletes sustaining 2.5 injuries per 1000 hours, and novice runners suffering 33 injuries per 1000 hours.[24] As such, researchers, sports medicine practitioners, and strength and conditioning coaches are striving to develop an understanding of which factors may increase an individual's risk of developing RRIs, which strategies can be used to ensure optimal rehabilitation and recovery from an injury, and how to best optimize athletic performance. Several recent systematic reviews have demonstrated strong evidence to support that a previous history of injury,[8,23] mismanaged training volume,[23] and time spent running[17] contribute to an increased risk of injury. In addition to these well-established factors, there is weak to moderate evidence to suggest that running biomechanics, age, sex, and shoe type contribute to injury risk.[8,23]

Despite knowledge of these risk factors, researchers, clinicians, and strength and conditioning coaches have been unable to truly leverage these insights to reduce injury rates. There are likely 2 primary reasons for this failure: (1) RRIs and indicators of performance are complex and multifactorial in nature, and (2) there are several key limitations related to the current clinical and research methodologies used in evaluating an athlete's injury risk, recovery, and performance. This Viewpoint explores these factors to demonstrate how recent advances in mobile technology may allow us to uncover novel insights related to the science and medicine of running.

RRIs Are Multifactorial

The multifactorial nature of RRIs means that it is unlikely that one independent factor (or even a small combination of factors) will be able to account for 100% of the variation. As such, no single factor should be considered in isolation when attempting to mitigate injury risk, rehabilitate, and improve performance. However, the methods we currently use to collect, aggregate, and extract meaning from these data create silos of often subjective and incomplete information, inhibiting our ability to unlock truly valuable insights. While early work investigating the application of more advanced statistical modeling in sports injury contexts has demonstrated some promise,[9] understanding the collective risk factors for RRIs and their likely complex interactions has largely been untouched, due in part to our approach to the problem. For instance, when considering training factors in distance runners, such as volume, intensity, and recovery, the current clinical standard is the use of athlete self-report. However, it is understood that self-report is fraught with reporting accuracy errors,[4] potentially affecting its value in a clinical scenario and introducing a large extent of measurement error into research. Furthermore, to capture information related to running biomechanics, clinicians and strength and conditioning professionals often leverage qualitative video analysis of an individual's running kinematics.[22] While this approach can provide useful information in guiding the plan of care for the individual, the

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interrater reliability of video analysis is variable, with reliability ranging from poor to excellent, depending on the variable and population of interest.[5,18] As a result, this method of assessment may lack the objectivity needed to determine thresholds of increased injury risk. One alternative to video analysis is the use of 3-D motion-capture systems; however, these systems are prohibitively expensive, while the setup and data processing are time intensive and require significant expertise. In addition, both 3-D motion capture and qualitative video analysis are commonly restricted to laboratory-based treadmill or running tracks, hindering the capture of valuable real-world biomechanical data.

Real-World Biomechanical Data

The digital revolution of the 21st century has resulted in an increase in the number of wearable and mobile-based technologies available to medical professionals, strength and conditioning coaches, and athletes at all levels. Recent advances in technology have seen the development of smartphones that can serve as mobile sensing, computing, and feedback platforms capable of capturing and aggregating longitudinal multimodal data related to an individual's function.[11] These mobile platforms may collect data themselves or pair with wearable sensors capable of collecting location (global positioning system [GPS]), heart rate (photoplethysmography or electrocardiogram sensor), and/or biomechanical movement (inertial measurement unit [IMU]) data outside of the laboratory environment. To date, mobile technology in medicine has primarily demonstrated its value in older adult populations, with continued success in identifying those at risk of falls[7] and capturing alterations in motor function in people with neurological conditions such as Parkinson's disease.[11] While the application of this technology in sports medicine is in its infancy, it has the potential to provide researchers, clinicians, and athletes with a unique opportunity to collect, visualize, and understand rich longitudinal data pertaining to running performance and injury in the real world, creating a new quantifiable, multifactorial model of athlete RRIs and performance monitoring.

As an example, smartphones and watches may be used to capture GPS data to provide a quantified measure of training volume, while embedded or independent electrocardiogram or photoplethysmography sensors can collect heart rate data to provide a measure of training intensity. Similarly, heart rate variability could provide a quantifiable measure of autonomic recovery between training sessions,[16] while sleep accelerometry data could provide valuable context, aiding in better understanding the reasons for protracted recovery through objective measurement of sleep quality.[19] Additionally, wireless IMUs can be worn on the lower back and/or lower limbs to capture spatiotemporal, kinetic, and kinematic running biomechanical data during training. These biomechanical data could be used as a quantifiable outcome measure and to provide athletes with real-time biofeedback related to running performance, while clinicians could leverage such biofeedback to maximize carryover during running gait retraining. Finally, the aggregation of large and complex longitudinal multisite, multimodal data sets may provide researchers with novel insights into factors that may increase an athlete's risk of developing RRIs (both common and rare) and influence performance, leading to the creation of actionable digital biomarkers.[25] Once the true interrelationship between multiple factors is understood on a population level, it will lay the groundwork for the development of novel injury risk reduction, rehabilitation, and performance-enhancement strategies at the individual level. The **FIGURE** illustrates a theoretical framework for a mobile monitoring system.

Strengths and Limitations

While the use of mobile and sensor technology is beginning to be realized in sports science and medicine, practitioners and researchers need to be aware of the specific strengths and limitations of such technology prior to its implementation in clinical practice and research. For instance, previous research has demonstrated excellent accuracy of a range of common consumer watch-based sensors during running (error less

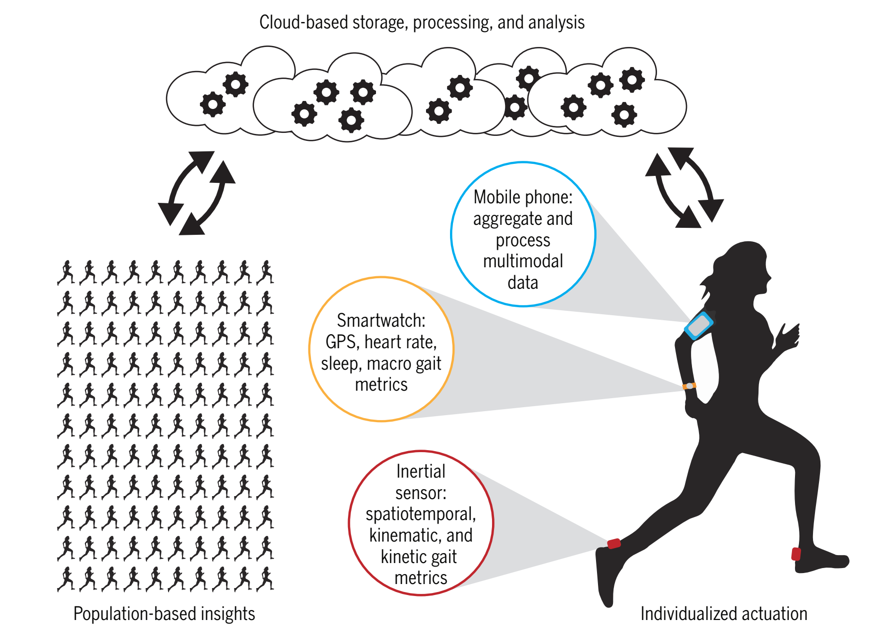

FIGURE. How data collected at an individual level can be aggregated to create population-based insights, which could inform actuation at an individual level. Abbreviation: GPS, global positioning system.

than 5%).[21] However, these systems are highly sensitive to factors such as wearing position, wrist movement, and skin contact.[1] Though IMU systems are capable of accurately quantifying spatiotemporal, kinetic, and kinematic gait variables, their accuracy is influenced by the choice of sensor placement,[14] sensor parameters (sampling frequency and resolution),[15] and the foot-strike pattern of the athlete.[14] Furthermore, one might assume that all consumer-based GPS systems are suitable for accurately quantifying information related to training distance, velocity, and acceleration; however, the accuracy of these measures is significantly influenced by the sampling frequency settings of the device.[20] For example, while a GPS device sampling at 1 Hz may be suitable for quantifying running distances, the device will not provide accurate data on instantaneous velocity and acceleration, which require sampling speeds of greater than 5 Hz and 10 Hz, respectively.[20] Finally, it is of utmost importance that those interested in deploying and developing such technology consider the person (practitioner, researcher, athlete) who will be using the system, and focus on the usability and user experience of the technology in this population. As such, if practitioners or researchers are considering the use of such technology in practice, then they should conduct a thorough investigation into the strengths and limitations of the technology in question to ensure it is fit for use. An evaluation framework[6] has been developed for digital and connected health technologies. Such a framework could be used to assist in defining the user requirements, identifying suitable technologies, comparing and assessing devices, and more holistically deciding on the best possible technology for the purpose.

Future Direction

While the primary goal of research in this space to date has been to establish the concurrent validity of these systems, little research has been conducted to investigate the role that mobile technology may play in improving athlete performance, identifying at-risk athletes, and assisting in the optimal rehabilitation and return to sport of injured athletes. A recent systematic review conducted by Benson and colleagues[2] highlighted that while wearable IMU devices have been used to investigate running biomechanics outside of the laboratory environment, most studies have focused on comparing injured and healthy control groups,[13] or fatigued and nonfatigued athletes,[3] failing to take the next step and conduct prospective evaluations. To date, only 1 study[12] has prospectively investigated the influence of gait characteristics on injury risk using wearable sensors. The study demonstrated that individuals running at a rate of 166 steps per minute or less, as measured by a Polar RCX5 wristwatch and S3+ Stride Sensor (Polar Electro Inc, Bethpage, NY), had a 5.85 greater odds of sustaining a shin injury than those running at a rate of 178 steps per minute or greater. Though the study shows the potential of such technology, the collection of large multimodal data sets, drawing information from many different domains related to the athlete's daily function and performance, combined with novel machine-learning and deep-learning analytical methods may provide actionable information related to RRIs and performance.

It is important to note that in this Viewpoint we simply present a concept. If mobile technology is harnessed appropriately, it could provide researchers and clinicians with an opportunity to obtain large amounts of rich multifactorial information related to athletic performance and injury. While we have presented select examples of potential avenues for this technology, it is currently unclear which specific measures may provide the most actionable data in this population. In other words, just because we can measure it does not mean the data are meaningful. Currently, we understand that when this novel technology is considered and applied appropriately in the running context, we can capture valid data that may augment current sports medicine and conditioning approaches. However, we have yet to fully unlock the potential of this technology and establish the most appropriate way to harness the large amounts of data it produces.

Despite the promise and potential demonstrated by a large number of peer-reviewed publications related to the validity of such systems, it would be a mistake to advance too fast toward developing new digitally enabled monitoring and training systems. While the first validation step has been achieved, the next phase in the development of systems should focus on engaging with all potential stakeholders and implementing a broad data-gathering program, using robust research methodologies. Both industry and academia should engage in this process to ensure the development of scientifically robust, valid, and reliable tools capable of generating actionable insights. By doing so, we as clinicians and researchers can begin to fully understand how this novel technology may augment practice in the future. By engaging early in this process, it will allow us to accumulate large multimodal data sets that may facilitate the creation of statistical models capable of separating the signal from the noise, to provide real insight into the most appropriate injury prevention, rehabilitation, and performance-enhancing strategies. The authors urge caution in progressing too quickly, which may result in the development of technologies that lack validity, ultimately failing to realize the value of this technology in sports medicine.

Key Points

- Running-related injuries are multifactorial in nature, and current methods used to collect, aggregate, and extract meaning from these data create silos of often subjective and incomplete information.
- It is unlikely that current approaches will allow us to unlock valuable insights into performance, injury risk, and recovery, hampering the advancement of running science and medicine.

- The application of digital technology to running science and medicine may allow for the generation of novel insights on a population level, facilitating actuation in clinical practice at an individual level.
- Clinicians, researchers, and industry should consider the strengths and limitations of the technology in question and carry out a structured technology review prior to implementation into practice.
- Clinicians, researchers, and industry should engage early in this process to ensure the development of actionable insights capable of aiding clinical practice. ◉

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The Effects of Needling Therapies on Muscle Force Production: A Systematic Review and Meta-analysis

Needling involves inserting a monofilament needle into soft tissue (skin, tendon, ligament, and muscle) to treat pain, loss of motion, or muscle dysfunction with the goal of improving function.[1,14] Several common needling techniques are used to treat muscle dysfunction. These include inserting a needle into a muscle, particularly in an area that is tender and/or taut, and leaving it in situ for a given time; manipulating the needle; and/or eliciting muscle contractions using electrical stimulation. Although not required, induction of a local reflex response, referred to as a "twitch response," is desired when needling.[14]

BACKGROUND: Needling has been shown to decrease pain in the short term; however, its effects on muscle force production are unclear.

OBJECTIVE: To evaluate the evidence regarding the comparative effects of needling on muscle force production.

METHODS: In this systematic review, an electronic search was performed using key words related to needling. Methodological quality of articles was appraised and effect sizes were calculated. The strength of evidence was determined, and meta-analysis was performed when similar methods were used in studies for similar conditions.

RESULTS: Twenty-one studies were included in this review, of which 9 were deemed to be of high quality (greater than 6/10 on the Physiotherapy Evidence Database [PEDro] scale), 11 of fair quality (5 to 6/10), and 1 of poor quality (less than 5/10). Three meta-analyses were performed. There was moderate strength of evidence and medium effect sizes for needling therapy to enhance force production in those with neck pain, and very low strength of evidence of no effect for individuals with nonspecific and postoperative shoulder pain and those with lateral epicondylalgia. Other studies not included in the 3 meta-analyses demonstrated no significant effect of needling on force production. These studies included individuals with carpal tunnel syndrome, knee osteoarthritis, ankle sprains, knee arthroscopy, or delayed-onset muscle soreness.

CONCLUSION: The majority of studies suggest no effect of dry needling on force production. High-quality studies with adequate power that control for the placebo effect and follow accepted reporting standards could make valuable contributions to the literature. This study was registered with the International Prospective Register of Systematic Reviews (PROSPERO, CRD42017080318).

LEVEL OF EVIDENCE: Therapy, level 1a.
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KEY WORDS: *acupuncture, dry needling, neck, strength, trigger points*

Needling has been purported to cause changes in the mechanisms of muscle function, such as mechanical signaling, fibroblast cytoskeletal remodeling, and mechanotransduction.[14] Needling can also cause biochemical changes related to pain, inflammation, and blood flow, which may influence force production.[14,30,42] Changes in muscle activation, thickness, nociception, and range of motion have been reported in those with back pain,[31,32] elbow pain,[20,22,34] and after anterior cruciate ligament reconstruction following needling.[44] Needling techniques are often nonstandardized and may include adjunct treatments, such as electrotherapy, making the specific effects of needling on force production unclear.[14,30,42]

Neck, low back, and knee pain and higher rates of reinjury after anterior cruciate ligament reconstruction have all been associated with decreased force production.[4,10,12,15,29,35,37,38,50] Interventions such as therapeutic exercise and neuromuscular electrical stimulation have been shown to improve force production.[4,7,10,15,29,35,37,50] Inserting a monofilament needle into a muscle may create a neurophysiological response that may alter force production.[14] Previous reviews

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have not included a sufficient number of studies of force production to draw specific conclusions on how needling may affect force production. However, these reviews assessed the effects of needling by physical therapists only and excluded acupuncture modalities or did not use acupuncture-specific search terms,[21,30,42] only assessed the effects of trigger point needling,[16,33] or included search terms related to pain and not specifically to force production.[16,30,33] One of these reviews concluded that needling had no effect on force production in the lower quarter of the body, based on 6 included studies, only 1 of which measured force production.[42] The purpose of this review was to use a broad search strategy to evaluate the evidence regarding the effects of needling on muscle force production.

METHODS

Study Design

This systematic review was performed under the parameters of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA).[41] This study was registered with the International Prospective Register of Systematic Reviews (PROSPERO, CRD42017080318).

Information Sources

An electronic search of PubMed, CINAHL, and SPORTDiscus was performed from inception of these databases to March 18, 2018.

Search and Eligibility Criteria

Each database was searched using key words related to needling therapies, which involve the use of needles inserted into muscles, including *dry needling*, *acupuncture*, *muscle*, and *strength* (**APPENDIX**, available at www.jospt.org). The search terms related to acupuncture and dry needling were included, due to similar techniques of inserting needles into muscle.[14]

Search and eligibility of articles were determined by identifying the population/patient or problem, intervention, comparison, and outcome of interest (**TABLE 1**).[43] Studies were included in this review if they met all the following criteria: (1) answered the review question, (2) randomized controlled trial, (3) English language, (4) full text available. Studies were excluded if (1) the intervention involved wet needling or injection of a solution, or (2) the needling was performed away from the site of interest. For example, if a participant received treatment for the lower leg and the clinician performed needling only to the hand based on traditional Chinese medicine constructs, then the article was excluded.

Study Selection

Studies were identified and compiled into a citation manager (Mendeley; RELX Group, London, UK).[49] After duplicates were deleted, a 2-step screening process was used to extract relevant articles. Two independent reviewers screened all identified papers using inclusion and exclusion criteria by first reading the titles (C.M. and M.M.), and then the abstracts (C.M. and Z.W.) of included studies based on titles. In the second phase, reviewers (C.M. and L.V.) used full text to determine whether the manuscripts met the inclusion criteria. A third reviewer (M.B.) evaluated discrepant cases. If the full text of an included article was not available, then requests were made for interlibrary loan services. The aim and design of this review was to investigate the comparative effects of needling therapies, and not within-group changes.

Quality Assessment of Studies

Methodological Quality Assessment The Physiotherapy Evidence Database (PEDro) scale was used to assess the methodological quality of all eligible articles. The PEDro scale consists of 11 total items, 10 of which are specific to internal validity and risk of bias.[36,42] Scores from the PEDro database were used when available. If an included article had not been scored in the PEDro database, then the primary author (C.M.) used the PEDro scale to appraise the study and the score was then agreed upon by 2 other coauthors in a collaborative discussion (L.V. and M.B.).

Strength of Evidence When studies measured force production using the same method and in individuals with similar conditions, 2 reviewers (C.M. and L.V.) assessed the strength of evidence using the Grading of Recommendations Assessment, Development and Evaluation (GRADE) tool.[3,21] Each GRADE analysis was assessed based on 5 domains (risk of bias, inconsistency of results, indirectness, imprecision, publication bias), and strength of evidence was reduced from a high-grade classification (high, moderate, low, very low) for each domain not satisfied.[21] Heterogeneity was assessed using the I^2 statistic when possible.[24] Publication bias was assessed using funnel plots.

TABLE 1 Description of Components of PICO in This Systematic Review

PICO Component	Description
Patient	Individuals who received any form of needling therapy to their muscle(s), including healthy/uninjured, injured, nonoperative, and operative. No restrictions regarding population type, injury, age, or sex
Intervention	Any form of needling therapy provided to a muscle, irrespective of body region. Studies restricted from inclusion include those in which an injection of a solution was introduced into the body, or where the needling intervention focused solely on using traditional Chinese medicine constructs, including energy systems or meridians, where needling was performed away from the site of interest
Comparison	Any intervention such as therapeutic exercise, modality, or form of placebo needling
Outcome	Any formal assessment of muscle force production

Abbreviation: PICO, patient/problem, intervention, comparison, and outcome.

Strength of evidence was determined by the primary author (C.M.) and confirmed by a second author (L.V.).

Data Analysis

The data of interest from the included studies were extracted into a custom-designed template, and descriptive analysis of the extracted data was performed (**TABLE 2**). To compare the effectiveness between needling and control groups across studies, the standardized mean difference (SMD) was calculated from the available data using G*Power (Heinrich-Heine Universität, Düsseldorf, Germany).[17] For each study, if the confidence interval (CI) of the SMD crossed the line of no effect, then the estimates were interpreted as evidence of no effect. Meta-analysis was not performed when studies did not measure force production with the same method or in similar populations. The program Review Manager (The Nordic Cochrane Centre, Copenhagen, Denmark) was utilized for meta-analysis calculations. For studies that underwent meta-analysis, publication bias was assessed with funnel plots.

RESULTS

Study Selection

A search of 3 databases yielded 5206 studies. After 4 studies were added manually and duplicates were removed, 4338 articles were narrowed through a 2-step screening process to 173 (**FIGURE 1**). Two authors (C.M. and L.V.) reviewed the full texts of the 173 studies identified from the screening process and were in 77% agreement on which studies to include in the systematic review. The 39 cases on which the reviewers did not agree were resolved by a third reviewer (M.B.). After full-text review, 21 studies were included in the systematic review.

Methodological Quality Assessment

The 21 studies underwent quality assessment using the PEDro scale (**TABLE 3**). Based on the total PEDro quality score, 9 studies were found to be of high quality (greater than 6/10), 11 of fair quality (5 to 6/10), and 1 of poor quality (less than 5/10). Of the 21 included studies, 12 did not adequately conceal participant allocation and therefore had a high risk of selection bias. Only 5 studies satisfied the intention-to-treat analysis criterion, indicating a high risk of reporting bias. None of the studies blinded the clinician performing the needling therapy, and only 3 studies adequately blinded participants to their treatment group by using anesthesia and placebo acupuncture needles.[28,39,52]

Strength of Evidence

There were 3 groupings of studies that measured force where the GRADE criteria were used (**TABLE 4**) and meta-analysis could be performed: (1) cervical isometric force production in participants with nonspecific neck pain (2 studies) (**FIGURE 2**), (2) grip strength in participants with lateral epicondylalgia (2 studies) (**FIGURE 3**), and (3) shoulder lateral abduction force production in participants with shoulder pain (2 studies) (**FIGURE 4**). Meta-analysis was not possible in the majority of studies due to differences in study design and methods of measuring force,[13,18,19,23,26-28,39,46,48,52,54] inability to accurately estimate effect size,[53] and 1 study being a pilot of another study.[5,6]

Body Region

Cervical Region Two studies demonstrated enhanced isometric force production in all planes when combining needling of the cervical spine and stretching compared to stretching alone.[8,9] The strength of evidence for needling therapies to improve cervical isometric force production was moderate, per the GRADE criteria (**TABLE 4**). Both studies yielded medium to large effect sizes (total estimated SMD, 0.53; 95% CI: 0.41, 0.66) (**FIGURE 2**).

