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Examining the Effects of Dynamic and Isometric Resistance Training on Knee Joint Kinetics During Unplanned Sidesteps in Elite Female Athletes

Daniel Kadlec,[1] Matthew J. Jordan,[2] Jacqueline Alderson,[3] and Sophia Nimphius[1]

[1]School of Medical and Health Sciences, Edith Cowan University, Joondalup, Western Australia, Australia; [2]Faculty of Kinesiology, Sport Medicine Centre, University of Calgary, Calgary, Canada; and [3]UWA Tech & Policy Lab, The University of Western Australia, Crawley, Western Australia, Australia

Abstract

Kadlec, D, Jordan, MJ, Alderson, J, and Nimphius, S. Examining the effects of dynamic and isometric resistance training on knee joint kinetics during unplanned sidesteps in elite female athletes. *J Strength Cond Res* 38(12): 2079–2087, 2024—The purpose of this study was to examine the effects of a 4-week block of isometric (isometric$_{RT}$) and dynamic resistance training (dynamic$_{RT}$) on kinetic variables associated with anterior cruciate ligament (ACL) injury risk during unplanned sidesteps in elite female athletes. Twenty-one elite female athletes competing for a women's international rugby union team were recruited with 15 ($n = 15$; age: 23.4 ± 4.7 years; 170.7 ± 8.4 cm; 84.4 ± 15.4 kg) completing assessment of knee flexion moment, knee valgus moment (KVM), knee internal rotation moment (KIRM), knee joint power during unplanned sidesteps, and lower limb strength before and after a 4-week intervention. Linear mixed effects models and one-dimensional statistical parametric mapping assessed the effect of the interventions. Statistical significance was set at $\alpha = 0.05$. Post-intervention the isometric$_{RT}$ group revealed reduced peak KVM during early stance ($p = 0.04$) while the dynamic$_{RT}$ group decreased peak KIRM ($p < 0.01$) and KIRM over 8.8–86.6% ($p < 0.01$) and 96.9–98.5% ($p = 0.047$). An exploratory combined group analysis revealed reductions in KVM over 7.9–21.8% ($p = 0.002$) and in KIRM over 8.3–90.5% ($p < 0.01$) and 96.2–98.5% ($p = 0.046$). Most lower limb isometric and dynamic strength measures increased after both resistance training interventions. Overall, both groups increased lower-body maximum strength while reducing kinetic knee joint variables associated with ACL injury risk during unplanned sidesteps. These results highlight the importance of increasing single-joint and multijoint strength in female athletes to mitigate the mechanical knee joint demands during sidestepping.

Key Words: ACL, strength, rugby, change of direction, injury risk

Introduction

Noncontact anterior cruciate ligament (ACL) injuries are prevalent during unplanned sidestepping, a common change of direction maneuver often occurring in evasive team sports (15,40). Over the past decade, the injury incidence has remained unchanged, with female athletes persistently suffering 2–8× higher injury rates compared with male athletes (1,2,47). Unfortunately, research narratives often commence arguments or prioritize the attribution of the injury disparity to inherent female biology (e.g., circulating estrogen, menstrual cycle variations, skeletal morphology, etc) despite limited evidence in support of this proposed hierarchy and focus on such claims (21). These explanations risk oversimplifying and overshadowing modifiable risk factors related to physical preparation and motor skill acquisition (11,38).

Address correspondence to Daniel Kadlec, d.kadlec@ecu.edu.au.

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Maximum strength is a well-established and modifiable risk factor contributing to an athlete's ability to mitigate mechanical demands during high-impact activities (32). Stronger athletes tolerate higher training loads (34) and are also at lower risk of suffering acute or overuse injuries (3,40), likely due to increased structural resilience of bones, ligaments, tendons and cartilage (18), improved muscle recruitment, and activation patterns (45). Similarly, increasing maximum strength decreased acute injuries to a third, and overuse injuries were almost halved (31). As such, affording athletes the opportunity to increase single-joint and multijoint strength is paramount to increase injury resiliency. In the context of sidestepping, stronger athletes, as quantified by unilateral isometric squat strength, experienced lower external peak knee flexion moments (KFM) and greater knee flexion angles at initial contact compared with weaker athletes (15), noting these factors are commonly associated with reduced ACL injury risk (14). Two studies have examined the effect of increasing lower limb strength on knee joint kinetics in male athletes (12,23), but both studies were unsuccessful in eliciting a reduction of external knee joint moments when the resistance training program was implemented. Despite these insights, there is limited, albeit potentially promising (49) research evaluating the efficacy of increasing lower limb strength on ACL risk during unplanned sidesteps in female athletes. Addressing this gap is paramount, given the higher injury rates observed in this demographic.