Shoulder Region Four studies assessed the effects of needling on force production in adults with nonoperative shoulder pain, postoperative shoulder pain, and older adults with shoulder pain. This review found that needling therapies do not improve force production at the shoulder. The 3 studies that support-

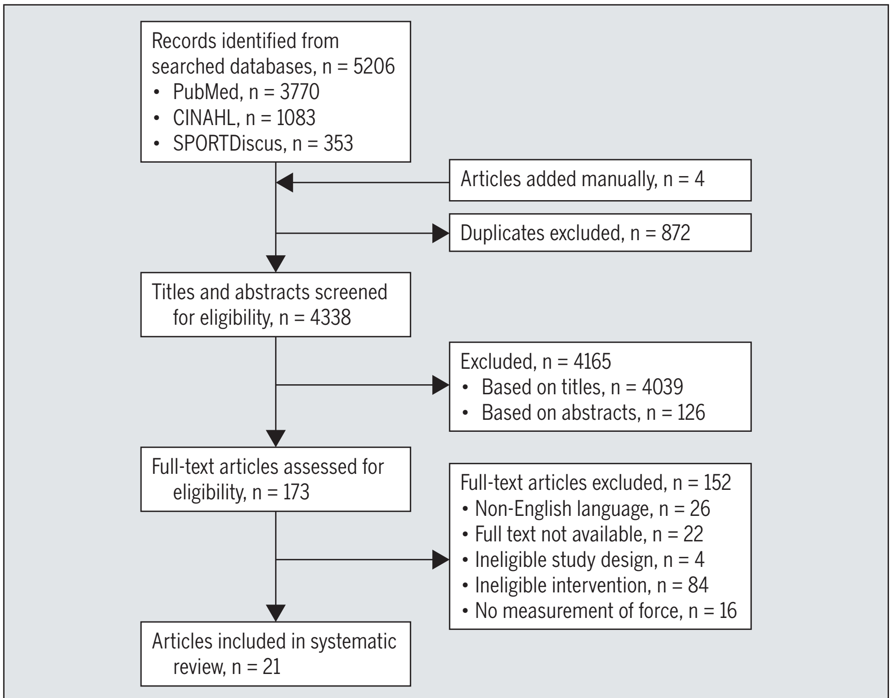


FIGURE 1. Review process of articles identified in this systematic review.

TABLE 2 The Effects of Dry Needling on Muscle Force Production

Body Region/Study	Total PEDro Score*	Participants, n	Mean ± SD Age, y	Sex, %	Type of Injury	Control/Experiment	Needling Technique	Dry Needling/Acupuncture	Measurement of Force Production	Group Difference, Yes/No†
Cervical: nonspecific neck pain										
Cerezo-Téllez et al[8]	6	44	43.6 ± 15	Control: female, 86.4; male, 13.6 Experimental: women, 77.3; men, 22.7	Neck pain	Needling plus stretching (n = 22) versus stretching alone (n = 22)	Deep dry needling to active trigger points in upper trapezius muscle using fast-in, fast-out technique	Dry needling	Isometric cervical force production	Yes
Cerezo-Téllez et al[9]	6	128	52 ± 16.6 versus 48 ± 15.7	Control, 14.8; experimental group, 21.9 It's unclear whether the percentage reported for each group represents men or women	Chronic nonspecific neck pain without radiation	Needling plus stretching (n = 64) versus stretching alone (n = 64)	Deep dry needling to active trigger points in cervical/shoulder muscles using fast-in, fast-out technique	Dry needling	Isometric cervical force production	Yes
Shoulder: nonoperative, adults										
Pérez-Palomares et al[45]	8	120	54.32 ± 11.45 versus 52.74 ± 11.81	Control: female, 55.6; male, 44.4 Experimental: female, 70; male, 30	Nonspecific shoulder pain	Personalized physical therapy (n = 63) versus dry needling of shoulder muscles plus personalized physical therapy (n = 57)	Dry needles inserted into trigger points in shoulder utilizing the fast-in, fast-out technique	Dry needling	Constant-Murley score strength subscale assessing lateral abduction strength	No
Shoulder: nonoperative, older adults										
Calvo-Lobo et al[5]	8	20	77.45 ± 7.6 versus 81.77 ± 8.7	Control: female, 70; male, 30 Experimental: female, 70; male, 30	Participants 65 y old or older with shoulder pain	Dry needling of 1 active and latent trigger point in the infraspinatus (n = 10) versus dry needling of 1 active trigger point that was most hyperalgesic (n = 10)	Dry needle inserted into trigger point in infraspinatus using fast-in, fast-out technique	Dry needling	Grip strength	No
Calvo-Lobo et al[6]	7	66	75.35 ± 6.97 versus 76.74 ± 8.20	Female, 65; male, 35	Participants 65 y old or older with shoulder pain	Dry needling of 1 active and latent trigger point in the infraspinatus (n = 33) versus dry needling of 1 active trigger point that was most hyperalgesic (n = 33)	Dry needle inserted into trigger point in infraspinatus using fast-in, fast-out technique	Dry needling	Grip strength	No

Table continues on page 158.

TABLE 2 The Effects of Dry Needling on Muscle Force Production (continued)

Body Region/Study	Total PEDro Score*	Partici-pants, n	Mean ± SD Age, y	Sex, %	Type of Injury	Control/Experiment	Needling Technique	Dry Needling/Acupunc-ture	Measurement of Force Production	Group Differ-ence, Yes/No†
Shoulder: postoperative										
Arias-Buría et al[2]	7	20	58 ± 3	Female, 75; male, 25	Participants all had post-operative shoulder pain secondary to either open reduction and internal fixation with proximal humeral internal locking system plate or rotator cuff tear repair	Physical therapy–only group (n = 10) or physical therapy and dry needling of trigger points in shoulder (n = 10)	Dry needling inserted into trigger points in shoulder using fast-in, fast-out technique	Dry needling	Constant-Murley score strength subscale assessing lateral abduction strength	No
Elbow/wrist/hand: lateral epicondylalgia										
Hsu et al[25]	5	35	44.81 ± 7.30 versus 45.89 ± 5.99	Control: female, 68.8; male, 31.2 Experimental: female, 78.9; male, 21.1	Participants with lateral epicondylalgia	Participants randomized into acupuncture (n = 19) or radial bone adjustment manipulation (n = 16) group	Needles were inserted into various acupoints and Ashi points according to a study published by the Hannover (Germany) Medical School. Needle was inserted into muscle layer and twisted to elicit de qi sensation and left in situ for 25 min	Acupuncture	Pain-free grip strength and maximum grip strength	No
Fink et al[18]	6	45	Mean, 52.5 versus 51.6	Control: female, 68.4; male, 31.6 Experimental: female, 54.8; male, 45.2	Participants with chronic lateral epicondylalgia	Participants randomized into acupuncture of local/regional points in elbow/hand (n = 23) or sham acupuncture (needling of nontraditional acupuncture points) group (n = 22)	Needles were inserted into acupoints along the lateral extensor group of the forearm. De qi sensation was elicited by twisting the needles and left in situ for 25 min	Acupuncture	Isometric strength of wrist extensors using custom device	Yes

Table continues on page 159.

TABLE 2 The Effects of Dry Needling on Muscle Force Production (continued)

Body Region/Study	Total PEDro Score*	Partici-pants, n	Mean ± SD Age, y	Sex, %	Type of Injury	Control/Experiment	Needling Technique	Dry Needling/Acupuncture	Measurement of Force Production	Group Difference, Yes/No†
Davidson et al[11]	5	16	Control, 49.25 ± 9.25; experimental, 45.75 ± 7.65	Control: female, 50; male, 50 Experimental: female, 75; male, 25	Participants with lateral "epicondylitis"	Participants randomized into acupuncture (n = 8) or ultrasound (n = 8) group	Needles were inserted to elicit a de qi response into affected areas	Acupuncture	Pain-free grip strength	No
Elbow/wrist/hand: healthy										
Zanin et al[53]	5‡	52	Range, 18-30	Authors did not specify, only stated that they included participants of both sexes	Healthy	Participants were randomized into 4 groups: needling at local acupoints (heart 3, n = 15), distant acupoints (heart 4, n = 14), control (bladder 60, n = 15), naïve control group (n = 8) Heart 3, flexor carpi ulnaris; heart 4, flexor carpi ulnaris; bladder 60, posterior to lateral malleolus	Needle was inserted into various acupoints	Acupuncture	Isometric strength of wrist flexor muscles and electromyographic signal intensity	Yes
Fleckenstein et al[19]	7	60	23.6 ± 2.8	Female, 37; male, 63	Healthy	Participants were randomized into needling (n = 12), sham needling (n = 12), laser (n = 12), sham laser (n=12), or no intervention (n = 12). Delayed-onset muscle soreness was induced to the biceps brachii muscle and maximal isometric voluntary force into elbow flexion was assessed	Needles were inserted into various acupoints in the arm	Acupuncture	Maximal isometric voluntary force into elbow flexion, measured 24, 48, and 72 h after delayed-onset muscle soreness was induced	No

Table continues on page 160.

ed needling had heterogeneous samples with varying conditions of severity, and found evidence of no effect; the 1 high-quality study that did not support needling had a much larger sample size.

There was no difference in change in lateral abduction shoulder strength between a group of adults with shoulder pain who received needling and physical therapy (n = 57) versus a group of adults who received physical therapy only (n = 63). Lateral abduction strength was measured using the Constant-Murley score strength subscale.[2,45] The corresponding author of the study provided us with the data for the Constant-Murley score subscales. There was evidence of no effect on lateral abduction strength immediately post needling (SMD, 0.05; 95% CI: –0.31, 0.41) and after 3 months (SMD, –0.09; 95% CI: –0.45, 0.27).[45]

TABLE 2 The Effects of Dry Needling on Muscle Force Production (continued)

Body Region/Study	Total PEDro Score*	Partici-pants, n	Mean ± SD Age, y	Sex, %	Type of Injury	Control/Experiment	Needling Technique	Dry Needling/ Acupunc-ture	Measurement of Force Production	Group Differ-ence, Yes/No†
Hübscher et al[28]	5	22	Range, 22-30	Female, 54; male, 46	Healthy	Participants were randomized into real acupuncture (n = 7), sham acupuncture (n = 8), and a "no needling" group (n = 7). Delayed-onset muscle soreness was induced to the biceps brachii muscle	Needles were inserted into various acupoints in the arm	Acupuncture	Maximal isometric voluntary force into elbow flexion, measured 24, 48, and 72 h after delayed-onset muscle soreness was induced	No
Elbow/wrist/hand: carpal tunnel syndrome										
Yao et al[52]	5	41	48.5 ± 10.5 versus 53.6 ± 7.65	Experimental: female, 80; male, 20 Control: female, 66; male, 34	Participants with carpal tunnel syndrome	Participants were randomized into acupuncture (n = 21) or placebo acupuncture with Streitberger placebo acupuncture needles (n = 20)	A de qi sensation was elicited when needle was inserted into various acupoints of the arm	Acupuncture	Tip and key pinch strength	No
Thigh/knee: postoperative										
Mayoral et al[39]	7	40	71.65 ± 6.06 versus 72.90 ± 7.85	Sex was statistically different between groups (*P* = .013) and adjusted via multivariate analysis, but authors did not break down the number of male and female participants in each group	Participants about to undergo knee arthroplasty	Participants were randomized into dry needling of thigh/knee muscles (n = 20) or placebo group (n = 20)	Needling was performed immediately after participant was anesthetized but right before surgery, using the fast-in, fast-out technique into identified trigger points	Dry needling	Isometric strength of knee flexors/extensors after a single contraction	No
Thigh/knee: knee osteoarthritis										
Plaster et al[46]	7	60	62.07 ± 7.60 versus 64.30 ± 10.24	Manual acupuncture: female, 87; male, 13 Electroacupuncture: female, 77; male, 23	Participants with knee osteoarthritis	Participants were randomized into manual acupuncture (n = 30) or electroacupuncture (n = 30) group	Manual acupuncture or electroacupuncture to various points in the thigh and lower leg and hands	Acupuncture	Isokinetic dynamometer to assess maximum isometric contraction	No

Table continues on page 161.

TABLE 2 The Effects of Dry Needling on Muscle Force Production (continued)

Body Region/Study	Total PEDro Score*	Partici-pants, n	Mean ± SD Age, y	Sex, %	Type of Injury	Control/Experiment	Needling Technique	Dry Needling/ Acupuncture	Measurement of Force Production	Group Difference, Yes/No†
Thigh/knee: healthy										
Haser et al[23]	6‡	30	Age range, 18-23 (mean, 18.4)	Not specified, but likely 100% male	Healthy elite soccer players	Players were randomized into dry needling of trigger points of anterior/posterior thigh muscles with water massage (n = 10), inactive laser device with water massage (n = 10), or a nontreatment group (n = 10)	Needle was inserted into trigger point. Once a twitch was elicited, the needle was immediately removed and a new needle was inserted, and this was repeated for 20 min. Water pressure massage was performed for 10 min	Dry needling/ acupuncture	Maximum force and endurance of knee flexors and extensors	Yes
Devereux et al[13]	6‡	40	25.6 ± 5.5	Male, 100	Field-sport athletes (any sport requiring jumping, twisting, turning, acceleration, and deceleration) practicing at least 2 times a week and competing for a championship	Randomized into 4 needling groups: (1) rectus femoris (n = 10), (2) gastrocnemius (n = 10), (3) rectus femoris and medial gastrocnemius (n = 10), (4) no dry needling (n = 10)	Dry needling was performed to active trigger points	Dry needling	My Jump app (iOS) for jump height, power output, optimal force, and optimal velocity	No
Ankle: healthy										
Huang et al[26]	5‡	45	Mean, 22.3 (range, 19-27)	Male, 100	Healthy	Participants were randomized into 5 groups: (1) manual acupuncture (n = 9), (2) electroacupuncture at 2 acupoints (n = 10), (3) manual acupuncture at 2 nonacupoints (n = 8), (4) electroacupuncture at 2 nonacupoints (n = 8), (5) control group (n = 10)	Needling was performed for 15 min in week 1, 20 min in week 2, and 30 min in weeks 3 through 8 for 3 sessions per wk	Acupuncture	Isometric dorsiflexion as measured by force transducer on custom-built device	No

Table continues on page 162.

TABLE 2 The Effects of Dry Needling on Muscle Force Production (continued)

Body Region/Study	Total PEDro Score*	Partici-pants, n	Mean ± SD Age, y	Sex, %	Type of Injury	Control/Experiment	Needling Technique	Dry Needling/ Acupuncture	Measurement of Force Production	Group Difference, Yes/No†
Huang et al[27]	4‡	30	20.9 ± 2.98	Male, 100	Healthy	Participants were placed into an electroacupuncture group (n = 15) or a control group (n = 15)	Needles were manipulated to induce a de qi sensation, a "needle sensation," then attached to electric device	Acupuncture	A pulley system where participants were required to lift weights in a 20° range of motion at the ankle	Yes
Zhou et al[54]	7‡	43	20.6 ± 2.2	Male, 100	Healthy	Participants were randomized into 4 groups: (1) manual acupuncture to acupoints in the tibialis anterior (n = 11), (2) electroacupuncture to acupoints in the tibialis anterior (n = 11), (3) electroacupuncture to sham points (n = 11), (4) control group (n = 10)	Needles were manipulated to induce a de qi sensation, a "needle sensation"	Acupuncture	Isometric dorsiflexion as measured by force transducer on custom-built device	Yes
Ankle: lateral ankle sprain										
Rossi et al[48]	8‡	20	28.9 ± 9.2	Male, 20; female, 80	Participants with lateral ankle sprain	Participants were randomized into spinal and peripheral dry needling (n = 9) or peripheral dry needling–only (n = 11) groups	Trigger point dry needling performed along the fibularis longus and brevis, and for the other group near the L5 segmental level along the multifidi and lower leg	Dry needling	Maximal ankle force with 5-s hold, balance, single-leg hop tests	No

Abbreviation: PEDro, Physiotherapy Evidence Database.
**Studies had to meet at least 7 out of 10 criteria to be deemed high quality, 5 to 6 for fair quality, and 4 or fewer for poor quality.*
†Group difference determined by 95% confidence interval.
‡No record found in the PEDro as of March 18, 2018.

Lateral shoulder abduction force was also measured by the Constant-Murley score strength subscale in adults post rotator cuff repair or proximal humeral fracture reduction via internal fixation surgery who received needling and physical therapy (n = 10) compared to physical therapy only (n = 10).[2] The study found no effect on lateral abduction strength (SMD, 0.69; 95% CI: –0.22, 1.60) after needling, because the 95% CI crossed the line of no effect.[2] The heterogeneity of the population sample (2 unrelated surgeries and lack of control of severity of either rotator cuff tears or humeral fracture) limited the ability to draw more specific conclusions. The GRADE strength of evidence regarding the use of needling therapies to improve force production in individuals with shoulder pain indicates very low–quality evidence of no effect (total estimated SMD, 0.23; 95% CI: –0.33, 0.79) (**TABLE 4**, **FIGURE 4**).

Two studies demonstrated no difference in grip strength between older adults with shoulder pain who received needling in the infraspinatus.[5,6] In one study, a needle was inserted into the most hyperalgesic active and latent trigger point in the infraspinatus; in the other study, the needle was inserted in the most hyperalgesic point in the infraspinatus.[5,6] Both studies were published by Calvo-

Lobo et al,[5,6] with the most recent study[6] (estimated SMD, −0.29; 95% CI: −0.79, 0.21) and the earlier pilot study[5] (estimated SMD, 0.23; 95% CI: −0.65, 1.11) showing evidence of no effect 1 week after treatment. A limitation of these studies is that grip strength was assessed, whereas shoulder force production was not.[5,6]

Elbow, Wrist, and Hand Three studies assessed the effects of needling in participants with lateral epicondylalgia. Davidson et al[11] found evidence of no effect (estimated SMD, 0.18; 95% CI: −0.80, 1.17) on grip strength when comparing needling to therapeutic ultrasound. Hsu et al[25] demonstrated evidence of no effect on grip strength at 8-week follow-up (estimated SMD, 0.00; 95% CI: −0.67, 0.66) when comparing needling to manipulation. Another study[18] demonstrated that needling improved isometric wrist extensor strength compared to sham needling at 2-week follow-up (estimated SMD, 0.75; 95% CI: 0.12, 1.40), but there was no difference at 2 months (estimated SMD, 0.55; 95% CI: −0.08, 1.19). Needling to improve grip strength in individuals with lateral epicondylalgia (total estimated SMD, 0.06; 95% CI: −0.49, 0.61) was given a very low strength of evidence of no effect (**TABLE 4**, **FIGURE 3**).

In one study,[53] there was a decrease in wrist flexor force production and in electromyographic signal intensity when measured immediately after needling (SMD was unable to be estimated). Another study[52] found no difference in key pinch strength (estimated SMD, 0.04; 95% CI: −0.64, 0.71) or tip pinch strength (estimated SMD, 0.09; 95% CI: −0.58, 0.76) between participants with carpal tunnel syndrome who received needling or placebo needling. Two studies[19,28] assessed the effects of needling therapies on the biceps brachii muscle after delayed-onset muscle soreness (DOMS) was induced. There was no difference between groups that received needling, sham needling, or no treatment in maximal isometric voluntary force into elbow flexion measured 1 to 3 days after DOMS.[19,28]

Knee and Thigh Region Four studies assessed the effects of force production after needling of the thigh. Needling before knee arthroplasty was not effective at improving maximum isometric knee flexion (estimated SMD, −0.13; 95% CI: −0.76, 0.51) or extension (estimated SMD, −0.17; 95% CI: −0.81, 0.47) force production when measured after surgery compared to sham needling.[39] Sixty participants with knee osteoarthritis were randomized into a manual acupuncture group or an electroacupuncture group, and there was no difference between groups in maximum voluntary isometric contraction (estimated SMD, 0.06; 95% CI: −0.44, 0.57) at a 60° angle on an isokinetic dynamometer at posttreatment.[46]

Haser et al[23] demonstrated a greater improvement in endurance of knee extensors with needling when compared to placebo (estimated SMD, 1.42; 95% CI: 0.45, 2.40) and the control group (estimated SMD, 1.22; 95% CI: 0.26, 2.17) at 4 weeks post baseline testing. Further, the needling group's knee extensor endurance was significantly better when compared to both the placebo group (estimated SMD, 1.85; 95% CI: 0.81, 2.90) and control group (estimated SMD, 1.73; 95% CI: 0.70, 2.76) at 2-month follow-up.[23] In the same study, needling resulted in greater improvement in knee flexion endurance when compared to placebo (estimated SMD, 1.44; 95% CI: 0.46, 2.42), but there was no difference in changes in knee flexion endurance when compared to the control group (estimated SMD, 0.51; 95% CI: −0.38, 1.40) at 4-week follow-up and at 2-month follow-up.[23] In another study,[13] there was evidence of no difference in jump height between a group receiving trigger point needling to the medial gastrocnemius muscle and a control group at 48-hour follow-up (estimated SMD, 0.34; 95% CI: −0.54, 1.22); no statistical significance was observed for any other groups or other measures of power and velocity.

Foot and Ankle Region Three studies assessed the effects of needling and dorsiflexion strength in healthy participants. The electroacupuncture group significantly improved dorsiflexion strength compared to the control group at 4-week follow-up (estimated SMD, 1.34; 95% CI: 0.55, 2.13).[27] The very large effect size suggests that electroacupuncture was superior to a control for improving dorsiflexion strength in healthy male participants. Another study[26] compared groups that received manual needling, sham needling, sham electroneedling, electroneedling, or control, and there was no difference in force production between treatment groups at posttreatment measurement (effect size was greater than 0.57 for all experimental groups). In the third study,[54] electroneedling, sham electroneedling, and manual needling were superior to the control group at increasing dorsiflexion strength (SMD unable to be estimated) at 6 weeks post treatment. As we were unable to estimate the effect size for this study, we were unable to compare data in this study between groups at the 6-week posttreatment time. These studies only assessed healthy male participants, had low numbers of participants, and did not satisfy the intention-to-treat analysis criterion.

One study[48] assessed the effects of needling on a population with lateral ankle sprains. Twenty individuals were randomized into 2 groups: (1) spinal needling (L5 segmental level along multifidi) and peripheral dry needling (fibularis longus and brevis), or (2) peripheral needling only. The peripheral needling group had evidence of no effect on invertor strength (estimated SMD, 0.73; 95% CI: −0.18, 1.64) on the treated side at 1-week follow-up compared to the spinal needling group. Also, there was evidence of no effect on plantar flexor evertor strength on both sides (estimated SMD, 0.47; 95% CI: −0.44, 1.36) at 1-week follow-up compared to the spinal needling group.[48] Although statistically significant improvements with medium effect sizes were noted, the CIs were wide and crossed the line of no effect.

TABLE 3 Methodological Quality Assessment of RCTs Based on 10 Internal Validity Criteria Adapted From the PEDro Scale[36]

Body Region/Study	Quality Criteria*										
	1	2	3	4	5	6	7	8	9	10	Quality†
Cervical											
Nonspecific neck pain											
Cerezo-Téllez et al[8]	Y	N	Y	N	N	Y	Y	N	Y	Y	6
Cerezo-Téllez et al[9]	Y	N	Y	N	N	Y	Y	N	Y	Y	6
Shoulder											
Nonoperative											
Adults											
Pérez-Palomares et al[45]	Y	Y	Y	N	N	Y	Y	Y	Y	Y	8
Older adults											
Calvo-Lobo et al[5]	Y	Y	Y	N	N	Y	Y	Y	Y	Y	8
Calvo-Lobo et al[6]	Y	N	Y	N	N	Y	Y	Y	Y	Y	7
Postoperative											
Arias-Buría et al[2]	Y	Y	Y	N	N	Y	Y	N	Y	Y	7
Elbow/wrist/hand											
Lateral epicondylalgia											
Hsu et al[25]	Y	N	Y	N	N	N	Y	N	Y	Y	5
Fink et al[18]	Y	N	Y	N	N	Y	Y	N	Y	Y	6
Davidson et al[11]	Y	N	N	N	N	Y	Y	N	Y	Y	5
Healthy											
Zanin et al[53]	Y	Y	?	N	N	?	Y	?	Y	Y	5‡
Carpal tunnel syndrome											
Yao et al[52]	Y	N	Y	Y	N	Y	N	N	N	Y	5
Delayed-onset muscle soreness											
Fleckenstein et al[19]	Y	Y	Y	N	N	Y	Y	N	Y	Y	7
Hübscher et al[28]	Y	Y	N	Y	N	Y	N	N	Y	N	5
Thigh/knee											
Postoperative											
Mayoral et al[39]	Y	N	Y	Y	N	Y	Y	N	Y	Y	7
Knee osteoarthritis											
Plaster et al[46]	Y	Y	Y	N	N	Y	Y	N	Y	Y	7
Healthy											
Haser et al[23]	Y	?	Y	N	N	Y	Y	N	Y	Y	6‡
Devereux et al[13]	Y	N	Y	N	N	N	Y	Y	Y	Y	6‡
Ankle											
Healthy											
Huang et al[26]	Y	?	Y	N	N	?	Y	?	Y	Y	5‡
Huang et al[27]	Y	?	?	N	N	?	Y	N	Y	Y	4‡
Zhou et al[54]	Y	Y	Y	N	N	Y	Y	N	Y	Y	7‡
Lateral ankle sprain											
Rossi et al[48]	Y	Y	Y	N	N	Y	Y	Y	Y	Y	8‡

Abbreviations: N, no; PEDro, Physiotherapy Evidence Database; ?, do not know/unclear; RCT, randomized controlled trial; Y, yes.
**1, Randomization allocation; 2, Allocation concealment; 3, Baseline comparability; 4, Subject blinding; 5, Therapist blinding; 6, Assessor blinding; 7, 85% completion of at least 1 outcome; 8, Intention-to-treat analysis; 9, Between-group statistical analysis; 10, Point/variability measures.*
†Number of "yes" scores. Studies had to meet at least 7 out of 10 criteria to be deemed high quality, 5 to 6 for fair quality, and 4 or fewer for poor quality.
‡No record found in the PEDro as of March 18, 2018.

Funnel plots were used to assess for publication bias for groups of studies where meta-analyses were performed. However, no conclusions could be made based on these funnel plots, because only 2 studies were included for each meta-analysis performed.

DISCUSSION

The purpose of this review was to determine whether inserting monofilament needles into muscles was associated with enhanced muscle force production. Strength of evidence of needling therapies to improve force production using the GRADE tool was rated moderate for nonspecific neck pain in sedentary workers. The included studies provided evidence of no effect on altering force production in participants with nonspecific and postoperative shoulder pain and with lateral epicondylalgia. Also, the level of evidence for these studies was given a very low rating per GRADE criteria. The strength of evidence for improving cervical isometric force production was moderate, and there was a medium effect size (SMD, 0.53; 95% CI: 0.41, 0.66). The majority of studies demonstrated evidence of no effect of needling on force production, with few exceptions.

The GRADE criteria were not able to be used for other studies due to force production not being measured with the same method or in a similar population. With the exception of a few studies (n = 7), the majority of studies demonstrated no effect of needling on muscle force production. Needling has not been shown to alter force production compared to placebo/control/alternative intervention in individuals with carpal tunnel syndrome, knee osteoarthritis, ankle sprains, those undergoing knee arthroscopy, and those with DOMS of the biceps brachii. There is some evidence to suggest that electroneedling was superior to control, however electroneedling was not more effective in enhancing force production than manual needling or sham needling.

There were significant limitations in the included studies for this review. Specifically, there was a strong likelihood of a placebo effect for most studies. Most studies failed to control for a potential placebo effect in their study design, except for 3 studies.[28,39,52] There was a lack of long-term follow-up for many studies, and many were limited in their conclusions due to small sample sizes and were thus susceptible to type I error.[2,5,6,11,13,18,23,26,28,39,46,48,52,53] Further, few (n = 4) of the included studies followed the Consolidated Standards of Reporting Trials (CONSORT) statement on reporting standards for studies, which limited this investigation's ability to properly assess methodologies.[5,6,45,52] Finally, only 8 of the 21 included studies registered their trials, which prevented assessment of reporting bias.[2,6,8,9,25,26,45,53]

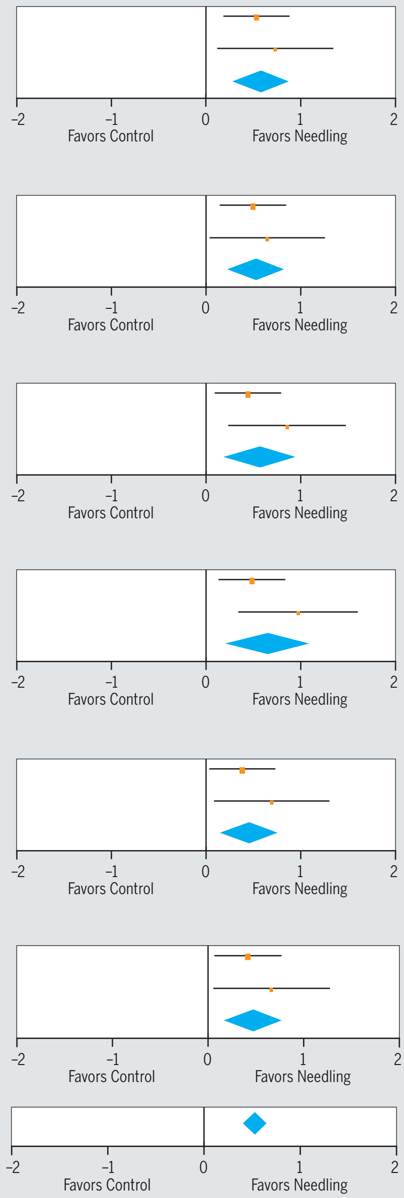
TABLE 4 Summary of Findings for Needling Therapies Using GRADE

	Cervical Isometric Force Production in Participants With Nonspecific Neck Pain[8,9]	Shoulder Lateral Abduction Force Production in Participants With Shoulder Pain[2,45]	Grip Force Production in Participants With Lateral Epicondylalgia[11,25]
Quality assessment			
Studies, n	2	2	2
Study design	Randomized trials	Randomized trials	Randomized trials
Risk of bias	Not serious	Not serious	Serious*
Inconsistency	Not serious	Serious†	Not serious
Indirectness	Not serious	Not serious	Not serious
Imprecision	Serious‡	Very serious‡§	Very serious‡§
Other considerations	None	Possible publication bias	None
Patients, n			
Needling therapies	86	67	27
Other treatments	86	73	24
Absolute effect‖	0.53 (0.41, 0.66)	0.23 (–0.33, 0.79)§	0.06 (–0.49, 0.61)§
GRADE quality of evidence	Moderate	Very low	Very low
Summary of findings	Needling to trigger points in muscles of the cervical spine and shoulder significantly improved isometric cervical strength	Needling to the shoulder muscles did not improve shoulder lateral abduction strength as measured by the Constant-Murley score strength subscale	Needling was shown to be no better than ultrasound or radial-head manipulation

Abbreviations: GRADE, Grading of Recommendations Assessment, Development and Evaluation; PEDro, Physiotherapy Evidence Database.
**Greater than 25% of studies have a PEDro scale score less than 6.*
†Statistically significant heterogeneity.
‡Small sample size (less than 400).
§Wide confidence intervals.
‖Values are standardized mean difference (95% confidence interval).

Cervical Isometric Force Production

Subgroup/Study	Needling Mean ± SD	Needling Total, n	Control Mean ± SD	Control Total, n	Weight	SMD IV, Random (95% Confidence Interval)
Cervical extension						
Cerezo-Téllez et al[9]	131.7 ± 65.68	64	99.68 ± 51.48	64	12.4%	0.54 (0.19, 0.89)
Cerezo-Téllez et al[8]	103.1 ± 33.9	22	80.3 ± 26.4	22	4.1%	0.74 (0.12, 1.35)
Subtotal*		86		86	16.6%	0.59 (0.28, 0.89)
Cervical flexion						
Cerezo-Téllez et al[9]	122.9 ± 74.4	64	91.39 ± 49.89	64	12.5%	0.49 (0.14, 0.85)
Cerezo-Téllez et al[8]	86.3 ± 28.4	22	69.8 ± 21.3	22	4.2%	0.65 (0.04, 1.25)
Subtotal†		86		86	16.7%	0.53 (0.23, 0.84)
Cervical left rotation						
Cerezo-Téllez et al[9]	113.8 ± 54.58	64	91.8 ± 43.52	64	12.6%	0.44 (0.09, 0.79)
Cerezo-Téllez et al[8]	83.8 ± 25.3	22	64.5 ± 18.4	22	4.0%	0.86 (0.24, 1.48)
Subtotal‡		86		86	16.6%	0.57 (0.20, 0.94)
Cervical right rotation						
Cerezo-Téllez et al[9]	111.9 ± 53.06	64	88.99 ± 40.32	64	12.5%	0.48 (0.13, 0.83)
Cerezo-Téllez et al[8]	85.2 ± 24.4	22	63.9 ± 18.3	22	3.9%	0.97 (0.34, 1.60)
Subtotal§		86		86	16.5%	0.65 (0.20, 1.11)
Cervical left sidebending						
Cerezo-Téllez et al[9]	111.5 ± 61.88	64	91.29 ± 41.12	64	12.7%	0.38 (0.03, 0.73)
Cerezo-Téllez et al[8]	88.5 ± 26.8	22	70.5 ± 24.2	22	4.2%	0.69 (0.08, 1.30)
Subtotal‖		86		86	16.8%	0.46 (0.16, 0.76)
Cervical right sidebending						
Cerezo-Téllez et al[9]	114.6 ± 62.08	64	92.49 ± 41.36	64	12.6%	0.42 (0.07, 0.77)
Cerezo-Téllez et al[8]	90.5 ± 26.7	22	72.5 ± 26.7	22	4.2%	0.66 (0.05, 1.27)
Subtotal¶		86		86	16.8%	0.48 (0.17, 0.78)
Total#		516		516	100.0%	0.53 (0.41, 0.66)



Abbreviations: IV, independent variable; SMD, standardized mean difference.

*Heterogeneity: $\tau^2 = 0.00$, $\chi^2 = 0.30$, $df = 1$ ($P = .58$), $I^2 = 0\%$. Test for overall effect: $z = 3.77$ ($P<.001$).

†Heterogeneity: $\tau^2 = 0.00$, $\chi^2 = 0.18$, $df = 1$ ($P = .67$), $I^2 = 0\%$. Test for overall effect: $z = 3.43$ ($P<.001$).

‡Heterogeneity: $\tau^2 = 0.02$, $\chi^2 = 1.30$, $df = 1$ ($P = .25$), $I^2 = 23\%$. Test for overall effect: $z = 2.99$ ($P = .003$).

§Heterogeneity: $\tau^2 = 0.05$, $\chi^2 = 1.76$, $df = 1$ ($P = .19$), $I^2 = 43\%$. Test for overall effect: $z = 2.82$ ($P = .005$).

‖Heterogeneity: $\tau^2 = 0.00$, $\chi^2 = 0.75$, $df = 1$ ($P = .39$), $I^2 = 0\%$. Test for overall effect: $z = 2.97$ ($P = .003$).

¶Heterogeneity: $\tau^2 = 0.00$, $\chi^2 = 0.47$, $df = 1$ ($P = .49$), $I^2 = 0\%$. Test for overall effect: $z = 3.08$ ($P = .002$).

#Heterogeneity: $\tau^2 = 0.00$, $\chi^2 = 5.41$, $df = 11$ ($P = .91$), $I^2 = 0\%$. Test for overall effect: $z = 8.39$ ($P<.001$). Test for subgroup differences: $\chi^2 = 0.79$, $df = 5$ ($P = .98$), $I^2 = 0\%$.

FIGURE 2. Effects of dry needling on cervical isometric force production. Cerezo-Téllez et al[8]: 30 days from baseline. Cerezo-Téllez et al[9]: 21 days from baseline. Means and standard deviations were estimated for Cerezo-Téllez et al[9] algebraically. Isometric force production was reported in Newtons.

Placebo Effect

These methodological drawbacks from needling therapy studies lead to a high risk of performance bias and lack of control of the placebo effect. Few studies (n = 8) had a control group or a group that did not receive any treatment, which limits our ability to determine the magnitude of the placebo effect for needling therapies (**TABLE 2**). In most studies, needling versus sham needling resulted in no difference between groups, suggesting that a placebo effect was, at least, potentially responsible for the changes in force production. Because none of the included studies specified details of the subject-investigator interaction, it was impossible to assess the context of the intervention.[40] Indeed, context is an important component of the placebo effect. Future studies should include more rigorous control of the placebo effect by scripting the subject-investigator interaction and explanation of the tested effects to adequately ensure that this interaction is identical for both the experimental and sham conditions.[40] Failure to control the placebo effect can lead to increased risk of bias and limit the conclusions this review can make on the effects of needling on force production.

Studies that demonstrated that needling was not superior to other treatment or sham needling suggest that it may not matter whether a participant received needling intervention, as long as he or she received treatment. Studies that demonstrated that needling was superior to other treatments may have effectively demonstrated the power of a placebo effect rather than a change in muscle function to maximize force production.

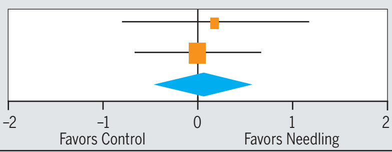
Short- and Long-Term Effects of Needling Therapies

Most of the included studies only assessed the short-term effects of needling. Force production was often assessed at posttreatment and a few weeks after treatment (n = 19), with only a couple studies assessing outcomes at 3 or 6 months post treatment (n = 2). Needling could be an effective adjunct intervention to facilitate force production in the short term, but may become ineffective in the long term once adequate strength is achieved by the patient—similar to neuromuscular electrical stimulation, which in the early stages of anterior cruciate ligament reconstruction rehabilitation improves quadriceps strength but is no longer needed when a patient has achieved adequate quadriceps strength.

Very few studies assessed long-term effects of needling. Pérez-Palomares et al[45] found evidence of no effect immediately post needling (SMD, 0.05; 95% CI: −0.31, 0.41) of the shoulder for altering lateral abduction strength, and no effect of needling at 3 months (SMD, −0.09; 95% CI: −0.45, 0.27). The available data

Isometric Grip Force Production

Subgroup/Study	Needling Mean ± SD	Needling Total, n	Control Mean ± SD	Control Total, n	Weight	SMD IV, Random (95% Confidence Interval)
Elbow						
Davidson et al[11]	138.2 ± 93.4	8	117.3 ± 120.4	8	31.4%	0.18 (−0.80, 1.17)
Hsu et al[25]	191.2 ± 80.0	19	191.4 ± 94.8	16	68.6%	0.00 (−0.67, 0.66)
Total*		27		24	100.0%	0.06 (−0.49, 0.61)

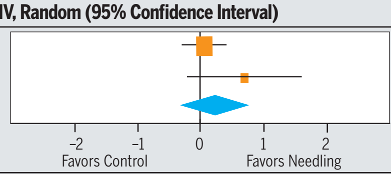


Abbreviations: IV, independent variable; SMD, standardized mean difference.
**Heterogeneity: $\tau^2 = 0.00$, $\chi^2 = 0.09$, $df = 1$ ($P = .76$), $I^2 = 0\%$. Test for overall effect: $z = 0.20$ ($P = .84$).*

FIGURE 3. Effect of dry needling on isometric grip force production in participants with lateral epicondylalgia. Davidson et al[11]: 14 days from baseline. Hsu et al[25]: 56 days from baseline. Force production was reported in kilograms and was changed to Newtons for this figure.

Shoulder Lateral Abduction Force Production

Study	Needling Mean ± SD	Needling Total, n	Control Mean ± SD	Control Total, n	Weight	SMD IV, Random (95% Confidence Interval)
Pérez-Palomares et al[45]	4.91 ± 2.46	57	4.76 ± 3.07	63	72.3%	0.05 (−0.31, 0.41)
Arias-Buría et al[2]	11.5 ± 4.8	10	8.0 ± 4.9	10	27.7%	0.69 (−0.22, 1.60)
Total*		67		73	100.0%	0.23 (−0.33, 0.79)



Abbreviations: IV, independent variable; SMD, standardized mean difference.
**Heterogeneity: $\tau^2 = 0.08$, $\chi^2 = 1.64$, $df = 1$ ($P = .20$), $I^2 = 39\%$. Test for overall effect: $z = 0.81$ ($P = .42$).*

FIGURE 4. Short-term effect of dry needling on shoulder lateral abduction force production. Pérez-Palomares et al[45]: at posttreatment. Arias-Buría et al[2]: 1 week from baseline. Force production was measured using the Constant-Murley score strength subscale.

do not enable meaningful conclusions regarding the effects of needling on force production of the shoulder musculature.

Furthermore, we recognize that a more direct measure of force production using dynamometry, as opposed to the Constant-Murley score strength subscale, may yield different results. For cervical isometric force production, a medium effect (pooled SMD, 0.53; 95% CI: 0.41, 0.66) was found at 21 and 30 days post treatment, and a medium to large effect (pooled SMD, 0.63; 95% CI: 0.51, 0.76) was maintained at 45 and 180 days post treatment.[8,9] This suggests that, at least at the cervical spine, needling can improve force production up to 180 days post treatment. These studies, however, were published by the same author group and, when pooled together, only yielded 86 participants per group.

Application of Needling Therapies to Improve Force Production

This review found that needling therapy may enhance force production compared to placebo/control groups for nonspecific neck pain in sedentary workers. Needling the cervical spine to improve isometric force production was given a moderate strength of evidence by following the GRADE criteria. Interestingly, as part of a physical therapy clinical practice guideline for the treatment of chronic neck pain in a multimodal approach, needling has received the highest recommendation, compared to other guidelines for other joints.[4] Other physical therapy clinical practice guidelines for other joints have rated the use of needling significantly lower.[4,7,10,15,29,35,37,38,51] Although only a few studies qualified for meta-analysis, the majority of studies found evidence of no effect of needling on force production, with the exception of a few (n = 7). Many had aforementioned methodological drawbacks and small numbers of participants, which limits our conclusions on the effects of needling on muscle force production.

Limitations

This review has several limitations to consider. First, the search was conducted in only 3 databases, which may limit the number of studies yielded (**APPENDIX**). PubMed was utilized because of its search capability to employ Medical Subject Headings terms and because PubMed commonly produces more references than other databases. CINAHL and SPORTDiscus were chosen specifically for their focus on journals associated with allied health care professions and on research related to sports and muscle physiology. Further, only articles written in English were included, which may limit the scope of some of the acupuncture literature. There was a formal assessment of publication bias of the studies grouped for meta-analysis using funnel plots; however, conclusions on publication bias were limited due to the low number of studies. None of the manuscript authors are acupuncturists, and a large number of articles were eliminated from this review based on the insertion of needles solely via traditional acupuncture constructs. Further, meta-analysis was not possible for all articles secondary to heterogeneity of the studies. Despite the limitations of our study, this is, to our knowledge, the only review to formally assess muscle force generation after needling and provide recommendations based on the quality and strength of the literature.

Future Research

Future studies should use reliable and valid methods of measurement, larger samples of participants, standardized needling techniques, and longer-term follow-up for clinicians to better select patient candidates for needling. Higher-quality articles with adequate power that control for the placebo effect and follow accepted reporting standards are necessary to fully understand the effects of needling on force production. Additional studies should conceal participant allocation using more robust randomization and blinding methods to reduce selection bias, reduce reporting bias by satisfying "intention-to-treat analysis," and include a control group that does not receive treatment to better understand the magnitude of the placebo effect. By mitigating these common risks of bias in needling studies, we can better understand whether the proposed effects of needling are only secondary to the placebo effect or to improved muscle function.