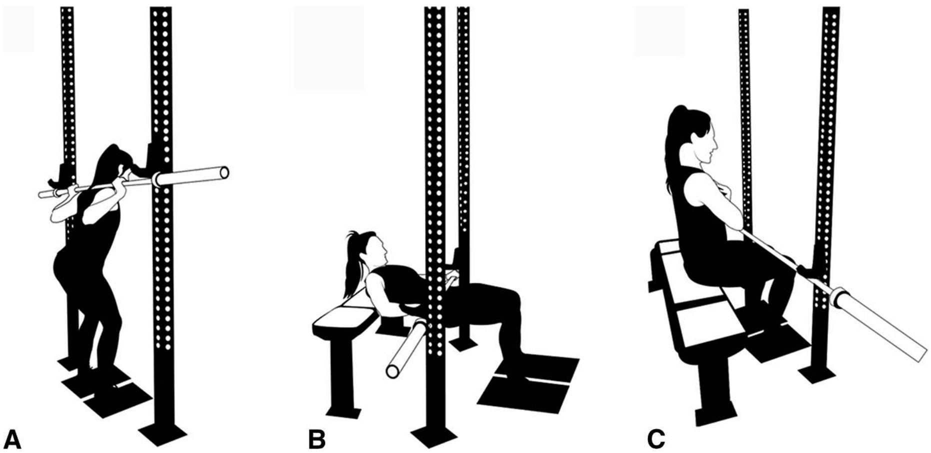

Figure 1. Visual representation of the (A) ISO_{SQUAT}, (B) ISO_{THRUST}, and (C) ISO_{CALF}.

Owing to the ACL's complex line of action, no single muscle or muscle group can directly mitigate the tri-planar mechanical demands applied to the knee joint (35,36). Thus, incorporating single-joint and multijoint training exercises may further facilitate maximum strength throughout the kinetic chain and mitigate the imposing demands during high-impact activities. This combined approach may better prepare athletes to tolerate the imposing demands of dynamic high-impact activities such as unplanned change of direction maneuvers. Traditionally, practitioners implemented different training methods to increase single-joint and multijoint strength, such as dynamic resistance training ($dynamic_{RT}$) over the whole range of motion (45). Recently, isometric resistance training ($isometric_{RT}$) conducted with maximal voluntary effort through specific joint ranges has increased in popularity due to its structural and neuromuscular adaptive response (8,19,29). $Isometric_{RT}$ has been proposed as a viable alternative mode of strength training that induces less fatigue than $dynamic_{RT}$, results in superior angle-specific rate of force development and peak force production and can benefit various sports-related dynamic performances (33,41). For example, increased force production at the trained angle was associated with improved performance in selected athletic tasks, such as vertical jumps, sprint cycling, and sprint kayaking (8,19,28). Despite these insights into $isometric_{RT,}$ it is currently unknown if improvements in range-specific force production associated with biomechanically disadvantaged joint dynamics can increase injury resiliency. As such, single-joint and multijoint $isometric_{RT}$ in joint ranges associated with peak joint moments during sidestepping may offer a specific approach to better mitigate the impact demands and attenuate ACL strain in female athletes.