CONCLUSION

THE MAJORITY OF STUDIES SUGGEST NO effect of dry needling on force production. High-quality studies with adequate power that control for the placebo effect and follow accepted reporting standards could make valuable contributions to the literature. Some data suggest a potential for improved cervical strength following needling, with a moderate strength of evidence rating per GRADE criteria. ◉

KEY POINTS

FINDINGS: The majority of evidence suggests no effect of dry needling on force production. Needling was shown to improve muscle force production in those with neck pain. Those studies where strength of evidence could be rated with Grading of Recommendations Assessment, Development and Evaluation (GRADE) criteria demonstrated moderate- to very low–quality evidence.

IMPLICATIONS: Overall, there is insufficient evidence to support the use of dry needling as an intervention to increase strength.

CAUTION: This review was limited due to a narrow search strategy. Further, meta-analysis was not able to be performed on all studies. Most included studies had a high risk of bias and methodological quality concerns.

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APPENDIX

SEARCH TERMS USED IN PUBMED, SPORTDISCUS, AND CINAHL

Specific Search	Term Combination
General	Head or cervical or neck or temporomandibular or shoulder or elbow or wrist or finger or arm or thoracic or rib or lumbar or low back or spine or back or pelvis or sacroiliac or hip or knee or thigh or ankle or foot or toe or muscle or joint or myofascial pain syndromes or myofascial or trigger points or muscle tone or skeletal muscle or musculoskeletal system or muscle fibers or fast-twitch muscle fibers or slow-twitch muscle fibers or muscle spindles or tissues or acupoints or ah-shi points or acupuncture points
Intervention	Trigger point acupuncture or acupuncture trigger point therapy or dry needling or acupuncture or myofascial trigger point needling or needle or Intramuscular needling or traditional Chinese medicine acupuncture
Strength	Strength or isokinetic or manual muscle testing or torque or power or speed or acceleration or dynamometry or force or EMG or electromyography or isometric or isotonic
"NOT" terms	Cancer or radiotherapy or laryngectomy or oviariectomy or laser or botulinum toxin or laparoscopic or bone grafting or immunotherapy or sleep or autoinjector device or poison or thyroid or photoneuromodulation or radiofrequency or robotic surgery or oxytocin or tumor
Final search	"General" terms and "intervention" terms and "strength" and "NOT" terms

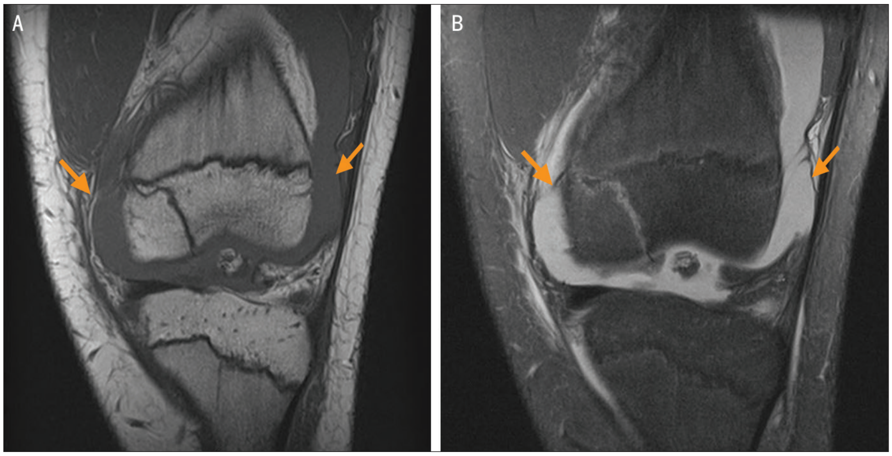

FIGURE 1. (A) T1-weighted and (B) T2-weighted magnetic resonance images coronal view showing a fracture that begins at the physis and extends to the articular surface. Hemarthrosis is present (arrows).

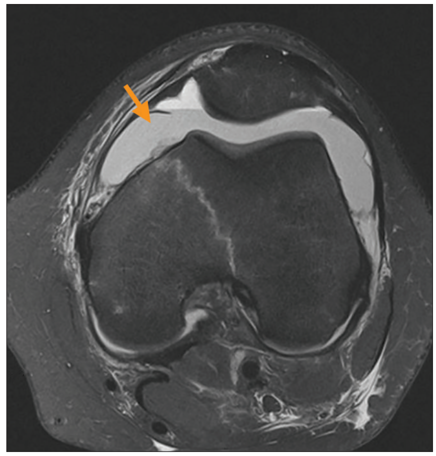

FIGURE 2. T2-weighted, fat-saturated magnetic resonance image axial view that shows a fracture (anterior to posterior from the medial femoral condyle) into the trochlear notch. Hemarthrosis is present (arrow).

Salter-Harris Type III Fracture in a Football Player

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A 15-YEAR-OLD HIGH SCHOOL FOOTBALL player sustained direct impact to his anteromedial left knee by a teammate's helmet during practice. He denied hearing an audible pop, but was unable to weight bear on the left leg. An initial on-field evaluation by the athletic trainer and team physician suggested an injury to the medial aspect of the knee, due to localized medial side pain and swelling. Valgus stress tests at 0° and 30° of knee flexion to assess medial knee stability were inconclusive due to muscle guarding. The physician referred the athlete immediately to an after-hours clinic for imaging to rule out a fracture.

Radiographs of the knee showed a nondisplaced Salter-Harris type II fracture. Because displacement of epiphyseal fractures is often underestimated on radiographs,[1] the treating physician ordered magnetic resonance imaging. The results of the magnetic resonance imaging allowed for a more specific diagnosis of the fracture as a Salter-Harris type III fracture of the left femur, as the fracture line extended into the articular surface (**FIGURES 1A**, **1B**, and **2**). This additional information helped determine the most appropriate treatment.[1,2]

Nonsurgical management, consisting of non–weight-bearing immobilization in a brace to control range of motion and a physical therapy program of non–weight-bearing lower extremity strengthening, edema control, and restoration of range of motion for 6 weeks, was prescribed. At 6 weeks, weight-bearing strengthening and proprioception exercises were incorporated into his rehabilitation program after physician clearance. He returned to running and agilities at 3 months, and to unrestricted physical activities (full sports participation) at 6 months. *J Orthop Sports Phys Ther 2019;49(3):209. doi:10.2519/jospt.2019.7984*

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Influence of Aging on Lower Extremity Sagittal Plane Variability During 5 Essential Subphases of Stance in Male Recreational Runners

Movement coordination is the ability of the central nervous system to organize and sequence joint pairs to create functional movements.[7,26,37] An increase in coordination strategies, or variability, represents an increasingly adaptive nervous system, whereas a decrease in variability implies a less adaptive system.[19,29] According to dynamic systems theory, coordination strategies are varied to manage intrinsic and extrinsic constraints placed on the body.[32] Common intrinsic constraints in the lower extremities are available motions at each joint[2,24] and the relative speed of each motion.[13,38] Conversely, extrinsic constraints can be environmental and task-oriented factors such as running-surface compliance[6] and speed adjustments away from preferred.[7] Normal aging, while a gradual process, is a decidedly influential constraint obscuring the balance between nervous system control and flexibility.

BACKGROUND: Interjoint coordination variability is a measure of the ability of the human system to regulate multiple movement strategies. Normal aging may reduce variability, resulting in a less adaptive system. Additionally, when older runners are asked to run at speeds greater than preferred, this added constraint may place older runners at greater risk for injury.

OBJECTIVES: To examine the influence of normal aging on coordination variability across 5 distinct subphases of stance in runners during preferred and fixed speeds.

METHODS: Twelve older (60 years of age or older) and 12 younger (30 years of age or younger) male recreational runners volunteered for this cross-sectional study. Three-dimensional gait analyses were collected at preferred and fixed speeds. Stance phase was divided into 5 subphases: (SP1) loading response, (SP2) peak braking, (SP3) peak compression, (SP4) midstance, and (SP5) peak propulsion. Continuous relative phase variability for sagittal plane joint pairs—hip-knee, knee-ankle, and hip-ankle—was calculated. Repeated-measures linear mixed models were employed to compare variability for each joint pair.

RESULTS: An age-by-stance subphase interaction was found for knee-ankle ($P<.01$) and hip-ankle ($P<.01$) pairs, while main effects for age and stance subphase were found for the hip-knee pair ($P<.05$). Specifically, loading response and peak braking variability were lower in older runners and greater across stance for knee-ankle and hip-ankle pairs, while midstance was lowest in the hip-knee pair for older and younger runners. No effects for running pace were found.

CONCLUSION: Less adaptive movement strategies seen in older runners may partially contribute to the increased eccentric stresses during periods of high load. *J Orthop Sports Phys Ther 2019;49(3):171-179. Epub 30 Nov 2018. doi:10.2519/jospt.2019.8419*

KEY WORDS: *aging, coordination, gait analysis, mechanics, motor control*

It is widely recognized that normal aging impacts running mechanics,[2,11,16] most prominently in the sagittal plane,[23,33] where decreases in joint excursions distally[1] place runners in more extended postures proximally.[34] Additionally, preferred running speed is significantly slowed with aging,[11] suggesting that older runners adjust their preferred paces to maintain metabolically efficient gait patterns.[31] However, many studies match running speeds in order to limit speed's influence on their results.[1,18,22] Introducing an extrinsic constraint to the system, such as a fixed pace, likely requires older runners to establish altered coordination strategies, affecting their variability. Additionally, many runners train as part of recreational or competitive teams, resulting in group paces that are not unique to each runner. Therefore, examining both preferred paces and deviations from preferred paces may help

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elucidate coordination differences found in recreational runners when training in more natural group environments.

The potential influences of speed and aging on coordination variability highlight the importance of a flexible neuromuscular system in the presence of novel motor tasks. For example, when asked to change walking speeds, older adults constrain their variability, while younger adults continuously vary their movement strategies to meet the demands of the task.[8] One method to quantify coordination variability is to estimate continuous relative phase (CRP) variability, a spatiotemporal measure that measures interjoint coordination and variability based on phase-planes.[38] Phase planes describe the inherent stability of a moving joint by estimating its angular position (spatial) and velocity (temporal) across the gait cycle.[20]

Continuous relative phase has previously been used to assess injury,[20,22,29] training,[15] and sex[1] differences in active adults. However, inconsistencies in results have been recognized, in part due to averaging values across the stance phase.[22] Normal aging is known to affect both braking and propulsive components of running,[2,4,12] with greater effects noted during braking.[4] Alterations in braking and horizontal forces may place runners at economical disadvantages.[5] Thus, examining coordination variability during specific subphases of stance may assist with highlighting unique changes occurring during essential stance-phase events.

The purpose of this study was to examine the effects of healthy aging on sagittal plane interjoint coordination variability in distinct subphases of stance during a running task at a preferred and a fixed pace. We hypothesized that older runners would have lower variability compared to younger runners and that this difference would be influenced by the running pace. Additionally, we hypothesized that the amount of variability exhibited by each coupling pair would be influenced by unique subphases of stance.

METHODS

Twelve older (mean ± SD age, 63.7 ± 2.6 years; height, 1.78 ± 0.06 m; weight, 75.2 ± 8.2 kg) and 12 younger (age, 23.3 ± 2.4 years; height, 1.80 ± 0.08 m; weight, 77.3 ± 12.2 kg) male runners volunteered to participate. Inclusion criteria were 30 or fewer years of age and 60 or more years of age, and running at least 16.1 km a week consistently for the last 6 months.[37] Training experience and habitual strike pattern (rearfoot or mid/forefoot) were not controlled, allowing for greater representation of typical running profiles. However, similar distributions of habitual strike patterns were noted between those in the older group (mid/forefoot, 3; rearfoot, 9) and those in the younger group (mid/forefoot, 4; rearfoot, 8). Participants were screened for eligibility using a medical history and injury questionnaire and were excluded from the study if they had any current health or medical complications and/or had any current (in the last 4 weeks) running-related lower extremity injuries. Written informed consent was obtained from each participant prior to the start of the study. All experimental procedures were approved by the Institutional Review Board of Virginia Commonwealth University.

Upon arriving, participants were fitted with neutral running footwear (New Balance 690; New Balance, Boston, MA). Passive retroreflective markers were placed on the lower extremities to establish rigid body segments representing the pelvis, thigh, shank, and foot. Anatomical markers were placed bilaterally over the iliac crests, L5-S1, greater trochanters, medial and lateral femoral condyles, medial and lateral malleoli, and first and fifth metatarsal heads to establish segment coordinate systems and joint centers of the hips, knees, and ankles.[40] Rigid clusters were placed on the pelvis, thigh, shank, and foot to track segments. Segmental tracking clusters were located along L5-S1 and the bilateral iliac crests, the posterolateral thigh, the distal shank, and the posterolateral heel. A static trial was collected in standing to establish joint centers, segment lengths, and relative positions of tracking markers. Following the static trial, anatomical markers were removed and the pelvis, thigh, shank, and foot were tracked using clusters of 4, 4, 4, and 3 markers, respectively.

Next, participants were instructed to run on a force-plate instrumented treadmill (Treadmetrix, Park City, UT) while 3-D kinematics and kinetics were recorded. Prior to collection, each participant began walking at a comfortable speed (approximately 0.45 to 0.67 m/s) until the participant verbally reported that he was ready to begin running. The treadmill speed increased incrementally until the participants verbally reported that they had reached their preferred running pace. Each participant ran at that pace for an additional 2 minutes until giving verbal confirmation that his gait had normalized. A 30-second period was recorded to capture approximately 30 to 45 foot strikes per side. Following the first collection, each participant was returned to a comfortable walking speed and, when ready (by verbal confirmation), increased up to a previously determined fixed speed of 3.35 m/s. The familiarization and collection processes were similarly repeated.

Data from the right lower extremity were analyzed for all participants. Markers were tracked using a 5-camera motion-analysis system and associated Track Manager software (Qualisys AB, Gothenburg, Sweden) to reconstruct the 3-D coordinates for each marker. Kinematic data were collected at a 120-Hz sampling rate and filtered with a fourth-order, low-pass Butterworth filter at 12 Hz. Ground reaction force was collected at a 1200-Hz sampling rate and used to establish critical events during each stance subphase. Three-dimensional joint angles were calculated with respect to the proximal segment using an *x*-*y*-*z* Cartesian coordinate system. Angular positions and velocities were calculated for hip flexion/extension, knee flexion/extension, and ankle dorsiflexion/plantar flexion. Stance phase was normalized to 101 data points. Visual3D (C-Motion, Inc, Germantown, MD) software was used to generate the 3-D kinematic and kinetic variables of interest.

Stance phase was defined as initial contact (vertical ground reaction force greater than 80 N) to toe-off (vertical ground reaction force less than 80 N) and divided into 5 subphases, based on vertical and horizontal anteroposterior maxims. The first subphase (SP1), "loading response," was defined as the percent of stance from initial contact to peak vertical impact force. This period is characterized by a stark increase in vertical forces, resulting in high loading rates and large impact peaks. When participants did not generate a notable impact peak, the maximum force between 8% and 12% of stance[27] was used. The second subphase (SP2), "peak braking," was defined as the period of stance from SP1 to peak horizontal posterior force. Peak braking represents the eccentric work required by the lower extremity to decelerate the center of mass prior to midstance. The third subphase (SP3), "peak compression," represents the percent of stance from SP2 to peak vertical active force. This period is characterized by peak knee flexion and center-of-mass displacement prior to midstance, when vertical forces are greatest and elastic energy can be estimated.[28] The fourth subphase (SP4), "midstance," represents the transition from posterior to anterior forces and marks the beginning of the propulsive phase. Finally, the fifth subphase (SP5), "peak propulsion," was defined as the percent of stance from SP4 to maximal anterior or horizontal force. This period represents peak positive work and power generation prior to toe-off. A graphical representation of the 5 subphases of stance in relation to a runner's typical running form and ground reaction forces is provided in **FIGURE 1**.

A custom MATLAB program (The MathWorks, Inc, Natick, MA) was used to calculate CRP estimates. Phase plots were constructed for hip, knee, and ankle flexion/extension or dorsiflexion/plantar flexion patterns using normalized angular position and velocity curves (**FIGURE 2**). Calculation methods for CRP were employed in accordance with previous studies[15,20,22,39] to allow for comparisons of results. In brief, sagittal plane joint angles and velocities for the hip, knee, and ankle were exported and interpolated to 100% of the stance phase. Angular position (equation 1) and velocity (equation 2) were normalized to a range of –1 to +1 to minimize differences in individual amplitude and frequency.[1,15,22,39] Specifically, the normalized minimum, maximum, and midpoint joint angles were defined as –1, +1, and 0, respectively, and used to calculate the normalized angular position at each percent of stance. Normalized

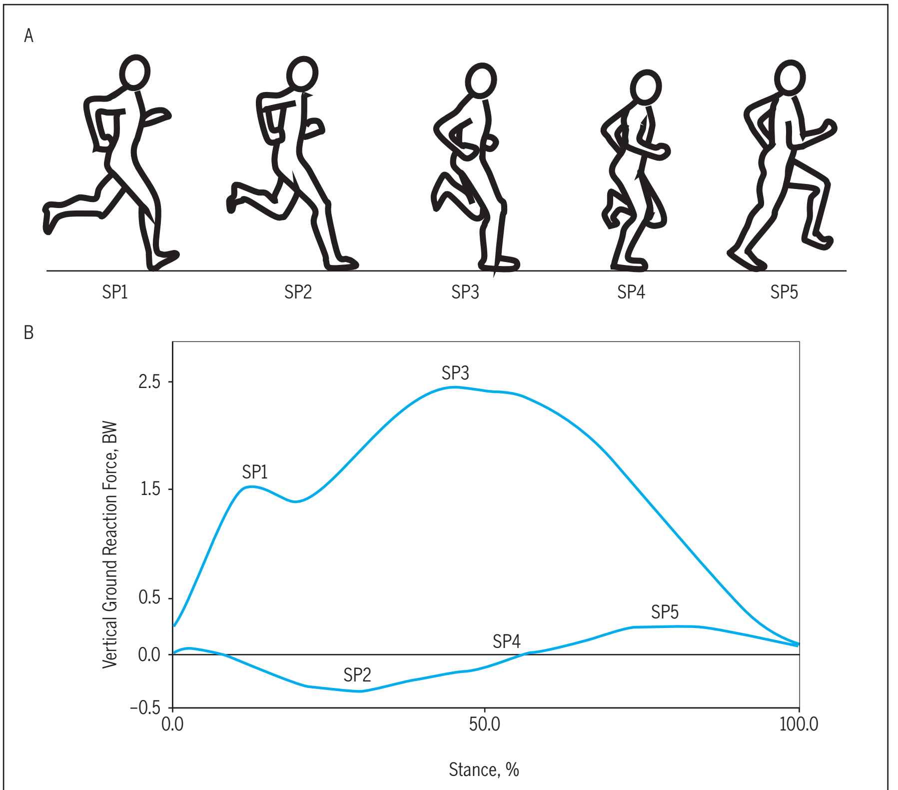

FIGURE 1. Illustrated and graphical representations of the 5 subphases of stance in relation to (A) running technique and (B) vertical and horizontal ground reaction forces. Abbreviations: BW, body weight; SP1, stance subphase 1 (loading response); SP2, stance subphase 2 (peak braking); SP3, stance subphase 3 (peak compression); SP4, stance subphase 4 (midstance); SP5, stance subphase 5 (peak propulsion).

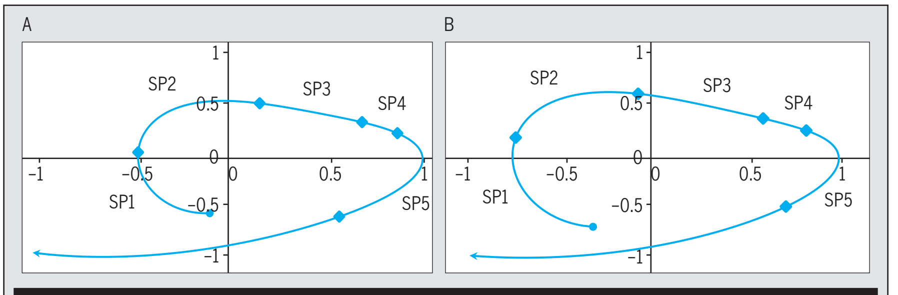

FIGURE 2. Normalized ankle joint phase plots for (A) younger and (B) older runners. Angular position moves along the *x*-axis and angular velocity moves along the *y*-axis. Circles and arrows depict initial contact and toe-off, respectively. Diamonds represent subphase segments. Abbreviations: SP1, stance subphase 1 (loading response); SP2, stance subphase 2 (peak braking); SP3, stance subphase 3 (peak compression); SP4, stance subphase 4 (midstance); SP5, stance subphase 5 (peak propulsion).

maximum joint velocity was defined as +1 and used to normalize angular velocity at each percent of stance.

Equation 1, normalized angular position: $\theta_i = \{\theta_i - [(\theta_{min} - \theta_{max})/2]\}/[(\theta_{max} - \theta_{min})/2] - 1$

Equation 2, normalized angular velocity: $\omega_i = \omega_i/|\omega|_{max}$, where θ is joint angle, ω is joint velocity, and i is a data point.

Phase angles (φ) for all 100 data points were calculated as $\varphi = \tan^{-1}(\omega/\theta)$, and represent the angle formed between the origin, data point, and right horizontal. Mean ensemble CRP curves were generated by subtracting the distal joint phase angle from the proximal joint phase angle (**FIGURES 3A** through **3C**). A CRP phase angle of 0° indicates that the 2 joint segments are in phase, while a CRP angle of ±180° indicates that the 2 joint segments are antiphase. A positive CRP angle indicates that the proximal joint leads the distal, whereas a negative CRP angle indicates the reverse.

To investigate group differences in sagittal plane coordination variability, interjoint coordination pairs of hip flexion/extension-knee flexion/extension (H-K), knee flexion/extension-ankle dorsiflexion/plantar flexion (K-A), and hip flexion/extension-ankle dorsiflexion/plantar flexion (H-A) were examined. Mean ensemble curves from all trials during the 30-second collection were averaged for each participant at each pace. Continuous relative phase variability (equation 3) was defined as the deviation in phase and was calculated as the between-stride standard deviations for each data point during the stance phase.[4]

Equation 3, variability: $\sum^{N}_{i} SD_i / N$

Continuous relative phase variability was calculated for each subphase of stance (SP1-SP5), for each coupling pair (H-K, H-A, K-A), and at each running pace (preferred versus fixed).

Statistical Analysis

Descriptive statistics for participant characteristics, ground reaction forces, loading rates, and variability measures, grouped by age, pace, and coupling pair where appropriate, were calculated as overall means and standard deviations. A power analysis for analysis of variance was used to calculate sample size. The parameters for the analysis were set as follows: power of 0.80, a type I error rate threshold of .05, and a large effect size of 0.50 to determine a sample size of 11.4 per group. Student t tests were employed to examine differences in group characteristics, group vertical and horizontal forces by pace, and pace vertical and horizontal forces by age group. Results are provided in **TABLES 1** and **2**. Group differences in CRP variability across the 5 subphases of stance during preferred-pace and fixed-pace running conditions were examined using repeated-measures generalized linear mixed models. A linear mixed model was employed to account for repeated within-subject variability measures during 2 running conditions. Linear mixed models were employed for each joint coupling pair, and, when appropriate, post hoc comparisons were employed using the Tukey-Kramer adjustment for multiple comparisons. All statistical analyses were performed using SAS (SAS Institute Inc, Cary, NC) software. Significance was set at $\alpha<.05$.

RESULTS

Significantly slower preferred paces were demonstrated by older runners compared to younger runners and the fixed pace. Summary statistics for participant vertical and horizontal ground reaction forces, normalized to body weight at each subphase of stance (SP1-SP5, excluding midstance), and speed of collection by age group are provided in **TABLE 2**. Older runners were found to exhibit significantly lower vertical and horizontal ground reaction forces at all subphases when running at their preferred pace, while force differences by age group at the fixed pace were only significant for SP2 and SP5. Additionally, younger runners exhibited similar vertical and horizontal forces at both paces, while older runners exhibited lower forces during preferred running for SP1 and SP5. Surprisingly, no group mean differences in loading rate were found at either pace,

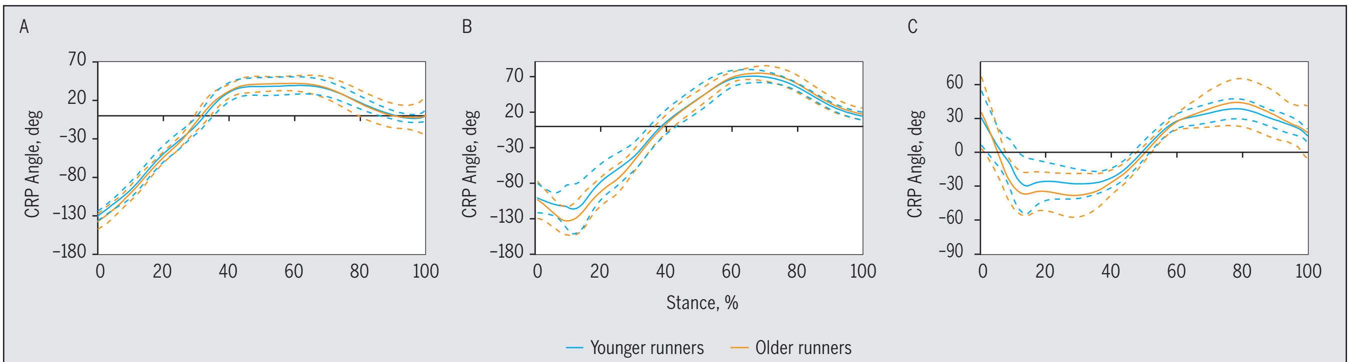

FIGURE 3. Group mean ensemble curves for the (A) hip-knee pair, (B) the hip-ankle pair, and (C) the knee-ankle pair across the stance phase. Blue lines indicate younger runners' mean CRP angles (dashed lines represent standard deviation). Orange lines indicate older runners' mean CRP angles (dashed lines represent standard deviation). Abbreviation: CRP, continuous relative phase.

and no pace differences were noted within each age group.

Age-group means and standard deviations for each subphase of stance for each interjoint coordination pair at each pace are provided in **TABLE 3**. A repeated-measures generalized linear mixed model was employed to examine age-group differences in variability across 5 subphases of stance during preferred- and fixed-pace running conditions. The H-K interjoint coordination variability revealed no main effect for pace (*P* = .35) or significant age-by-stance subphase interaction (*P* = .31) or age-by-pace interaction (*P* = .77). A significant main effect for age (*P*<.01) was found, with significantly lower variability in older runners (mean, 6.98; 95% confidence interval: 5.97, 8.0) versus younger runners (mean, 9.91; 95% confidence interval: 8.89, 10.9). Additionally, a significant main effect for stance subphase was noted (*P*<.01), with SP4 (midstance) demonstrating significantly lower variability than SP1, SP2, and SP5 (*P*<.01) (**FIGURE 4A**).

The H-A interjoint coordination variability revealed no main effect for pace (*P* = .62) or significant age-by-pace interaction (*P* = .83). There was a significant age-by-stance subphase interaction (*P*<.01), with older runners demonstrating lower variability during SP1 (loading response) and SP2 (peak braking) (*P*<.01) than younger runners, while no differences were noted between SP3, SP4, and SP5 (**FIGURE 4B**). In younger runners, SP1 exhibited the greatest amount of variability compared to SP2 through SP5 (*P*<.01), and SP2 exhibited greater variability than SP3 through SP5 (*P*<.01). No differences were noted between SP3, SP4, and SP5. In older runners, SP1 and SP2 exhibited greater variability than SP3 through SP5 (*P*<.05), while no differences were noted between SP3, SP4, and SP5.

Last, K-A interjoint coordination variability revealed no main effect for pace (*P* = .75) or age-by-pace interaction (*P* = .26). The model revealed a significant age-by-stance subphase interaction (*P*<.01), with older runners demonstrating lower variability compared to younger runners for SP1, SP2, and SP3 (*P*R.01), but not SP4 or SP5 (**FIGURE 4C**). In younger runners, both SP1 and SP2 exhibited greater variability than SP3 through SP5 (*P*<.01), while in older runners, both SP1 and SP2 demonstrated greater variability than SP3 and SP4 (*P*<.01), but not SP5.

DISCUSSION

The purpose of the study was to assess coordination variability in younger and older runners across 5 subphases of stance during treadmill running at both preferred and fixed speeds. We hypothesized that there would be a difference in coordination variability between age groups and that these differences would be influenced by the runner's pace and subphases of stance. Our hypothesis was partially confirmed. Overall, for each coupling pair, older male runners were found to be less variable in their coordination patterns than younger runners, regardless of pace. Additionally, older runners demonstrated lower variability across stance in H-K coupling and during loading response and peak braking (SP1 and SP2) in coupling pairs H-A and K-A, and were less variable during peak compression in K-A coupling. Contrasting results using vector coding techniques[34] found that older runners exhibited no differences in variability compared to younger runners. While both methods are used to assess interjoint coordination and variability, CRP addresses both spatial and temporal characteristics of movement,[22]

TABLE 1 Participant Demographics and Preferred Paces for Older and Younger Male Runners*

	Older (n = 12)	Younger (n = 12)
Age, y	63.7 ± 2.6†	23.3 ± 2.4
Mass, kg	75.2 ± 8.2	77.3 ± 12.2
Height, m	1.78 ± 0.06	1.80 ± 0.08
Weekly distance, km	28.0	27.7
Preferred speed, m/s	2.83 ± 0.27†	3.33 ± 0.49

**Values are mean or mean ± SD.*
†Significant difference between age groups (P<.05).

TABLE 2 Participant Vertical and Horizontal Ground Reaction Forces at Each Subphase When Running at Preferred and Fixed Paces*

	Older (n = 12)		Younger (n = 12)	
	Preferred	Fixed	Preferred	Fixed
Pace, m/s	2.83 ± 0.27†	3.35	3.33 ± 0.49	3.35
Peak impact force, BW	1.29 ± 0.1†‡	1.43 ± 0.2	1.44 ± 0.3	1.53 ± 0.3
Peak braking force, BW	0.25 ± 0.04‡	0.23 ± 0.04‡	0.33 ± 0.08	0.33 ± 0.06
Peak active force, BW	1.92 ± 0.1‡	2.02 ± 0.3	2.14 ± 0.4	2.17 ± 0.3
Peak propulsive force, BW	0.19 ± 0.03†‡	0.23 ± 0.04‡	0.27 ± 0.07	0.28 ± 0.05
Loading rate, BW	39.1 ± 7.2	44.1 ± 8.2	41.2 ± 8.8	45.6 ± 10.8

Abbreviation: BW, body weight.
**Values are mean or mean ± SD. Midstance (stance subphase 4) is not displayed because the horizontal ground reaction force was zero.*
†Significant within-group pace difference (P<.05).
‡Significant difference between age groups (P<.05).

highlighting the importance of controlling and adapting movement velocities.[38]

A disruption in braking was previously witnessed in older female adults, and that study found that coordination variability was most affected during the braking phase of gait when challenged by an extrinsic constraint.[4] Normal aging is known to negatively impact a runner's strength and flexibility, narrowing joint mobility and minimizing joint power.[17] While correlations between strength and running mechanics are equivocal,[14,17] a reduction in eccentric strength required for braking may create a freezing of central processing strategies in an attempt to buffer initial forces.[38,39]

Similarities in loading rates were noted between age groups, despite older runners exhibiting significantly lower impact peaks. Shorter time to peak is likely the reason for the similarities and may be attributed to known decreases in step lengths[12] and ankle joint moments[11,12] in older runners, suggesting a reduced ability to stabilize during applied loads.[12] Additionally, the gastroc complex shows increased preactivation and remains active when extrinsic constraints such as high speeds and braking forces are placed on the system.[25] Thus, a narrowing of movement strategies witnessed in the older runners during the first phase of stance may be related to quicker transition times during increased instability concurrent with increased activation of the distal posterior compartment, potentially stressing passive and active tissues of the ankle.

Individuals currently diagnosed with running-related injuries are known to demonstrate low variability values.[20] All runners included in the current study were injury free. Therefore, it is unknown whether stereotyping coordination results from or contributes to injury. It is reasonable that older runners who develop an injury during training may reduce their variability even further, making rehabilitation both critical and complex. Injury prevention and rehabilitation programs that include eccentric strengthening and increases in dynamic ankle stability may benefit older runners by focusing on eccentric control and stability of the lower extremity during more vigorous activities.

The findings of the current study are in partial agreement with previous studies[4,7] examining the effects of aging on coordination variability during walking. Chiu and Chou[7] found that speeds deviating from a preferred walking speed increased variability in younger adults, but not in older adults. Similarly, the current study found no change in coordination variability in older runners after increasing their speed from a preferred pace to a fixed pace. It is plausible that experienced older runners may have trained their neuromuscular system to run in groups at paces greater than their preferred speed, requiring no adjustments in movement strategies. However, both paces exhibited lower variability of

TABLE 3 PARTICIPANT VARIABILITY FOR EACH COUPLING PAIR DURING EACH SUBPHASE OF STANCE AT A PREFERRED AND A FIXED RUNNING SPEED*

		Older Runners		Younger Runners		*P* Values		
Coupling Pair	Stance Subphase†	Preferred	Fixed	Preferred	Fixed	Group	Stance Subphase	Interaction
Hip-knee	SP1	7.54 ± 2.3	7.54 ± 1.1	11.7 ± 2.6	10.2 ± 2.1	<.01‡	<.01§	.31
Flexion	SP2	7.13 ± 1.4	8.09 ± 1.1	10.3 ± 1.9	10.4 ± 1.8			
	SP3	5.43 ± 1.5	6.48 ± 1.7	9.22 ± 2.5	9.59 ± 3.3			
	SP4	4.75 ± 1.3	6.32 ± 1.6	8.32 ± 2.1	8.65 ± 2.9			
	SP5	9.35 ± 3.5	8.71 ± 2.3	9.71 ± 2.7	10.5 ± 3.4			
Hip-ankle	SP1	13.0 ± 7.8	12.8 ± 6.7	25.7 ± 11.0	24.3 ± 9.0	<.01‡	<.01§	<.01‖
Flexion	SP2	9.38 ± 2.4	10.7 ± 3.1	16.5 ± 5.8	18.2 ± 5.7			<.01‖
	SP3	6.52 ± 2.1	7.98 ± 2.7	10.1 ± 4.9	10.9 ± 4.6			.08
	SP4	6.36 ± 2.0	7.50 ± 2.7	9.80 ± 5.2	10.3 ± 5.0			.49
	SP5	5.35 ± 5.2	6.31 ± 3.6	7.09 ± 4.7	7.54 ± 5.8			.85
Knee-ankle	SP1	9.19 ± 3.6	10.5 ± 3.8	18.2 ± 5.6	18.4 ± 4.9	<.01‡	<.01§	<.01‖
Flexion	SP2	6.93 ± 1.9	8.99 ± 2.8	14.0 ± 4.2	15.8 ± 5.3			<.01‖
	SP3	3.73 ± 0.6	5.62 ± 1.9	7.44 ± 2.5	9.13 ± 3.3			.01‖
	SP4	4.15 ± 0.6	4.87 ± 1.7	7.66 ± 1.8	8.00 ± 2.6			.26
	SP5	7.67 ± 2.3	8.25 ± 2.8	10.9 ± 4.0	8.37 ± 1.8			.97

*Values are mean ± SD unless otherwise indicated.
†SP1, stance subphase 1 (loading response); SP2, stance subphase 2 (peak braking); SP3, stance subphase 3 (peak compression); SP4, stance subphase 4 (midstance); and SP5, stance subphase 5 (peak propulsion).
‡Significant difference between age groups (P<.05).
§Significant within-group subphase difference (P<.05).
‖Significant age-by-subphase interaction (P<.05).*

movement in older runners, confirming a reduction in movement strategies accompanying normal aging.

Conversely, changes in pace had no effect on interjoint variability in the younger runners, deviating from previous evidence. A potential confounding influence may be that the preferred pace selected by the younger runners was very close to the fixed pace (3.33 m/s versus 3.35 m/s). A fixed speed (3.35 m/s) was chosen because many recreational runners participate in training groups where the group speed may be dictated by younger or faster runners. According to dynamic systems theory, changes in coordination strategies arise from exceeding critical thresholds that require the central nervous system to accommodate to an environment that has been scaled up or down.[37] It is likely that the younger male runners in this study did not exceed their critical threshold, averting the need for altering their variability. Eight of the 12 younger runners self-selected a pace faster than the fixed speed (3.63 ± 0.19 m/s). Therefore, the lack of expected change in variability may stem from the inclusion of younger runners who habitually self-select paces faster than 3.35 m/s.

The current study compared interjoint coordination variability difference across 5 subphases of stance. This is the first study to examine the influence of distinct phases of stance on coordination variability in older runners using CRP. Previous studies examining CRP variability in running found minimal differences between subphases[22]; however, those results were based on generalizing subphases to percents of stance (20%, 50%, 80%, 100%). This current alternative, and novel, method allowed the investigators to compare coordinative responses between groups based on specific kinetic events: loading and braking, compression and transition, and, finally, propulsion.

Most noticeably, high coordination variability in coupling pairs involving the ankle was found during SP1 and SP2 for all participants. High variability may be necessary during loading and braking when prompt deceleration creates an unstable system, requiring an unfolding of degrees of freedom to create new stable states.[38] Low variability would, therefore, prevent runners from transitioning out of an unstable state into a new stable state.[21] Parallel results were seen in the associated high cost of braking forces[5]; thus, improvements in eccentric control of the lower extremity may assist with the transfer of potential energy stored during braking to kinetic energy returned during propulsion.[35] Plyometric training programs have been shown to increase energy return[30] and may improve the flexibility of the central nervous system.

Following SP1 and SP2, variability decreased and was relatively small by peak compression and midstance, when vertical forces are highest. Surprisingly, older runners increased their K-A coordination variability in SP5 to levels similar to SP1 and SP2. These results again suggest that older runners move between stable states during periods when strength deficiencies may hamper performance. Similar findings have been noted in young runners exhibiting high, medium, or low collision (axial) forces, where high vertical forces were significantly related to low coordination variability.[39] Dissimilarly, the younger male runners in the current study exhibited higher vertical and horizontal forces compared to older runners, while maintaining higher variability. These results suggest that high global variability measures in interjoint coordination allow for enhanced flexibility and adaptability by the system. However, when confronted with external constraints such as high collision forces, changes in variability may be required to buffer such loads.

Limitations

The current study recruited male recreational runners, making generalizations across sexes limited. However, previous studies have inferred sex-specific differences in coordination variability with respect to aging.[1] Therefore, only male runners were analyzed. Additionally, habitual strike pattern was not controlled in an attempt to increase generalizability of results to typical recreational runners. A majority of recreational runners exhibit

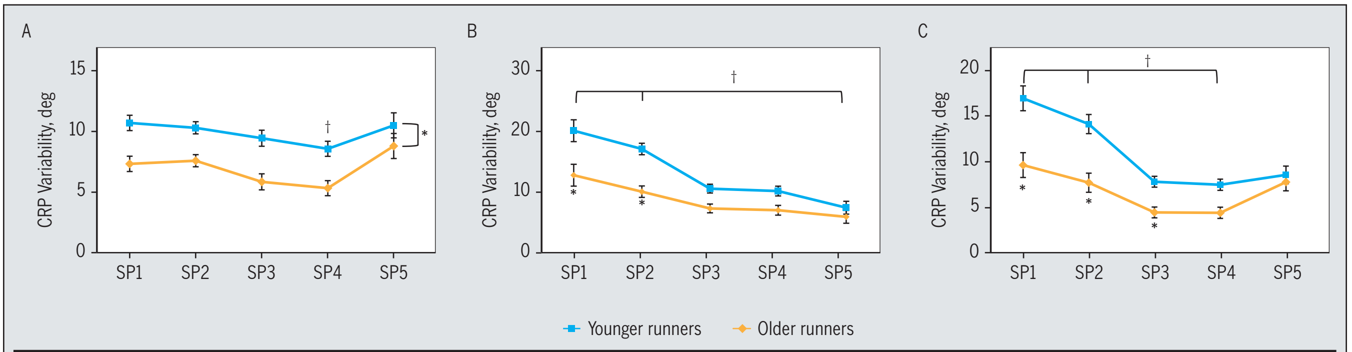

FIGURE 4. Coordination variability for coupling pairs: (A) hip-knee, (B) hip-ankle, and (C) knee-ankle across the 5 phases of stance (SP1-SP5). Values of CRP variability are represented as means, and error bars indicate standard deviations. *Significant difference between age groups. †Significant within-group subphase difference. Panels B and C also displayed a significant age-by-subphase interaction. Abbreviations: CRP, continuous relative phase; SP1, stance subphase 1 (loading response); SP2, stance subphase 2 (peak braking); SP3, stance subphase 3 (peak compression); SP4, stance subphase 4 (midstance); SP5, stance subphase 5 (peak propulsion).

a rearfoot strike pattern,[10] and the proportions of runners exhibiting midfoot and rearfoot strike patterns were nearly identical between age groups. Nonetheless, differences in force attenuation, joint stiffness, and compliance[3,18] are known, questioning their influence on variability.

In the current study, analysis was restricted to motions in the sagittal plane, as these appear to be most affected by normal aging.[8] While differences in running mechanics exist in the sagittal plane,[11,24] variations in running mechanics with aging may be multiplanar.[17] Injury and performance are frequently associated with secondary plane movements,[9] suggesting that differences in coordination variability may be multiplanar. Therefore, sex comparisons may be more important when analyzing secondary motions, as female runners are known to be at greater risk of injury as a result of deviations in the frontal and transverse planes during running.[36]

CONCLUSION

Overall, older runners demonstrate lower variability compared to younger runners, regardless of pace. Specifically, a stereotyping of coordination is witnessed during loading and braking phases of stance. In both groups, variability was shown to decrease with an increase in vertical forces and as the lower extremity transitions out of braking into propulsion. While not yet studied, decreases in variability may be associated with the increases in leg stiffness witnessed during peak compression as mechanisms for storing energy in a more stable state. However, an overall less variable system may have implications for injury susceptibility as the system is more eccentrically stressed, requiring more work from active and passive structures. Gait training strategies involving increasing distal muscle activation to maintain distal stability may augment movement patterns and improve performance and risk of injury in older men. ◉

KEY POINTS

FINDINGS: Variability during the loading and braking response of gait was significantly lower in older runners compared to younger runners, which may result in higher and repetitive impact forces. Additionally, higher variability is seen during the first half of stance and decreases as vertical forces increase in preparation for propulsion. Finally, pace was not found to influence variability measures in either age group.

IMPLICATIONS: A stereotyping of coordination focused at the ankle may be a neuromuscular response to increased instability during loading and braking when proximal strength deficits exist in older runners. Training strategies that include increasing eccentric control and distal stability during dynamic activities may decrease injury risk in older runners and improve gait plasticity.

CAUTION: Differences may also exist in the secondary planes and have additional influence on injury risk and prevention.

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Real-Time Biofeedback of Performance to Reduce Braking Forces Associated With Running-Related Injury: An Exploratory Study

Recreational running is one of the most accessible physical activities and has one of the highest participation rates of any sport worldwide.[41] There are numerous recognized health benefits, but the incidence of running-related injury (RRI) is high. Up to 79% of runners are affected, and approximately half of recreational distance runners will experience an RRI in any given year.[18,39] Female runners are at greater risk of developing an RRI than are male runners.[39] Recreational runners are particularly at risk, as lack of running experience has been cited as one of the most important risk factors for RRI.[8,22,40] Notably, a significant portion of those injured do not return to running.[5]

BACKGROUND: The high rate of running-related injury may be associated with increased peak braking forces (PBFs) and vertical loading rates. Gait retraining has been suggested by some experts to be an effective method to reduce loading parameters.

OBJECTIVES: To investigate whether PBF could be decreased following an 8-session gait retraining program among a group of female recreational runners and which self-selected kinematic strategies could achieve this decrease.

METHODS: In this exploratory study, 12 female recreational runners with high PBFs (greater than 0.27 body weight) completed an 8-session gait retraining program with real-time biofeedback of braking forces over the course of a half-marathon training program. Baseline and follow-up kinetics and kinematics were analyzed with a repeated-measures analysis of variance.