This study addressed a gap in the current research by exploring the effects of a lower-limb resistance training intervention embedded in an elite training environment. The aim was to evaluate whether knee joint kinetics associated with ACL injury risk during unplanned sidesteps differed following an $isometric_{RT}$ or $dynamic_{RT}$ intervention. Specifically, it was hypothesized that $isometric_{RT}$ in sidestep-specific joint angle ranges of motion would result in a greater reduction in mechanical demands applied to the knee joint associated with ACL injury risk than $dynamic_{RT}$. In addition, an exploratory analysis was conducted to determine the effectiveness of a resistance training intervention on a cohort level (generic improvement in motor capacity independent of the training method).

Methods

Experimental Approach to the Problem

A block-randomized intervention study with a repeated measures pre-to-post-test design was used to determine the effects of 2 different resistance training interventions ($isometric_{RT}$ and $dynamic_{RT}$) on knee joint kinetics during unplanned sidestepping. Three-dimensional (3D) motion capture with a ground-embedded force plate was used to record kinematics and kinetics during unplanned sidestepping tasks before and after the resistance training intervention. Subjects followed a resistance training program twice per week for 4 weeks with either $isometric_{RT}$ or $dynamic_{RT}$ exercises to examine changes in peak negative power value for the knee (JP_{KNEE}), peak KFM, peak knee valgus moment (KVM), and peak knee internal rotation moment (KIRM). In addition, peak force for the isometric plantar flexion (ISO_{CALF}), isometric squat (ISO_{SQUAT}), isometric hip thrust (ISO_{THRUST}), and 1 repetition maximum (1RM) for the calf raise, parallel squat, and hip thrust were assessed preintervention and postintervention. All preintervention and postintervention tests were conducted on 1 day, beginning with the isometric strength tests, followed by the dynamic 1RM tests before executing the unplanned sidesteps. The whole testing procedure took ~90 minutes per subject.

Subjects

Twenty-one elite female athletes competing for a women's international rugby team (23.4 ± 4.7 years; 170.7 ± 8.4 cm; 84.4 ± 15.4 kg) volunteered for the study. All subjects had at least 3 years of rugby experience and 1 year of resistance training experience and were free of a lower-body injury or an existing medical condition that would compromise participation at the time of testing and actively competing in their sport. However, during the intervention, 6 subjects ($dynamic_{RT}$: $n = 2$; $isometric_{RT}$: $n = 4$) dropped out due to contact injuries suffered in club games or logistical challenges with the training requirements. All subjects provided written informed consent before participation (Edith Cowan University Research Ethics Approval #22459). All subjects were part of the extended national program and recruited from 2 local clubs. Throughout the intervention, the subjects continued with their regular skill sessions (3 sessions per week), speed work (1–2 sessions per week), and conditioning training (1–2 sessions per week) for approximately 12 hours per week.

This was consistent across all subjects. A minimum sample size of 10 per group was calculated from an a priori power analysis using G*Power (Version 3.1.9.6, University of Dusseldorf, Dusseldorf, Germany). This was based on a previously observed Cohen's *d* of 0.77 for the change in KVM preintervention to postintervention in unplanned sidesteps (17), a power of 0.80, and a type 1 error of 0.05.

Procedures

Isometric Strength Testing. Maximal voluntary isometric contraction (MVIC) strength for ISO_{CALF}, ISO_{SQUAT}, and ISO_{THRUST} was tested after a standardized warm-up. Subjects performed a test-specific warm-up, which consisted of pushing against a fixed object for 5 seconds at a self-determined 50% effort followed by 3 seconds at a self-determined 90% maximal effort with a 1-minute recovery between warm-up efforts. The subjects then completed 3 MVIC efforts lasting 5 seconds with the instruction "push as hard and fast as you can" for each MVIC test (39). The trial with the highest summed maximum force was used in the statistical analysis for each test.

Each subject started with the squat, followed by the hip thrust, followed by calf raise, and then hip abduction and hip adduction MVIC. The chosen joint angles for each test were based on previous research demonstrating at which joint ranges peak knee moments occurred during unplanned sidesteps (20,24). For MVIC of ISO_{SQUAT}, ISO_{THRUST}, and ISO_{CALF}, the vertical ground reaction force was obtained from each limb using 2 dual uniaxial force plates (PASCO Force Platform PS-2141, PASCO, Roseville, CA) sampled at 1,000 Hz. ISO_{SQUAT} subjects performed an isometric squat in a Smith machine against an immovable bar across their upper bar with knees fixed at 130–140°, and hips fixed at 130–140° and each foot flat on a force plate (25,39) (Figure 1A). For ISO_{THRUST}, subjects performed an isometric hip thrust in a Smith machine against an immovable bar across the distal end of their femur while seated with the upper backs on a bench, hips flexed at 150–160°, knees flexed at 120–130°, and their shins perpendicular to the ground and feet flat on the force plate (Figure 1B). For ISO_{CALF}, subjects sat on a box with knees flexed at 90° with 10° of ankle dorsal flexion and crossed arms across the chest. The immovable bar was placed on top of the distal end of the thigh (48) (Figure 1C).

Dynamic Strength Testing. All 1RM tests were conducted after the unplanned sidestepping assessment. Each subject performed 3 progressively heavier warm up sets (5 repetitions at 50%, 3 repetitions at 75%, and 1 repetition at 90% of the predicted 1RM) for each lift, followed by 2–3 sets of 1RM testing sets. Rest periods between the testing sets were 3–5 minutes. For each test, subjects increased the load after a successful trial up to the point where the load could not be lifted. Each subject started with the parallel squat, followed by the hip thrust and the seated calf raise.

For the 1RM back squat, the subject's feet were slightly wider than shoulder width apart, with toes pointed forward or slightly outward. Subjects descended until the hip joint was level with the knee joint. An attempt was declared invalid when the load could not be lifted, or a proper depth was not attained (37). The 1RM hip thrust was performed with the subject's upper backs on a bench. The subject's feet were slightly wider than shoulder width apart, with toes pointed forward or slightly outward. The barbell was padded with a thick bar pad and placed over the hips. Subjects were instructed to thrust the bar upward while maintaining a neutral spine and pelvis. An attempt was declared invalid when the load could not be lifted to a full lock out (16). The 1RM calf raise was tested in a seated calf raise machine (Body-Solid, Sydney, Australia), where the weighted bar was placed on top of their knees. In the starting position, ankle dorsal flexion was 10–15° and only the balls of the foot were in contact with the machine. The subject then plantar flexed until they reached maximum range. An attempt was declared invalid when the necessary dorsal flexion could no longer be achieved (48).

Sidestep Protocol. A warm-up consisting of minimum of 3 successful preplanned sidesteps and crossover steps to the opposing direction was performed with the right limb executing all cutting movements. Subjects had a 7–10 m run-up to obtain a consistent approach velocity between 3.5 and 4.5 $m \cdot s^{-1}$ before executing the sidestep on the force plate (46). A trial was repeated when a subject's approach velocity deviated outside of the velocity range if the entire foot did not contact inside the force plate boundary or if they initiated the cut in the incorrect direction. The sidestep angle of 45° was indicated using a runway line marked on the force plate but was not examined by trial as actual sidestep angle is often much lower on execution (46).

The subjects performed in randomized order either a sidestep or a crossover cut in response to 2 different visual stimuli. A 43.2 cm screen, placed 3 m beyond the force plate, displayed a 30 cm arrow indicating the sidestep or cross over cut direction on breaking the laser of a set of timing gates on approach. The timing gates were positioned 2 m anterior to the force plate and set at 0.8 m height and 1.5 m apart (as defined by the subject approach direction). The arrow appeared with a 400 ms delay after breaking the beam, coinciding with the toe-off of the penultimate step. While only left sidestep-directed trials (off the right stance leg) were analyzed, crossover cuts to the right ensured subjects could not anticipate the direction. Subjects were instructed to maintain a consistent approach velocity throughout and focus on the screen to avoid force plate targeting with the execution leg. Testing was finished after each subject had completed 3 valid sidesteps, which were used for subsequent analysis.