RESULTS: There was an average reduction of 15% in PBF (–0.04 body weight; 95% confidence interval [CI]: –0.07, –0.02 body weight; $P = .001$; effect size, 0.62), accompanied by a 7% increase in step frequency (11.3 steps per minute; 95% CI: 1.8, 20.9 steps per minute; $P = .024$; effect size, 0.38) and a 6% decrease in step length (–5.5 cm; 95% CI: –9.9, –1.0 cm; $P = .020$; effect size, 0.40), from baseline to follow-up.

CONCLUSION: The gait retraining program significantly reduced the PBF among a group of female recreational runners. This was achieved through a combination of increased step frequency and decreased step length. Furthermore, the modified gait pattern was incorporated into the runners' natural gait pattern by the completion of the program. Based on these results, the outlined gait retraining program should be further investigated to assess whether it may be an effective injury prevention strategy for recreational runners. This study was registered with ClinicalTrials.gov (NCT03302975).

LEVEL OF EVIDENCE: Prevention, level 4.
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KEY WORDS: *gait analysis, kinematics, kinetics, prevention (injury), running*

There have been many proposed factors in the development of RRIs. While training error and lower-limb anatomy are undoubtedly implicated, biomechanical factors are also believed to be involved.[21] Among biomechanical variables, high magnitudes and rates of loading during early stance have been associated with RRI, though findings have not been causal.[7,15,25,32,33,38,51] The magnitude of the vertical impact transient and the rate of vertical loading (average or instantaneous) have been the most commonly studied. Davis et al[15] reported that females with a higher average vertical loading rate (AVLR) were at greater risk of prospectively developing an RRI requiring medical attention than were those runners who had never sustained an RRI. In another prospective study, Bredeweg et al[7] reported that while baseline instantaneous vertical loading rate (IVLR) was higher in males who became injured, there was no difference between injured and uninjured females. Importantly, both of these studies compared injured versus uninjured runners—instead

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of high versus low loading rate—which may limit the scope of conclusions from such prospective cohort studies. Another recent prospective study found no association between loading rate and RRI among female runners.[29] In retrospective analyses, stress fractures and plantar fasciitis have been linked to higher vertical loading rates,[25,32,33] but causation cannot be inferred.

Anterior-to-posterior ground reaction force parameters may also be involved in RRI etiology. As shown in a recent study,[29] the anterior-to-posterior ground reaction force during loading demonstrated an almost 8-fold increased risk of injury in runners with a peak braking force (PBF) of greater than 0.27 body weight (BW) compared to those with a PBF of less than 0.23 BW. This correlation of higher PBF and greater risk fits with injury prediction theories. Specifically, it is known that bones do not withstand shear (horizontal) forces as well as they withstand compressive (vertical) forces, despite the magnitudes being several times greater for the latter.[34,37] The same may be true for other soft tissue structures, which in the lower extremities contain primarily axially oriented fibers built to withstand vertical more than horizontal stresses and strains. Shear forces applied to the foot and lower leg may also increase the risk of certain injuries to these regions.[31,48] Given this potential link between PBF and RRI risk, it is important to investigate methods to reduce this variable during running.

Gait retraining has been suggested by some experts to be the most effective method to reduce loading parameters.[2,13,14] There have been several examples of running gait retraining programs that have proven effective.[9,10,17,30,35,46] Perhaps the most compelling of these studies to date is Chan et al's[9] recent large randomized controlled trial investigating the effectiveness of a gait retraining program aimed at reducing vertical loading rates in healthy novice runners. At 12-month follow-up, the authors reported a reduction of 62% in RRI risk in the gait retraining group compared to the control group. Given the substantial impact that a gait retraining intervention might have on injury risk, it is important to test protocols to determine their effectiveness at achieving their targeted outcome (a reduction in loading parameters), as well as to determine the kinematic changes that are produced in order to guide clinical application.[28]

The purpose of this study was to investigate whether PBF could be decreased following an 8-session, real-time biofeedback gait retraining program among a group of female recreational runners. Given the varied contribution of several kinematic and spatiotemporal parameters to higher vertical and anterior-to-posterior loading magnitudes and rates,[19,28] a secondary objective was to determine the self-selected kinematic strategies employed to achieve this reduction. We hypothesized that a 15-week gait retraining program would achieve statistically significant (P<.05) reductions in the target outcome (PBF), as well as secondary kinetic outcomes (AVLR, IVLR, and vertical impact transient). We also hypothesized that participants would preferentially choose to reduce their step length and foot-strike angle at initial contact.

METHODS

Participants

Female recreational runners between 18 and 60 years of age were recruited from the local running community via flyers and social media posts in October 2017. To obtain a running sample without formal run training, inclusion was set to limit eligible participants to a history of no more than 2 half-marathons. Participants were required to have been running for at least 3 months and were excluded if they (1) sustained a lower extremity injury in the previous 3 months, (2) had any history of lower-limb surgery, or (3) had any current low back or lower extremity pain while running. Written consent was obtained from all participants, and ethics approval was granted by the University of British Columbia Clinical Research Ethics Board. This protocol was registered with ClinicalTrials.gov (NCT03302975).

Interested participants were initially screened for inclusion/exclusion by phone or e-mail, and eligible individuals were invited to undergo an initial biomechanical screen. As the ultimate goal of any gait retraining program is to reduce the level of injury risk, we chose to include only those runners with a PBF of greater than 0.27 BW, based on a previous study demonstrating increased injury risk above this level.[29] Eligible participants performed the biomechanical running screen on an instrumented treadmill (Treadmetrix, Park City, UT) in their usual running shoes and at a self-selected speed that was representative of a moderate-intensity run (a Borg rating of perceived exertion of 13, indicative of "somewhat hard").[4] The mean PBF across 3 captures of 15 seconds (30 stance phases per foot) was calculated, and those with a PBF of less than 0.27 BW were excluded from participation in the study.

Baseline Assessment

Individuals who met the initial biomechanical screening criterion (a PBF of greater than 0.27 BW) were invited to the laboratory for the baseline testing session (week 0) and administered a detailed training and injury questionnaire. As in the screening session, participants ran in their usual running shoes at a self-selected speed representative of a moderate-intensity run. Participants were provided no instructions pertaining to running mechanics during the baseline testing session. Three-dimensional kinematic data (sampled at 240 Hz) and kinetic data (sampled at 2400 Hz) were collected from 3 consecutive captures of 15 seconds, each during the last minute of a single continuous running bout of 3 to 5 minutes on an instrumented force treadmill. A bilateral lower extremity marker set consisting of 42 reflective markers was affixed to each participant prior to testing, and a static calibration trial was initially collected to form a musculoskeletal model based on a study by MacLean et al,[24] using a 6-camera motion-analysis system (Qualisys AB, Gothenburg, Sweden).

Following the static trial, 16 calibration markers were removed, leaving 26 tracking and calibration markers on for both static and dynamic trials. To obtain a proxy for the horizontal distance between the heel and center of mass in the absence of a full-body marker set, a virtual marker was created at the midpoint between the posterior superior iliac spine markers in order to calculate the horizontal distance between the heel and sacrum at initial contact. A sacral marker has been shown to be a reliable proxy for center of mass in the sagittal plane during gait.[50]

Our primary kinetic outcome of interest was PBF, based on a previous study that showed increased risk of injury with higher values.[29] We defined PBF as the maximum posterior force observed from initial contact to 50% of stance. Secondary kinetic outcomes were selected based on their inclusion in the RRI literature, and consisted of vertical impact transient,[21,25] AVLR,[25,51] and IVLR.[21,25,32] Kinematic outcomes included step length, step frequency, the horizontal distance from the heel to the sacrum, shank angle at initial contact, and foot-strike angle. Kinematic variables were selected based on their contribution to higher braking forces, as reported in previous studies,[20,23,28] and their potential to cue lower PBF during running retraining in a clinical setting. The limb with the greater mean PBF was chosen as the study limb.

Half-Marathon Training Program

At the baseline session, participants were given a structured, 15-week half-marathon training program identical to the one presented in Napier et al.[29] During weeks where there was a lab-based gait retraining session, this took the place of the easy recovery run. The program was supervised by a sports physical therapist with 14 years of experience. Throughout the training program, participants completed a weekly online questionnaire to record the number of and reason for missed training days, hours run per week, number of workouts completed, and any general comments regarding the training program and pain experienced.

Gait Retraining Program

The gait retraining program consisted of 8 lab-based sessions at weeks 1, 2, 4, 6, 8, 10, 12, and 14 of the half-marathon training program, with sessions starting at 15 minutes of continuous running in week 1 and increasing to 30 minutes by week 10 (**FIGURE 1**). Gait retraining during the lab-based sessions was facilitated by real-time biofeedback of the braking force using Visual3DServer (C-Motion, Inc, Germantown, MD). To promote motor learning, a faded feedback design was used, with removal of biofeedback (monitor turned off) for periods during the training session commencing at session 5.[30,35,46] Kinetic data were streamed to a monitor positioned directly in front of the treadmill, and PBF was recorded at the beginning, middle, and end of each training session for post hoc comparison.

Participants were instructed to attempt to keep the peaks on a rolling graph below a green line that had a value of 0.245 BW (the mean PBF from Napier et al[29]), with the encouragement that lower was better. No other cues were given, so that participants could develop their own strategies to lower PBF. Self-reported difficulty in achieving the target zone was recorded at each training session using an 11-point numeric rating scale, with terminal descriptors of 0 as "no difficulty" and 10 as "unable to perform." Pain was quantified during training sessions using an 11-point numeric rating scale, with 0 indicating "no pain at all" and 10 the "worst pain imaginable." Participants were instructed to maintain the modifications outside the lab-based training sessions during their half-marathon training program in the community.

Adherence, Difficulty, and Adverse Events

Adherence to the training program was assessed as the total number of lab-based training sessions attended for each participant. Compliance with the prescribed half-marathon training program was obtained from weekly, participant-completed online questionnaire responses detailing the daily amount of running for the duration of the study, and weekly totals (in hours) were calculated. Additionally, an 11-point numeric rating scale (0 is "not confident at all" and 10 is "very confident") in the weekly questionnaire was used to assess confidence in the ability of participants to maintain the modified gait pattern while running in the community.

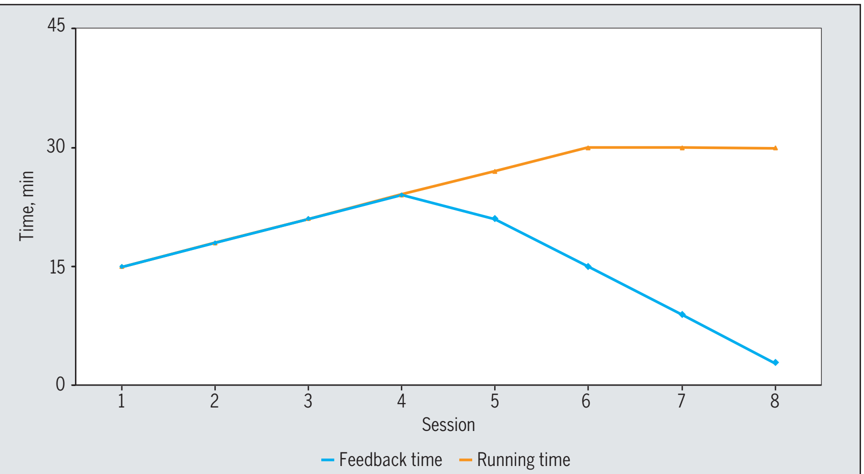

FIGURE 1. Total running time and time with feedback during the 8 lab-based training sessions. For the first 4 sessions, participants received feedback 100% of the time. By session 8, feedback was only provided 10% of the total time.

Finally, adverse events were assessed using open-ended questions in the weekly questionnaire. For the purpose of analysis, adverse events were defined as new pain or discomfort lasting longer than 2 weeks in duration or requiring treatment.

Follow-up Assessment

Participants returned to the lab in week 15 for biomechanical testing. Markers were applied and biomechanical data were collected in the same manner as at baseline testing. Participants ran at their baseline preferred speed. After an initial warm-up period, participants were instructed to "run naturally" while the first 3 consecutive captures of data were collected (follow-up natural gait). They were then asked to run with their new "modified gait" (follow-up modified gait) while 3 further consecutive captures of data were collected.

Statistical Analysis

Sample-size calculations were conducted in G*Power Version 3.1.9.3 (Heinrich-Heine Universität, Düsseldorf, Germany). Sample size for this study was calculated to detect a clinically meaningful reduction of 0.04 BW (the boundaries of the middle tertile in Napier et al[29]) for the primary outcome (PBF). To obtain 80% power to detect significant (P<.05) differences in PBF from baseline to follow-up measurements, we determined that 13 participants were required. Taking into account an attrition rate of 20% based on previous studies using a similar population,[29,36] we aimed to recruit 16 participants for this study.

All data were tested for normality using the Shapiro-Wilk test and assessed for skewness and kurtosis. The primary outcome was PBF, and the primary end point was follow-up natural gait. All other biomechanical and clinical outcomes were considered secondary. Within-subject comparisons using repeated-measures analysis of variance (baseline versus follow-up, natural gait versus follow-up modified gait, and gait retraining session 1 versus session 8) were used to compare the-effect of the gait retraining program on primary and secondary outcomes, and effect sizes were reported. Post hoc 2-tailed comparisons were conducted using the criterion of P<.05. A large effect size was determined as greater than 0.80, moderate as greater than 0.40, and small as less than 0.40.[11] All statistical analyses were performed using SPSS Statistics for Windows Version 22.0 (IBM Corporation, Armonk, NY).

RESULTS

A total of 183 individuals underwent eligibility screening (**FIGURE 2**). Forty-six individuals met inclusion criteria and attended the laboratory for biomechanical screening. Of these, 16 met the biomechanical screening criterion of PBF greater than 0.27 BW and underwent baseline testing. Twelve participants completed the 15-week half-marathon training program and follow-up biomechanical gait assessment (**TABLE 1**). Reasons for loss to follow-up included acute back injury unrelated to running (n = 2), acute illness (n = 1), and pregnancy (n = 1).

When comparing follow-up natural gait to baseline (**TABLE 2**), there was an average reduction of 15% (–0.04 BW; 95% confidence interval [CI]: –0.07, –0.02 BW; P = .001; effect size, 0.62) in PBF. When training sessions were analyzed on an individual level, it was noted that PBF did not change significantly between the second and the last session (P = .136) (**FIGURE 3**). There was also a non–statistically significant reduction in AVLR and IVLR of 18% (–7.91 BW/s; 95% CI: –16.79, 0.98 BW/s; P = .076; effect size, 0.26) and 19% (–10.51 BW/s; 95% CI: –21.76, 0.74 BW/s; P = .064; effect size, 0.28), respectively. Kinematic analysis of baseline and follow-up natural gaits revealed an increase of 7% (11.3 steps per minute; 95% CI: 1.8, 20.9 steps per minute; P = .024; effect size, 0.38) in step frequency and a decrease of 6% (–5.5 cm; 95% CI: –9.9, –1.0 cm; P = .020; effect size, 0.40) in step length.

Comparing follow-up modified gait kinetic data to baseline (**TABLE 3**), there

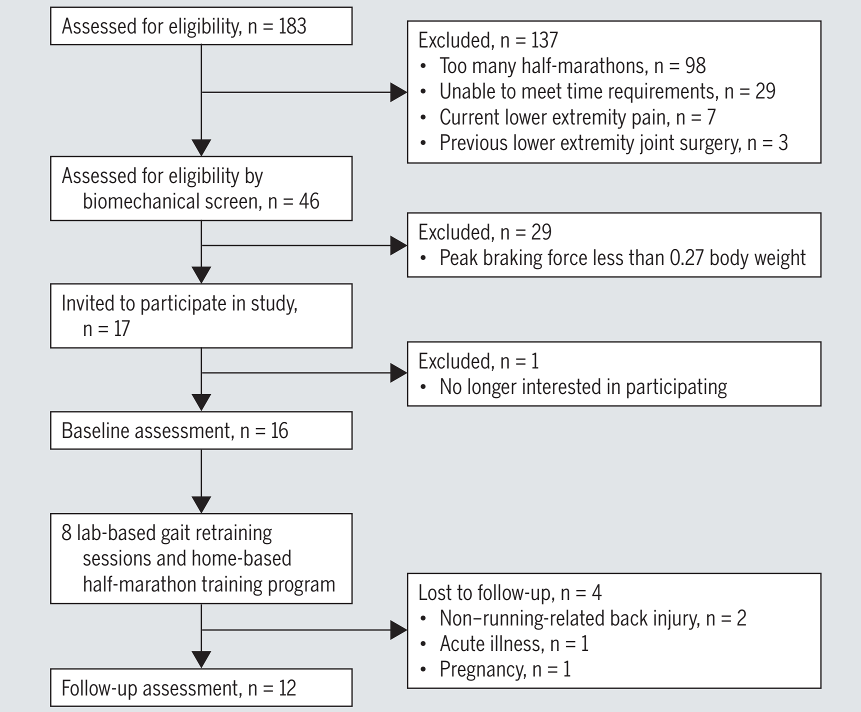

FIGURE 2. Flow of participants through the study.

was an average reduction in PBF of 18% (−0.05 BW; 95% CI: −0.08, −0.03 BW; P = .001; effect size, 0.66). There was also an associated 24% reduction in AVLR (−10.49 BW/s; 95% CI: −19.41, −1.58 BW/s; P = .025; effect size, 0.38) and IVLR (−13.13 BW/s; 95% CI: −24.59, −1.68 BW/s; P = .028; effect size, 0.37). Analysis of the kinematic data revealed an increase of 9% (15.2 steps per minute; 95% CI: 2.8, 27.6 steps per minute; P = .021; effect size, 0.40) in step frequency and a decrease of 8% (−7.0 cm; 95% CI: −12.3, −1.6 cm; P = .016; effect size, 0.43) in step length.

Self-reported difficulty in achieving the target threshold of PBF for a given training session did not change significantly from the first (4.8 ± 2.4 points) to the last session (4.6 ± 1.3 points) (**FIGURE 3**). Confidence in the participants' perceived ability to achieve the modified gait pattern in the community, however, improved from 5.9 ± 1.6 points out of 10 in week 2 to 7.5 ± 1.3 points in week 15 (**FIGURE 3**).

Attendance at the lab-based training sessions by the 12 participants who completed the training program was almost perfect. All participants except 1 attended all 8 sessions. Compliance with the half-marathon training program was also good. Participants completed a median of 52 out of 60 runs (interquartile range, 50.5-56.5) over the duration of the half-marathon training program, for a mean ± SD of 2.88 ± 0.40 hours of running per week.

Nine individuals reported some pain during the gait retraining sessions. However, average pain was low (0.7 ± 0.3 points out of 10) and resolved before the next prescribed run in all cases. There were no self-reported adverse events or additional treatments reported over the course of the half-marathon training program. However, 1 lab-based training session (session 8) was terminated at 24 minutes due to bilateral shin pain.

DISCUSSION

THIS STUDY IS THE FIRST, TO OUR knowledge, to assess biomechanics following a gait retraining program to reduce PBF in recreational runners. This is in contrast to previous studies that have utilized real-time biofeedback of kinetic parameters to reduce vertical loading.[9,10,12] Our findings indicate that female recreational runners can effectively reduce their PBF over the course of an 8-session, real-time-biofeedback

TABLE 1 Demographics of Participants*

	Baseline (n = 16)	Follow-up (n = 12)
Age, y	39.2 ± 8.7	39.4 ± 9.1
Height, m	1.70 ± 0.06	1.70 ± 0.05
Body mass, kg	64.8 ± 7.3	63.7 ± 5.9
Body mass index, kg/m^2	22.6 ± 2.3	22.2 ± 1.7
Running experience, y	11.3 ± 7.9	9.6 ± 8.3
Prior weekly volume, km	14.0 ± 9.5	14.5 ± 9.1
Baseline preferred speed, m/s	2.57 ± 0.16	2.56 ± 0.18

*Values are mean ± SD.

TABLE 2 Kinetic and Kinematic Outcomes of Participants (n = 12) at Baseline and Follow-up (Natural Gait)

Outcome	Baseline*	SEM	Follow-up (Natural Gait)*	SEM	Mean Difference†	*P* Value	Effect Size
Kinetic							
PBF, BW	0.28 ± 0.04	0.01	0.24 ± 0.02	0.01	−0.04 (−0.07, −0.02)	.001	0.62
VIT, BW	1.56 ± 0.15	0.04	1.46 ± 0.25	0.07	−0.11 (−0.29, 0.08)	.233	0.13
AVLR, BW/s	43.96 ± 11.64	3.36	36.05 ± 7.45	2.15	−7.91 (−16.79, 0.98)	.076	0.26
IVLR, BW/s	55.49 ± 15.51	4.48	44.98 ± 10.10	2.91	−10.51 (−21.76, 0.74)	.064	0.28
Kinematic							
HSAC, cm	24.2 ± 2.4	0.7	24.5 ± 3.4	1.0	0.2 (−1.9, 1.5)	.778	0.01
SA, deg‡	6.6 ± 2.5	0.7	5.6 ± 2.9	0.8	−1.0 (−2.2, 0.1)	.076	0.26
FSA, deg§	6.3 ± 6.1	1.8	6.1 ± 5.8	1.7	−0.2 (−4.0, 3.5)	.886	0.00
SF, steps per minute	170.6 ± 9.2	2.7	181.9 ± 16.8	4.9	11.3 (1.8, 20.9)	.024	0.38
SL, cm	90.6 ± 6.8	2.0	85.2 ± 5.1	1.5	−5.5 (−9.9, −1.0)	.020	0.40

Abbreviations: AVLR, average vertical loading rate; BW, body weight; FSA, foot-strike angle; HSAC, heel-to-sacrum distance; IVLR, instantaneous vertical loading rate; PBF, peak braking force; SA, shank angle; SEM, standard error of the mean; SF, step frequency; SL, step length; VIT, vertical impact transient.
*Values are mean ± SD.
†Values in parentheses are 95% confidence interval.
‡Measured from the vertical, with a positive angle indicating that the ankle is anterior to the knee.
§Measured from the horizontal, with a positive angle indicating a more rearfoot strike.

gait retraining program. Furthermore, this modified pattern can be learned to the extent that it is incorporated into an individual's natural gait pattern. Further studies are needed to document this relationship.