Data Collection. Three-dimensional motion data were synchronously collected at 250 Hz using an 8-camera Vicon T-series motion analysis system (ViconPeak Ltd., Oxford, United Kingdom). Ground reaction forces were synchronously collected at 2000 Hz using a 600 × 900 mm force plate (Advanced Mechanical Technology Inc., Watertown, MA). Thirty-eight retroreflective markers were affixed to each subject following the University of Western Australia lower-body and torso marker set and model (Version 5). Single markers were attached to the left and right calcanei, left and right head of the first and fifth metatarsals, left and right anterior and posterior superior iliac spines, sternal notch, xiphoid process, seventh cervical vertebrae, and 12th thoracic vertebrae. Marker clusters were attached to the thighs and shanks of both legs. All testing was performed barefoot to decrease effect of different shoes at testing sessions before and after the intervention as standardized shoes were not available for this research (7). To define each ankle and knee joint center, respectively, single markers were attached to the medial and lateral malleoli and medial and lateral tibial plateau in the static calibration trials, which were removed for the dynamic trials. Functional knee and hip tasks were performed to identify knee and hip joint centers and axes, respectively (5).

Data were processed using Vicon Nexus (Version 2.5, Vicon Motion Systems, United Kingdom), low-pass–filtered at a cutoff frequency of 15 Hz, using a fourth-order, zero-lag, Butterworth recursive filter, and analyzed with Visual 3D software (C-motion, Inc., Rockville.MD). The cutoff frequency was determined using residual analysis (49) and visual inspection of the kinematic data. Joint kinetics were calculated during the cutting step from the initial contact to toe-off, with peak joint kinetics extracted from the initial contact to weight acceptance (first local minimum in the ground reaction force or 30% of stance) (4). External joint moments were calculated for flexion-extension, adduction-abduction, and internal-external rotation in the hip and knee, and for the ankle joint in plantar flexion-dorsal flexion, abduction-adduction, and inversion-eversion. Instantaneous joint power was calculated from joint angular velocities multiplied by net joint moments for each trial ($p = M \cdot \omega$) and summed for all planes. Peak KFM, KVM, KIRM, and JP_{KNEE} between the initial contact and weight acceptance were used for further analysis.

Sidestep angle was calculated using the x-coordinates and y-coordinates of the stance foot ankle joint center at the initial contact (x1 and y1) and the coordinates of the contralateral ankle joint center at the initial contact (x2 and y2) using equation (1) (10). The immediate entry velocity was defined as the horizontal velocity of the center of mass at the initial contact of the execution step.

$$\text{Sidestep angle} = \tan^{-1}\left(\frac{a}{b}\right);\ \text{where } a = |x2 - x1| \text{ and } b = |y2 - y1| \tag{1}$$

Resistance Training Intervention. Subjects were allocated to either a dynamic_{RT} ($n = 11$) or isometric_{RT} ($n = 10$) intervention using block randomization, wherein the allocation was based on the order in which they were tested. Subjects in the isometric_{RT} group performed a MVIC against an immovable bar with the instruction "push as hard and fast as possible" for the ankle, knee, and hip joints as previously done during the isometric testing. Each athlete performed in total 10 sets of 3 repetitions, each lasting 3 seconds of maximal isometric bouts. The isometric_{RT} and dynamic_{RT} groups performed on average 2, 4, and 4 sets of isometric or dynamic calf raises, squats, and hip thrusts, respectively. The set distribution for each subject is presented in the Supplemental Digital Content 1 (see Table 1, http://links.lww.com/JSCR/A532), as it was individualized based on the relative 1RMs, training age, and injury history and was programmed in collaboration with the respective high-performance staff. Intraset rest periods of 5 seconds and interset rest periods of 3 minutes were used, respectively. All subjects in the dynamic_{RT} training group performed a seated calf raise, parallel squat, and hip thrust as done during the dynamic testing. Each athlete performed a total of 10 sets of 3 repetitions at 85–90% of their tested 1RM in the respective exercise. The cadence of each exercise was set to a 2-second downward phase and a 1-second upward phase. Interset rest periods of 3 minutes were used. Time under tension was ~90 seconds in both groups per session. Nine subjects in the dynamic_{RT} group and 6 subjects in the isometric_{RT} group completed 100% of the training sessions and were included in the statistical analysis.