On average, the gait retraining program produced a 15% reduction in our primary outcome variable of PBF. Based on our a priori inclusion criteria, the average baseline magnitude of PBF (0.28 BW) would have placed our participants in the highest tertile in the study by Napier et al.[29] Follow-up magnitudes of PBF averaged 0.24 BW, which would have placed our participants in the middle tertile of the previous study. A reduction in PBF of this magnitude is likely to be clinically meaningful, as it corresponds to a 5-fold decrease in RRI risk.[29]

Importantly, AVLR and IVLR were also reduced by 18% and 19%, respectively, from baseline to follow-up, though the changes were not statistically significant. A reduction in vertical loading rate suggests that the strategies employed to reduce PBF might have the added benefit of decreasing these parameters. The magnitude of these reductions is on par with the differences for AVLR (approximately 22%) and IVLR (approximately 17%) between groups (never injured versus injuries that required medical attention) in the prospective study by Davis et al.[15] Esculier et al[17] also reported similar reductions (approximately 26%) in AVLR in their gait retraining intervention. Furthermore, retrospective studies examining the association between vertical loading rate and tibial stress fractures have found the difference in vertical loading rate between injured participants and controls to be, on average, 12%.[38] Vertical loading rate may increase RRI risk, because it represents the greatest force exerted on the body over the shortest time frame (less than 30 milliseconds), and it may therefore be difficult for tissues to accommodate this high-frequency stress. Hence, an indirect benefit of the current gait retraining program may be to further lower injury risk by way of reducing vertical loading rate.

Kinematic analysis revealed that participants reduced their PBF magnitude by shortening step length and increasing step frequency, without changing their running speed. On average, participants increased their step frequency by 7%, which is consistent with the 5% to 10% reported by previous intervention studies that have decreased loading parameters.[20,45] Due to differences in baseline values, not all participants similarly increased their step frequency. When participants were asked to report their strategy for the modified gait pattern, all but 3 reported their strategy to be either "increasing step frequency" or "taking shorter steps." There was no difference in horizontal distance from the heel to the sacrum (a surrogate measure for heel-to-center of mass distance).

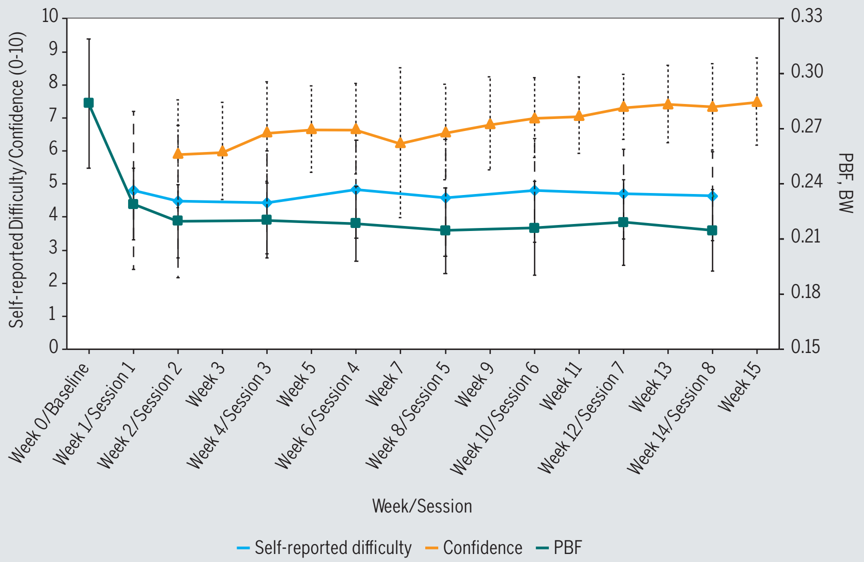

FIGURE 3. Peak braking force (positive is braking) during lab-based sessions. Self-reported difficulty in achieving the target zone was recorded at each training session, with terminal descriptors of 0 as "no difficulty" and 10 as "unable to perform." Self-reported confidence in the ability to maintain the modified gait pattern while running in the community was reported weekly, with 0 as "not confident at all" and 10 as "very confident." Error bars show standard deviation. Abbreviations: BW, body weight; PBF, peak braking force.

This is in contrast with previous studies that showed a relationship between greater heel-to-center of mass distance and increased braking forces.[20,23] However, as posited in a previous study,[28] there may be no further benefit to reducing this distance once step length has been reduced. Furthermore, there was no difference in shank angle between baseline and follow-up, meaning that a more vertical orientation of the shank at initial contact is not necessary to produce a reduction in PBF. This result is in agreement with findings in the aforementioned study,[28] in which the angle of the shank did not contribute to the explained variance of PBF. Two previous studies that examined knee flexion angle at initial contact—a measure related to shank angle—also determined that knee flexion angle is not an important determinantPBF.[23,42] Importantly, shank angle is often used clinically to estimate the degree of overstriding, but the above findings suggest that it may not be indicative of PBF.

Additionally, there was no difference in foot-strike angle between baseline and follow-up. This is in contrast to previous findings, which showed that a more forefoot strike angle was related to lower PBF and vertical loading rates.[28] However, this was after accounting for speed and step length. Interestingly, in a study examining the independent effect of foot-strike pattern and step length on kinetic parameters, Bowersock et al[6] reported that decreasing step length, but not changing foot-strike pattern, reduced braking forces.

Further, the lack of change in foot-strike angle is in contrast with 2 previous studies that reported lower vertical ground reaction force measures in runners with lower foot-strike angles.[1,10] However, unlike those studies, we chose to include all foot-strike types in our study sample, potentially contributing to a floor effect on decreasing foot-strike angle below a certain level. When individual participant data were reviewed, it was noted that all participants who had a foot-strike angle greater than 10° (n = 3) reduced their foot-strike angle at follow-up, but there was no clear pattern below this angle. In summary, this finding provides evidence that rearfoot-strike patterns need not change to midfoot or forefoot patterns to reduce vertical and anterior-to-posterior loading parameters, except possibly in the case of more pronounced rearfoot strikes (foot-strike angle greater than 10°).

The gait retraining program in this study was designed to follow a faded feedback paradigm over multiple sessions to improve learning and retention of the modified gait pattern.[13,47] Participants were provided with real-time, externally focused feedback on braking force without further instruction on how to achieve a reduction in this parameter.[3,49] The amount of feedback was reduced from sessions 5 to 8 in order to facilitate transfer of the modified gait to the participants' natural pattern. In a recent editorial on optimizing gait retraining, Davis[13] advised that evidence should be provided regarding whether the gait pattern has been retrained or whether the runner has simply been able to reproduce the modified pattern when tested. Therefore, we assessed the participants' natural gait patterns at follow-up before asking them to run with the modified gait pattern. Our findings indicate that the gait retraining program was effective at altering the natural gait among participants, with participants achieving a significant reduction in PBF in this condition.

There were no self-reported adverse events, either during the lab-based training sessions or during the half-marathon training program, and average pain during the lab-based training sessions was less than 1/10. The lack of adverse events indicates that this intervention is potentially safe. However, given that some individuals did report some calf and quadriceps discomfort early in the training program, we advise that the program be accompanied by an ankle- and knee-strengthening program to minimize risk of injury.

This exploratory study is not without limitations. First, the value of this retraining program toward RRI prevention is unknown and cannot be determined from this study. Furthermore, this study was designed to be preliminary in nature, in order to test whether individuals could be retrained to reduce their PBF. Because of the absence of a control group, we cannot suggest that this intervention is superior to a half-marathon training program alone due to the potential mediation the half-marathon program may have on the effect of the gait retraining intervention. While it is unlikely that the biomechanical changes seen would have occurred without the retraining program,[26] the carryover effects to overall RRI risk reduction cannot be ascertained. A randomized controlled trial is warranted to compare this type of gait retraining program to one that

TABLE 3 Kinetic and Kinematic Outcomes of Participants (n = 12) at Baseline and Follow-up (Modified Gait)

Outcome	Baseline*	SEM	Follow-up (Modified Gait)*	SEM	Mean Difference†	*P* Value	Effect Size
Kinetic							
PBF, BW	0.28 ± 0.04	0.01	0.23 ± 0.02	0.01	–0.05 (–0.08, –0.03)	.001	0.66
VIT, BW	1.56 ± 0.15	0.04	1.43 ± 0.27	0.08	–0.14 (–0.32, 0.05)	.126	0.20
AVLR, BW/s	43.96 ± 11.64	3.36	33.46 ± 7.86	2.27	–10.49 (–19.41, –1.58)	.025	0.38
IVLR, BW/s	55.49 ± 15.51	4.48	42.36 ± 10.78	3.11	–13.13 (–24.59, –1.68)	.028	0.37
Kinematic							
HSAC, cm	24.2 ± 2.4	0.7	24.9 ± 4.1	1.2	0.7 (–1.4, 2.8)	.503	0.04
SA, deg‡	6.6 ± 2.5	0.7	5.8 ± 3.1	0.9	–0.8 (–2.2, 0.6)	.255	0.12
FSA, deg§	6.3 ± 6.1	1.8	5.1 ± 5.8	1.7	–1.2 (–5.2, 2.8)	.518	0.04
SF, steps per minute	170.6 ± 9.2	2.7	185.8 ± 21.5	6.2	15.2 (2.8, 27.6)	.021	0.40
SL, cm	90.6 ± 6.8	2.0	83.7 ± 6.1	1.8	–7.0 (–12.3, –1.6)	.016	0.43

Abbreviations: AVLR, average vertical loading rate; BW, body weight; FSA, foot-strike angle; HSAC, heel-to-sacrum distance; IVLR, instantaneous vertical loading rate; PBF, peak braking force; SA, shank angle; SEM, standard error of the mean; SF, step frequency; SL, step length; VIT, vertical impact transient.
**Values are mean ± SD.*
†Values in parentheses are 95% confidence interval.
‡Measured from the vertical, with a positive angle indicating that the ankle is anterior to the knee.
§Measured from the horizontal, with a positive angle indicating a more rearfoot strike.

could be carried out in a clinical environment using kinematic cues.

Second, this study only followed participants up to the end of the 15-week half-marathon training program and did not evaluate participants after the training ended. As such, the long-term retention of this modified gait pattern is unknown.

Third, given that participants consisted of female recreational runners, we can only generalize our findings to this group. With differences in type and mechanism of RRI reported between male and female runners, it is important to study these populations in isolation.[7,16,43] However, as long as the principles of this training protocol are adhered to, it is possible that male runners and trained runners could see the same benefits.

Fourth, the individuals who received the gait retraining intervention all had a high PBF (as per the screening criterion). While this was aimed at improving clinical relevance, we cannot exclude the risk of selection bias among our sample, as participants included in the study might have been motivated to change their running gait and the screening criterion might have created a ceiling effect by which PBF would only have been able to decrease.

Finally, it is unknown whether the gait modifications observed in the laboratory were transferred to the community. Given the increasing availability and capability of wearable devices, data should be collected in the community to determine whether transference from the lab is occurring.[27,44]

CONCLUSION

The gait retraining program in this study significantly reduced PBF, as well as vertical loading rates, among a group of female recreational runners. This was achieved through a combination of increased step frequency and decreased step length. Furthermore, the modified gait pattern was incorporated into the runners' natural gait pattern by the completion of the gait retraining program. Based on these results, the outlined gait retraining program should be further investigated to assess whether it may provide an effective injury prevention strategy for recreational runners. Further investigation into a clinical application of this program is warranted to enable wider use. ◉

KEY POINTS

FINDINGS: A gait retraining program using real-time biofeedback of braking forces effectively reduced peak braking force (PBF) and vertical loading rate in female recreational runners displaying a high PBF. This reduction was clinically significant and was achieved primarily through an increase in step frequency and a decrease in step length from baseline to follow-up.

IMPLICATIONS: Real-time biofeedback of braking force may effectively reduce high PBF, which has been associated with increased running-related injury risk. Clinically, this may be achieved via a reduction in step length or an increase in step frequency, independent of changing foot-strike or shank angle.

CAUTION: This study was designed to be preliminary in nature, in order to test whether individuals could be retrained to reduce their PBF. Whether changing PBF in healthy female runners would reduce the risk of injury or promote recovery from running-related injuries is not yet known.

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[EDITOR'S NOTE]

2018 *JOSPT* Award Recipients

GUY G. SIMONEAU, *PT, PhD, ATC, FAPTA*
Interim Editor-in-Chief
J Orthop Sports Phys Ther 2019;49(3):117. doi:10.2519/jospt.2019.0101

During the American Physical Therapy Association's Combined Sections Meeting in Washington, DC in January 2019, JOSPT recognized the authors of the most outstanding research and clinical practice manuscripts published by JOSPT during 2018.

The following annual awards, presented for 16 years by the *Journal of Orthopaedic & Sports Physical Therapy*, recognize the most outstanding articles published in the last calendar year. An award committee of 5 (2 from the Academy of Orthopaedic Physical Therapy, 2 from the American Academy of Sports Physical Therapy, and 1 from the Editorial Board) selected the award recipients from a strong field of eligible articles.

The *Journal of Orthopaedic & Sports Physical Therapy's* 2018 George J. Davies–James A. Gould Excellence in Clinical Inquiry Award

The George J. Davies–James A. Gould Excellence in Clinical Inquiry Award recognizes the best article published in *JOSPT* during a calendar year among the categories of clinical research reports (articles assigned a level of evidence), clinical commentaries, case reports, and resident's case problems.

The 2018 George J. Davies–James A. Gould Excellence in Clinical Inquiry Award was presented to Joseph R. Kardouni, PT, PhD; Tracie L. Shing, MPH; Craig J. McKinnon, MPH; Dennis E. Scofield, MAEd; and Susan P. Proctor, DSc for their July 2018 article, "Risk for Lower Extremity Injury After Concussion: A Matched Cohort Study in Soldiers."[1]

The *Journal of Orthopaedic & Sports Physical Therapy's* 2018 JOSPT Excellence in Research Award

The JOSPT Excellence in Research Award recognizes the best article published in the *Journal* during a calendar year within the category of nonclinical research reports or brief reports (articles that are not assigned a level of evidence) and clinical commentaries on research topics.

The 2018 JOSPT Excellence in Research Award was presented to Kathryn J. Schneider, PT, PhD; Willem H. Meeuwisse, MD, PhD; Luz Palacios-Derflingher, PhD; and Carolyn A. Emery, PT, PhD for their December 2018 article, "Changes in Measures of Cervical Spine Function, Vestibulo-ocular Reflex, Dynamic Balance, and Divided Attention Following Sport-Related Concussion in Elite Youth Ice Hockey Players."[2]

These articles were selected from the articles that *JOSPT* published in 2018 that had high potential for impact on the fields of musculoskeletal and sports-related injury, rehabilitation, and health.

Congratulations to the 2018 award recipients for their outstanding work. We look forward to *JOSPT* continuing to publish and highlight excellent research with clinical implications for practitioners. ◉

George Davies presenting the 2018 *JOSPT* George J. Davies–James A. Gould Excellence in Clinical Inquiry Award to Dr Joseph Kardouni.

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[VIEWPOINT]

ASHLEY D. SMITH, PT, PhD[1,2] • GEOFF SCHNEIDER, PT, DSc, PhD[3-5]

Psychological Manifestations and Chronic Pain in Whiplash-Associated Disorder Mechanisms: The Whole Pie, Please

J Orthop Sports Phys Ther 2019;49(3):118-121. doi:10.2519/jospt.2019.0603

In the last decade, as the biopsychosocial model of patient health care has expanded, there has been an increased focus on the influence of psychological manifestations on patient symptoms and health-related outcomes. Buzz words, including "psychologically informed" physical therapy, have developed as researchers and practitioners attempt to find the missing link in the pain puzzle to improve patient outcomes. However, in this apparent rush to address psychological manifestations, have we failed to fully acknowledge anatomical underpinnings of symptoms in chronic pain?[12]

Our Viewpoint will explore the scientific underpinnings of psychological manifestations in chronic whiplash-associated disorders (WADs)—where opinions vary widely concerning the reason for persistent symptoms and nonrecovery. Suggested reasons for nonrecovery have included everything from lesions that cannot be detected on current imaging, to litigation psychosis, to psychiatric conditions.[3] Given that approximately 50% of individuals report persistent symptoms 12 months post injury,[2] the search for a valid reason for nonrecovery seems justified to ease the significant burden of this condition. We will also provide an epidemiological and scientific foundation for the management of chronic WAD, incorporating the spectrum of the biopsychosocial model.

The Dilemma

One challenge for clinicians is to determine how best to prioritize treatment options. It is unclear which underlying mechanisms need to be targeted and how to best target these mechanisms to address both the physical manifestations associated with higher levels of pain and disability in association with the psychological manifestations. Will treatments aimed at physical mechanisms to reduce pain and disability—such as multimodal therapy, pharmacology interventions, or interventional pain procedures—successfully target underlying mechanisms associated with psychological manifestations? Alternatively, do psychological treatments significantly improve pain and disability and physical outcomes (eg, strength, endurance, and range of motion) through reductions in psychological distress and improvements in mood, cognitions, and beliefs?

Both of these options suggest that shared mechanisms underlie the clinical features and, as a result, a possible mutual maintenance of symptoms. A prospective study of trauma victims with concurrent pain and disability and posttraumatic stress symptoms immediately following trauma reported a mutual maintenance of pain and stress symptoms. However, 1 year following trauma, posttraumatic stress symptoms influenced pain, but not vice versa.[5] Thus, a contrary viewpoint is that separate mechanisms underlie the respective manifestations. Viewed through

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this lens, each mechanism is separately modifiable and needs to be appropriately addressed.

In uninjured individuals, there are different neural representations for physical pain and social pain.[15] Functional magnetic resonance imaging patterns have been able to discriminate between noxious stimulation and rejection (seeing a picture of ex-partners) from their respective control conditions with greater than 80% accuracy. When applying the respective noxious or rejection pattern to "out-of-sample" individuals, the noxious pattern correctly identified individuals exposed to the noxious stimulus experimental paradigm, but not the pattern arising from the rejection paradigm, and vice versa. Physical pain and social pain were separately modifiable. The same may apply to chronic WAD.

Nociception Is Important for Managing Clinical Manifestations of Chronic WAD

We have highlighted the substantial role played by nociception ("the neural process of encoding noxious stimuli"[4]) in both the physical and psychological manifestations of chronic WAD. There was a clear U-shaped pattern for psychological manifestations. When individuals presented with higher levels of pain-related disability, higher levels of psychological distress, posttraumatic stress symptoms, and worse pain, cognitions, and beliefs followed.[9] Over the ensuing 12-month period, prior to treatment to reduce pain, none of the psychological (or physical) features changed.[9]

This study demonstrated that interventions directed toward nociception (physical mechanisms) may be more successful than psychological interventions alone in improving both physical and psychological clinical manifestations in chronic WAD. Within 1 month of radiofrequency neurotomy (applied to the sensory supply of the target cervical facet joint) to prevent transduction of nociception and for 11 months following treatment, pain and disability were significantly reduced, while pain cognitions and beliefs, psychological distress, and posttraumatic stress severity were also improved.[9] Physical features also improved. All psychological features returned to baseline status upon pain resumption, suggesting that psychological features paralleled pain and disability levels.[10] Treatment directed toward nociception (addressing the physical mechanisms underlying pain) improved both physical and psychological manifestations, replicating previous findings in chronic WAD[13] and in individuals undergoing hip and knee arthroplasties.[6]

In contrast, few studies of psychological interventions have reported reduced pain and disability in conjunction with physical symptoms. Poor expectations for recovery, passive coping, and posttraumatic symptoms in the acute phase of WAD are associated with development of chronic pain and disability,[1] suggesting that interventions directed at these features may assist in managing chronic WAD. However, psychological interventions delivered by physical therapists for WAD do not provide short- or long-term improvements in pain or disability, despite short-term improvements in fear of movement.[8] Physical therapist–led Stress Inoculation Training, in combination with exercise in acute whiplash,[11] may be a beneficial alternative, although the effects on pain and disability reduction were small.[11]

Psychological Features Are Important for Successful Treatment

Although the interventions used in our studies provided a significant reduction in pain intensity and improvement in disability, recovery was not complete.[10] Psychological distress levels were also still slightly elevated when compared to a healthy individual comparison group, indicating that underlying psychological mechanisms may be underpinning residual pain and disability levels, again suggesting separate modifiable mechanisms.[15]

Multiple Influences on Recovery From WAD

There are epidemiological models that can help the clinician understand the roles of physical and psychological features in chronic WAD. Multiple "pies"—the analogy of the pie accounts for the multifactorial nature of disease outcomes[7]—or causes may influence recovery from WAD. Each pie represents a sufficient cause (**FIGURE**). Hence, each instance of recovery will occur through a sufficient cause. Multiple pies (sufficient causes) indicate that multiple mechanisms may result in recovery. Each sufficient cause

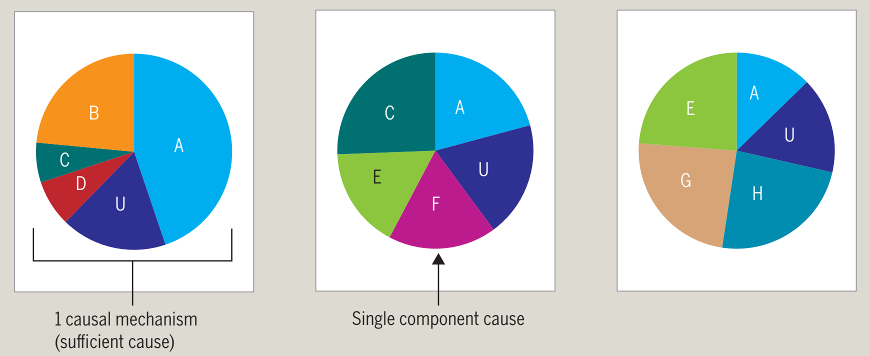

FIGURE. The causal pie model. Each circle represents a possible model of recovery, which is 1 causal mechanism (brackets), and any one letter represents a single component cause (arrow) that is associated with recovery from whiplash-associated disorder: (A) reduction of tissue lesion/nociception; (B) lower levels of posttraumatic stress symptoms; (C) absence of passive coping; (D) presence of preinjury fitness; (E) absence of emotional/affective disturbances; (F) high recovery expectations and effective cognitions and beliefs; (G) absence of or improvement in hypersensitivity/nociplastic pain mechanisms; (H) social and environmental context; (U) all other unspecified events, conditions, and characteristics that may have occurred to lead to the outcome.

requires an interaction between various "component causes."