Statistical Analyses

Theean and *SD* were calculated for all discrete variables. Initially, we tested the proposed hypothesis and performed a between-group analysis. No interaction effects were found. Subsequently, we conducted an exploratory combined group analysis to determine the effectiveness of a resistance training intervention on a cohort level (generic improvement in motor capacity independent of the training method).

Repeated measures correlations for the within-individual relationship between dependent variables were determined to confirm the subsequent use of separate linear mixed effects models (LMM). No very large correlation (i.e., $r = 0.7–0.9$ explaining more than 50% of variance) was found, thereby justifying a multivariate mixed effects model (44). A LMM with restricted maximum likelihood (REML) was performed to compare time points (pretraining and post-training), intervention groups (dynamic_{RT} and isometric_{RT}), and their interaction. The model was fitted using REML estimation because the way subjects differ may be related to their starting values. The REML enables more accurate estimates of the variance and model parameters when a correlation between fixed effects and random effects may exist. Intervention group and time (and their interaction) were specified as fixed effects with random intercepts set for subjects. The subject was set as a random effect, and by-subjects random slopes for the effect of group and time (and their interaction). The model specification was as follows: dependent variable ~1 + group × time + (1 + group + time + group:time | subject). Significance was calculated using the gamlj package (Version 2.5.5), which applies Satterthwaite's method to estimate degrees of freedom and generate *p*-values. Assumptions of linearity, normality, and homoscedasticity were confirmed through inspection of plots. One trial each from 2 subjects was excluded from the analysis due to calibration error.

One-dimensional (1D) statistical parametric mapping (SPM) was used to evaluate if significant differences existed between the patterns and the timing of KFM, KVM, KIRM, and JP_{KNEE} for both intervention groups and the combined data set (42). A SPM paired sample *t* test was performed on the normalized time series data on the execution step (0–100% stance period) to determine if a significant ($p < 0.05$) difference was present preintervention and postintervention. All 1D SPM analyses were implemented in Canopy (Version 2.1.9, Enthought, TX) using the open-source package located at http://www.spm1d.org/"RFT1D."

A paired *t* test was used to examine within-group changes and a two-sample *t* test for between-group differences in strength following the intervention, respectively. Hedge's *g* effect size with a 95% confidence interval (CI), to account for small sample sizes, was calculated using formulas (2) and (3) and interpreted as small ($d = 0.2$), medium ($d = 0.5$), and large ($d = 0.8$) for all dependent variables (30).

$$\text{Hedges's } g = \text{Cohen's } d \times \left(1 - \frac{3}{4(n_1 + n_2) - 9}\right) \tag{2}$$

$$\text{Cohen's } d = \frac{Mean_{post} - Mean_{pre}}{\sqrt{\frac{(n_{post} - 1)^* SD^2_{post} + (n_{pre} - 1)^* SD^2_{pre}}{n_{post} + n_{pre} - 2}}} \tag{3}$$

Statistical significance was set at $\alpha \leq 0.05$. The statistical analyses were performed in R Studio (Version 1.4.11.06, R Core Team 2018, http://www.R-project.org/).

Results

No significant interaction effects were detected between groups after the intervention period for any strength measures ISO_{SQUAT} ($p = 0.46$), ISO_{THRUST} ($p = 0.29$), ISO_{CALF} ($p = 0.42$), $1RM_{SQUAT}$ ($p = 0.08$), $1RM_{THRUST}$ ($p = 0.51$), and $1RM_{CALF}$ ($p = 0.26$). Post hoc analyses of the within-group analysis for

Table 1

Joint by joint isometric and dynamic strength for dynamic$_{RT}$ and isometric$_{RT}$ and effect sizes differences (Hedge's *g* with 95% confidence intervals) between pretraining and post-testing (mean ± *SD*).*