In our example, each "component cause" is a condition associated with recovery from WAD. There are at least 10 prognostic factors or component causes associated with chronic WAD.[14] Absence of these factors may predict improved prognosis. Recovery from WAD, incorporating a causal pie model, may include the following potentially modifiable components: (1) reduction of tissue lesion/nociception, (2) lower levels of posttraumatic stress symptoms, (3) absence of passive coping, (4) presence of preinjury fitness, (5) absence of emotional/affective disturbances, (6) high recovery expectations and effective cognitions and beliefs, (7) absence of or improvement in hypersensitivity/nociplastic pain mechanisms, and (8) social and environmental context, such as sufficient social support or financial incentives.

The pie model also acknowledges that we have yet to fully uncover all the underlying mechanisms that influence recovery in chronic WAD. For example, stress system dysregulation and genetic heritability are beginning to be investigated and may explain additional variance in persistent pain in chronic WAD. The pie model is only as good as the known component causes, which will be refined over time. The very nature of the pie model indicates the joint action of a number of component causes. The pie may also vary depending on the outcome of interest. Combinations of component causes that result in recovery may differ depending on whether the clinician is predicting return-to-work, disability, or pain outcomes. There may be different sufficient causes for each individual, and for each predicted outcome.

A recovery model may theoretically involve a significant reduction in nociception (model 1) in combination with reduced posttraumatic stress symptoms, lack of passive coping mechanisms, good preinjury fitness levels, and absence of depressive mood. Another recovery model (model 2) may involve a moderate reduction in nociception, a reduction in hyperarousal symptoms, good preinjury fitness levels, appropriate management of nociplastic pain mechanisms, and high recovery expectations. Recovery for another person (model 3) may involve only a minor reduction in nociception but require effective management of nociplastic pain mechanisms. This may need to be complemented with a significant improvement in depressive mood and large improvement in financial incentive and social support. The relative proportions of these component causes will vary among individuals, and depend on the interaction between these factors within each individual. For example, exercise may produce greater levels of hypoalgesia and descending pain modulation for some, and effectively impact nociplastic pain mechanisms and mental health. For others with inferior exercise-induced hypoalgesia, reliance on pharmacology or other interventional nociceptive modulation procedures may be indicated, in conjunction with psychological counseling, to positively influence outcomes.

Four Key Questions for Physical Therapists

Considering the complexity of chronic WAD and patient-centered care, as front-line health care providers, there are at least 4 important questions to consider.

1. Do we develop appropriate professional relationships and referral networks to manage the complexity of chronic WAD? Consider whether it is appropriate to collaborate with pain medicine specialists (radiologists, physiatrists, anesthesiologists), psychologists, and experts in delivery of pharmaceutical knowledge to help the individual with chronic WAD. Perhaps this may help us determine the most appropriate combination of treatments for effective modulation of the respective mechanisms underlying chronic pain.
2. Do we ruthlessly investigate the effectiveness of nonsurgical care and the most effective treatment, irrespective of service delivery provider?
3. Do we have sufficient knowledge of clinical epidemiology to understand the health-related implications of different disease processes, the contributing factors to each, and how our clinical decisions influence this process?
4. Are we willing to use standardized outcome measures to develop large data sets to investigate the moderating interactions between different variables that have proven elusive in clinical studies? This may require alignment with research partnerships/collaborators with sufficient big-data training to effectively use this information.

To modulate both the physical and psychological features of chronic WAD effectively, one piece of pie does not necessarily seem to be enough. Why have a piece when you can have the whole pie? The outcome appears far more palatable. ◉

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The Potential Role of the Cervical Spine in Sports-Related Concussion: Clinical Perspectives and Considerations for Risk Reduction

According to the most recent consensus statement on concussion in sport, sports-related concussion (SRC) is a traumatic brain injury that results from biomechanical forces to the body, including the head and neck.[46] These forces induce pathophysiological changes in the brain, leading to somatic, physical, cognitive, and emotional symptoms, as well as sleep disturbances.[46] Although pathophysiological changes are typically transient, with symptoms often resolving within 10 to 14 days in adults,[46] a percentage of individuals with SRC experience persistent symptoms, resulting in prolonged activity and participation limitations.[44-46] Impacts to the head or body can result in linear and rotational head acceleration, which in some cases can lead to damage to brain tissue.[21,25,40,62] The force (*g*) and duration of an impact (seconds) influence the magnitude of an impact[25]; however, the magnitude of force associated with SRC is extremely variable, with no consistent findings between impact magnitude and clinical outcomes.[26] Musculoskeletal function, particularly neck strength and activation of neck muscles, may serve as a key mediator of the relationship between impact magnitude and the resulting transfer of energy from the head to the brain.[7,25,33]

SYNOPSIS: Sports-related concussion (SRC) occurs due to biomechanical forces to the head or neck that can result in pathophysiological changes in the brain. The musculature of the cervical spine has been identified as one potential factor in reducing SRC risk as well as for underlying sex differences in SRC rates. Recent research has demonstrated that linear and rotational head acceleration, as well as the magnitude of force upon impact, is influenced by cervical spine biomechanics. Increased neck strength and girth are associated with reduced linear and rotational head acceleration during impact. Past work has also shown that overall neck strength and girth are reduced in athletes with SRC. Additionally, differences in cervical spine biomechanics are hypothesized as a critical factor underlying sex differences in SRC rates. Specifically, compared to males, females tend to have less neck strength and girth, which are associated with increased linear and rotational head acceleration. Although our ability to detect SRC has greatly improved, our ability to prevent SRC from occurring and decrease the severity of clinical outcomes postinjury is limited. However, we suggest, along with others, that cervical spine biomechanics may be a modifiable factor in reducing SRC risk. In this commentary, we review the role of the cervical spine in reducing SRC risk, and how this risk differs by sex. We discuss clinical considerations for the examination of the cervical spine and the potential clinical relevance for SRC prevention. Additionally, we provide suggestions for future research examining cervical spine properties as modifiable factors in reducing SRC risk.
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KEY WORDS: *head injury, mild traumatic brain injury, neck*

Epidemiological studies have demonstrated higher rates of SRC in female university athletes compared to their male counterparts when competing in comparable sports.[13,15,17,48] Relative to males, females also experience more severe symptoms and longer recovery patterns post SRC.[12,47] Sex differences in cervical spine biomechanics are one hypothesis put forth regarding differences in SRC rates and clinical outcomes post SRC in males and females.[12,14,65] This article focuses on the role that cervical spine biomechanics and function play in SRC risk, specifically with regard to neck strength,

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neck girth, neck strength imbalances, and cervical spine posture. We address how these risk factors differ based on sex. Additionally, we provide considerations for clinical examination and clinical relevance to highlight the potential role that physical therapists, athletic trainers, and other sports medicine personnel can play in SRC risk reduction. As there is limited evidence to support specific recommendations, the goal of this paper is to highlight the importance of assessing the cervical spine with respect to SRC risk, and potential ways of incorporating these measures into clinical practice and future research.

Cervical Spine Biomechanics and Function in SRC Risk

Neck Strength and Girth Neck strength and girth have been described as potential modifiable risk factors in SRC prevention, with research demonstrating that lower neck strength and neck girth are associated with increased head acceleration during impact.[5,8,9,20] Whereas most studies to date have assessed the relationship between neck strength and girth on linear rotation and acceleration, only 1 has prospectively assessed this relationship with SRC risk. Collins and colleagues[11] found that neck strength values at baseline were lower in high school athletes who subsequently sustained an SRC relative to those who did not, and further that for every 1-lb (approximately 0.45-kg) increase in neck strength, SRC risk decreased by 5%.[11] The proposed mechanism by which neck strength decreases SRC risk relates to the ability of the neck to decelerate head movement, decreasing the transfer of energy to the brain during impact. A stronger neck can decrease head acceleration[8,27] and is associated with reduced head velocity, peak acceleration, and displacement during impact in human and simulation studies.[9,20,33,70] Sternocleidomastoid (SCM) muscle strength may be of particular importance in reducing SRC risk, as SCM strength specifically has been shown to be predictive of linear and rotational head acceleration when heading a soccer ball.[8]

Furthermore, past work suggests that males have significantly greater neck strength than females in neck extension, flexion, and lateral flexion, even after accounting for differences in body mass,[10,20,29,66] and that females have significantly smaller head-neck segment mass and neck girth compared to males.[5,20] These sex differences in neck muscle strength and girth are thought to contribute to females experiencing increased head acceleration during impact.[9,64] However, it should be noted that Collins et al[11] found that male athletes who had sustained a concussion, compared to uninjured athletes, had lower overall baseline neck strength, which was not significant in female athletes.

Muscle strength imbalances in the cervical spine may also play an important role in head acceleration and SRC risk.[16,29] Isometric tests demonstrate that cervical extension strength is generally greater than flexion strength.[49] It has been suggested, however, that when extension and flexion strength production are similar, the head and neck may be more protected during impact.[16,29] This suggestion is supported by research showing that, regardless of sex, a flexion-extension strength ratio close to 1 correlates with lower head acceleration during impact.[16]

Cervical Spine Posture Cervical spine posture may affect the force-generating capacity of neck muscles, which could influence SRC risk.[29] A common structural alteration in head positioning is forward head posture, defined as the external auditory meatus being positioned anterior to the shoulder joint.[37] Forward head posture alters the normal mechanics of the neck[68] and is generally more common in females.[53] Forward head posture also increases activation of the SCM and upper trapezius and subsequently inhibits the deep muscles responsible for segmental stability and neck proprioception.[2,39,42,43] Further, forward head posture is associated with a decreased flexion-extension strength ratio,[3] which, as mentioned previously, has an impact on head acceleration forces.[16] Thus, forward head posture may result in increased head acceleration during impact due to the muscle imbalances noted in this posture.

Potential Clinical Considerations for SRC Prevention

Neck Strength, Girth, and Endurance To date, only 1 study has linked greater neck strength with decreased SRC risk, and no studies have shown which age- and sex-specific degree of neck strength is critical for risk reduction. However, based on the studies discussed above, it is suggested that head acceleration during impact is affected by head and neck size/girth as well as neck strength.[8,16] Thus, increasing neck strength and potentially girth and reducing neck strength imbalances may, in turn, reduce SRC risk. Based on this research, we suggest that clinicians consider performing a thorough cervical spine strength assessment for athletes who are at risk for SRC (**TABLE**). Where normative strength values exist, clinicians can use these values to identify reduced strength and potential areas of focus.[8,10,11,50,56,67] Where normative values do not exist in the literature, clinicians should still consider collecting baseline strength and girth values to identify changes over time or in response to a specific strengthening protocol.

An examination of standard isometric cervical spine strength should be considered in all 3 planes of movement to quantify flexion/extension, lateral flexion, and rotation. Additionally, isolated SCM strength can be measured by isometrically resisting flexion with the neck rotated to the contralateral side.[30] To measure cervical spine strength, we recommend the use of a handheld dynamometer or other devices that allow for clear quantification of muscle strength and strength imbalances (**TABLE**). If the handheld dynamometer is the device of choice, we further recommend that the handheld dynamometer be strapped to the table to optimize stability and minimize inconsistencies in clinician force (**FIGURE**).[19] With this strength assessment, we recommend that clinicians also consider assessing the flexion-extension strength ratio, as a ratio close to 1 correlates with lower head acceleration during impact.[16]

Further, clinicians should consider screening for pain during strength testing, as baseline reports of neck pain have been correlated with increased SRC risk in youth athletes.[57] The type and severity of pain may influence the examination values obtained. We suggest that clinicians consider addressing patients' reports of neck pain or headaches and be cognizant of pain characteristics (eg, acute versus chronic, radiating versus localized) when determining baseline strength values or prior to implementing a strengthening protocol.

There is evidence that isolated strengthening of the neck may serve to protect against SRC[31] and reduce functional impairments in the cervical spine.[4] Further, isometric neck strengthening has been shown to reduce neck injury and SRC risk in sport.[31] Thus, we recommend that clinicians consider implementing a pre–athletic participation strengthening program. This strengthening program should be targeted to increase neck strength in an effort to modify the risk factors associated with SRC. Given the busy nature of a preseason schedule, clinicians should use their own judgment when determining the volume and intensity of the exercises.

With regard to neck girth, one can hypothesize that because increased neck girth is correlated with lower-head linear and rotational accelerations during impact,[5,8] interventions to increase neck girth would create a protective advantage for reducing SRC risk. Some research has sought to create reference values for neck girth[10,11]; however, given the variety of anatomical structures that influence neck circumference (eg, subcutaneous fat and individual muscle volumes), the best interventions for increasing neck girth are not clear at this time.

We hypothesize that in addition to an isometric protocol for superficial cervi-

TABLE — Potential Cervical Spine Examinations and Clinical Considerations in Reducing SRC Risk

Factor of Interest	Potential Examinations to Consider	Measurements to Consider	Clinical Relevance	Avenues for Future Research
Neck strength and girth	Isometric neck strength measures in all 3 planes of motion to quantify flexion, extension, lateral flexion, rotation, and flexion in rotation (sternocleidomastoid)	Isometric strength measurements with a handheld dynamometer,[5,10,19,67,69] fixed dynamometer,[16,19,50,56] or handheld tension scale[11]	Lower neck strength is associated with increased head linear and rotational accelerations during impact,[5,8,9,20] as well as increased SRC risk.[11] Additionally, every 1-lb (approximately 0.45-kg) increase in neck strength decreased concussion risk by 5%[11]	Development of age- and sex-specific strength normative values Relationship between neck strength and SRC risk, including reducing linear and rotational head acceleration Relationship between neck strength and clinical outcomes post SRC
	Neck circumference measurement	Circumference measurement above[10] or below[11] the thyroid cartilage	Lower neck girth is associated with increased head linear and rotational accelerations during impact,[5,8] as well as increased SRC risk[11]	Relationship between girth and SRC risk, including reducing linear and rotational head acceleration Relationship between girth and isometric neck strength
Neck endurance	Neck muscle endurance measures	Cervical flexor[24,28,34] and extensor[35,58] endurance tests	As increased activation of the deep cervical flexors is thought to enhance stability and posture in the cervical spine[22,38] and possibly play a role in controlling head accelerations,[32,60,71] there is potential for increases in neck endurance in these muscles to be associated with decreased risk of SRC	Relationship between deep muscle endurance and SRC risk Relationship between deep muscle endurance and clinical outcomes post SRC
Strength imbalances	Asymmetry in neck strength measures across the 3 planes of motion	Calculation of a strength imbalance score within planes of motion[16]	A flexion-extension ratio that is close to 1 correlates with lower head accelerations during impact,[16] which may allow for more neck protection[16,29]	Relationship between neck muscle asymmetries and SRC risk
Posture	Observation for forward head posture	Craniovertebral angle measurement[55]	It is speculated that because forward head posture is associated with a decreased flexion-extension strength ratio,[3] more extreme postural impairments may be associated with SRC risk. Obtaining this specific measure may be important, as smaller craniovertebral angles are associated with forward head posture impairments[72]	Relationship between head-neck posture and linear and rotational head acceleration Relationship between head-neck posture and severity of clinical outcomes post SRC

Abbreviation: SRC, sports-related concussion.

cal muscles, increasing the endurance capacity of the deep cervical flexors and extensors may be important for reducing SRC risk. Deep cervical flexor activation is thought to enhance stability and improve posture in the cervical spine,[22,38] and when activated properly can help to decrease reliance on superficial muscles for controlled movement of the cervical spine.[23] Additionally, research has suggested that some of the deep muscles of the neck may play a role in decreasing head accelerations.[32,60,71] Although the majority of studies have assessed cervical flexor endurance, reliable measures for both cervical flexor endurance[1,24,28,34] and cervical extensor endurance[35,58] exist. Normative data have been developed for the cervical flexor endurance test[18,36] and can be utilized for reference values; we are not aware of normative values for neck extensor endurance. While we recommend that cervical spine assessment and strengthening protocols be performed for both sexes, we believe they are of particular importance for the female athlete, given the previously mentioned sex differences in neck muscle strength.

Cervical Spine Posture A thorough postural assessment should be considered as part of an athlete's examination. Forward head posture can be observed clinically from the sagittal direction with the athlete in a standing or sitting position. Measuring the craniovertebral angle with a goniometer may further assist with quantifying forward head posture.[55] Smaller craniovertebral angles have been significantly associated with forward head posture impairments.[72] Intervening on postural impairments often implies correcting forward head posture and normalizing associated muscular imbalances. When the postural assessment is complemented by the strength assessment, an individualized intervention plan can be put into place to correct postural imbalances. This plan will vary based on the athlete's individual presentation; however, there are some general practices for reducing forward head posture that are supported by the literature. Exercises combining cervical retraction and axial extension are commonly prescribed to restore muscle balances in individuals with forward head posture.[41] We also recommend taking note of the muscles that are commonly affected by forward head posture, including the SCM,[54] upper trapezius,[6] levator scapulae,[6] and suboccipital muscles.[6]

FIGURE. In the supine position, the athlete is performing isometric cervical flexion at midrange cervical flexion. The clinician is able to quantify the athlete's strength by using the handheld dynamometer, which is strapped to the table to optimize stability and minimize inconsistencies in clinician force.

Questions for Future Research

Most studies to date have examined linear and rotational head acceleration in laboratory situations or have related neck strength to a past history of concussion. Given the relationship between greater neck strength and girth and reduced head acceleration and rotational forces, coupled with work of Collins et al[11] demonstrating that overall neck strength is lower in those who experience SRC, the evidence is strong enough to warrant future prospective, highly powered studies that further examine the role of neck strength as a preventative measure for SRC, as well as a potential intervention for SRC-related symptoms. That is, studies should include measurements of cervical spine characteristics in athletes before SRCs occur to determine whether those with increased neck strength and girth, less neck muscle asymmetry, greater endurance, and neutral alignment of the head and neck experience fewer SRCs. Furthermore, cervical spine characteristics may impact clinical outcomes post SRC by reducing the number of symptoms, symptom severity, and recovery timelines. Thus, it is important to collect data on these variables and understand their relationship to clinical outcomes.

Furthermore, although the magnitude of acceleration and rotation forces on impact may be a proxy for expected SRC risk due to the range of force magnitudes that result in concussive injuries,[25] the amount of force required to cause an SRC is not known. Nor do we know whether these forces have direct effects on clinical outcome measures post injury (eg, symptoms, symptom severity, and recovery timelines) or on the severity of potential brain tissue damage post impact. Thus, prospective studies are needed that examine for relationships between cervical spine characteristics, such as neck strength and endurance, neck girth, and posture, as well as biomechanical factors thought to increase SRC risk, such as head acceleration and rotation. Baseline biomechanical measures are likely to be of particular importance in contact and collision sports, where SRC risk is greater, and have the potential to provide additional information about SRC risk and clinical outcomes. Given what is known about differences in head acceleration and rotational forces between males and females, coupled with observations that female athletes incur more SRCs and experience a greater number of symptoms and severity, as well as prolonged recovery time, it is important that studies are adequately powered to examine sex differences.

In addition, it is imperative to develop sex-specific norms for neck strength that are associated with reduced risk of SRC. Normative data on isometric strength for cervical flexion, extension, sidebending, and rotation have been published for males and females,[50,56] with females having weaker necks compared to males, even when accounting for body weight, body mass index, height, and neck length.[50,56,67] However, it is not known whether there are specific strength values in male and female athletes that may be associated with fewer SRCs and, more importantly, fewer clinical symptoms, reduced symptom severity, and reduced recovery time.

Additionally, the influence of innate anatomical variations of the cervical spine between males and females warrants further investigation.[61] Specifically, females tend to have increased ligamentous laxity,[51,52,59] smaller vertebral body width,[63] and less consistent vertebral coupling,[63] which have been suggested to decrease dynamic stability of the cervical spine.[61] These geometric differences between male and female necks,[67] along with factors such as the ratio of muscle strength around the cervical spine, also warrant further investigation with respect to their roles in SRC risk or prevention. If sex-specific strength targets and muscle strength balance goals can be identified, then preactivity training programs can be designed to meet those targets.

Finally, future research examining the relationship between cervical spine characteristics and SRC risk should consider sport-specific factors and level of competition. That is, greater neck strength and girth, reduced muscle asymmetries, and neutral alignment of the head and neck may be of greater importance for athletes participating in high-impact sports associated with greater magnitude of impacts to the head and body. Athletes participating in sports with no, or limited, contact may not need to incorporate these protocols in pre–athletic participation assessments. Nonetheless, we believe it is still important to collect normative values and understand differences in cervical spine characteristics in athletes who compete in collision, contact, limited-contact, and noncontact sports.

CONCLUSION

Significant advancements have been made in the diagnosis and management of SRC, yet we are still falling short in preventing and reducing the risk of these injuries. As such, an important focus moving forward is to determine ways to prevent SRCs and reduce the severity of their impact when they do occur. Neck strength, girth, and cervical spine posture have been identified as potential factors that may reduce SRC risk by decreasing linear and rotational head acceleration and the magnitude of force upon impact. Further, it is speculated that biomechanical differences in the cervical spine between males and females may impact sex differences in SRC rates. Thus, we suggest that it is important to focus on the biomechanical properties of the cervical spine, as these properties may represent a modifiable factor in reducing SRC risk.

Clinically, it is important to comprehensively assess the cervical spine, including strength, girth, and postural assessments, prior to engagement in sport, and particularly in those for whom there is a high risk of impact, to determine who would benefit from preactivity cervical spine interventions. Established normative values and baseline measurements would help in implementing intervention and preventative measures. In addition, future research that focuses on how cervical spine biomechanics influence SRC risk, sex differences in SRC rates, and whether reductions in head acceleration and rotation forces directly impact SRC outcomes is needed. ◉

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