Measure	Pre	*SD*	Post	*SD*	*p*	*g*	[95% CI]
Isometric$_{RT}$ ($n = 6$)							
ISO_{SQUAT} (N·kg^{-1})	32.45	4.32	35.50	5.22	0.17	0.59	[−0.50 to 1.65]
ISO_{THRUST} (N·kg^{-1})	14.38	2.36	15.93	2.06	0.03†	0.65	[−0.45 to 1.71]
ISO_{CALF} (N·kg^{-1})	20.03	7.40	25.30	3.41	<0.01‡	1.36	[0.14 to 2.53]
$1RM_{SQUAT}$ (Kg·kg^{-1})	1.20	0.15	1.21	0.14	0.65	0.11	[−0.98 to 1.19]
$1RM_{THRUST}$ (Kg·kg^{-1})	1.92	0.28	2.23	0.29	0.03†	1.01	[−0.19 to 2.16]
$1RM_{CALF}$ (Kg·kg^{-1})	1.20	0.20	1.30	0.19	0.03†	0.47	[−0.65 to 1.56]
ISO_{ABD} (N·kg^{-1})	8.81	0.46	8.53	0.83	0.24	−0.41	[−1.09 to 0.27]
ISO_{ADD} (N·kg^{-1})	8.10	0.78	7.52	1.18	0.12	−0.56	[−1.24 to 0.14]
Dynamic$_{RT}$ ($n = 9$)							
ISO_{SQUAT} (N·kg^{-1})	30.72	8.16	32.34	6.50	0.10	0.21	[−0.68 to 1.09]
ISO_{THRUST} (N·kg^{-1})	14.73	3.45	17.70	2.57	0.02†	0.93	[−0.02 to 1.85]
ISO_{CALF} (N·kg^{-1})	21.34	4.73	24.89	3.21	0.05	0.82	[−0.10 to 1.75]
$1RM_{SQUAT}$ (Kg·kg^{-1})	1.04	0.21	1.20	0.23	<0.01‡	0.71	[−0.22 to 1.61]
$1RM_{THRUST}$ (Kg·kg^{-1})	1.66	0.43	1.99	0.38	<0.01‡	0.79	[−0.14 to 1.70]
$1RM_{CALF}$ (Kg·kg^{-1})	1.05	0.20	1.20	0.15	<0.01‡	0.79	[−0.14, 1.70]
ISO_{ABD} (N·kg^{-1})	8.76	1.00	8.55	1.33	0.52	−0.17	[−0.70 to 0.35]
ISO_{ADD} (N·kg^{-1})	8.21	0.88	8.82	1.20	0.04†	0.57	[0.03 to 1.10]

*ISO_{SQUAT} = isometric squat; ISO_{THRUST} = isometric hip thrust; 1RM = 1 repetition maximum.
†Significant within-group difference from pretesting and post-testing ($p \leq 0.05$).
‡Significant to ($p \leq 0.01$).

changes after the dynamic$_{RT}$ and isometric$_{RT}$ are presented in Table 1.

The entry velocity in the isometric$_{RT}$ group (Pre: 2.76 ± 0.26 m·s^{-1}; Post: 2.78 ± 0.24, m·s^{-1}; $p = 0.84$) and dynamic$_{RT}$ group (Pre: 2.79 ± 0.28 m·s^{-1}; Post: 2.77 ± 0.29, m·s^{-1}; $p = 0.77$) remained unchanged preintervention to postintervention. Similarly, change of direction angle for the isometric$_{RT}$ group (Pre: 40.1 ± 4.8°, Post: 40.3 ± 5.1°; $p = 0.61$) and the dynamic$_{RT}$ group (Pre: 40.7 ± 5.5°; Post: 40.4 ± 6.1°; $p = 0.51$) did not differ preintervention to postintervention.

No significant interaction effects were detected between groups after the intervention period for peak KFM ($p = 0.98$), peak KVM ($p = 0.76$), peak KIRM ($p = 0.23$), and JP_{KNEE} ($p = 0.30$). Post hoc analyses of the within-group analysis for changes in the dynamic$_{RT}$ and isometric$_{RT}$ and the exploratory combined group analysis are presented in Table 2.

Figure 2 depicts the results from the SPM analyses for the change in knee joint kinetics for each intervention group and the exploratory combined group. KIRM significantly decreased over selected regions of the stance phase (20.6–25.5%; $p = 0.024$ and 51.4–77.9%; $p < 0.01$) in the isometric$_{RT}$ group and over a majority of the stance phase (8.8–86.6%; $p < 0.01$ and 96.9–98.5%; $p = 0.047$) in the dynamic$_{RT}$ group. The exploratory combined analysis indicated

Table 2

Relative peak joint kinetics and effect sizes differences (Hedge's *g* with 95% confidence intervals) between pretesting and post-testing (mean ± *SD*).*

Measure	Pre	*SD*	Post	*SD*	*p*	*g*	[95% CI]
Isometric$_{RT}$ ($n = 6$)							
KFM (Nm·kg^{-1})	1.85	0.65	1.72	0.66	0.32	0.19	[−0.49 to 0.87]
KVM (Nm·kg^{-1})	−0.56	0.34	−0.42	0.29	0.04†	0.45	[−0.24 to 1.13]
KIRM (Nm·kg^{-1})	−0.27	0.11	−0.18	0.13	0.21	0.72	[0.02 to 1.42]
JP_{KNEE} (W·kg^{-1})	−13.81	7.31	−11.75	4.49	0.43	0.33	[−0.35 to 1.01]
Dynamic$_{RT}$ ($n = 9$)							
KFM (Nm·kg^{-1})	2.25	1.14	2.06	0.76	0.48	0.19	[−0.33 to 0.72]
KVM (Nm·kg^{-1})	−0.48	0.34	−0.26	0.28	0.17	0.61	[0.06 to 1.14]
KIRM (Nm·kg^{-1})	−0.34	0.16	−0.17	0.09	0.01†	1.38	[0.79 to 1.97]
JP_{KNEE} (W·kg^{-1})	−14.94	8.50	−15.75	7.50	0.50	0.10	[−0.43 to 0.62]
Combined ($n = 15$)							
KFM (Nm·kg^{-1})	2.03	0.89	1.94	0.74	0.25	0.19	[−0.23 to 0.61]
KVM (Nm·kg^{-1})	−0.51	0.34	−0.34	0.29	0.04†	0.55	[0.12 to 0.98]
KIRM (Nm·kg^{-1})	−0.32	0.14	−0.17	0.11	0.01†	1.15	[0.69 to 1.60]
JP_{KNEE} (W·kg^{-1})	−14.52	8.01	−14.26	6.77	0.86	0.03	[−0.38 to 0.45]

*KFM = knee flexion moment; KVM = knee valgus moment; KIRM = knee internal rotation moment; JP_{KNEE} = peak power knee.
†Indicates a significant within-group difference preintervention to postintervention ($p \leq 0.05$).

reduced KIRM over a majority of the stance phase (8.3–90.5%; $p < 0.01$ and 96.2–98.5%; $p = 0.046$). Furthermore, KVM significantly decreased in the exploratory combined cohort during early stance phase (7.9–21.8%; $p = 0.002$). There were no changes at any point in the stance phase for JP_{KNEE} (see Figure 1, Supplemental Digital Content 1, http://links.lww.com/JSCR/A532) for either intervention group or the exploratory combined cohort.

Discussion

This study compared the effects of dynamic and isometric resistance training interventions on knee joint kinetics associated with ACL strain during unplanned sidesteps in female athletes. Both resistance training interventions demonstrated an increase in most strength measures (Table 1). However, contrary to the initial hypothesis, no between-group differences were detected preintervention to postintervention for any knee joint kinetic variable. The subsequent within-group analysis demonstrated significantly reduced peak KVM in the isometric$_{RT}$ and peak KIRM in the dynamic$_{RT}$ group. The SPM analysis indicated KIRM significantly decreased over selected regions of the stance phase after the isometric$_{RT}$ (20.6–25.5% and 51.4–77.9%) versus the majority of stance after the dynamic$_{RT}$ (8.8–86.6% and 96.9–98.5%). It is important to be cautious when interpreting the results within each group since our SPM analysis focused on within-group comparisons from pretesting to post-testing and not between-group comparisons. The explorative analysis of the data at a cohort level by combining both groups to determine the effectiveness of improving strength independent of the method of

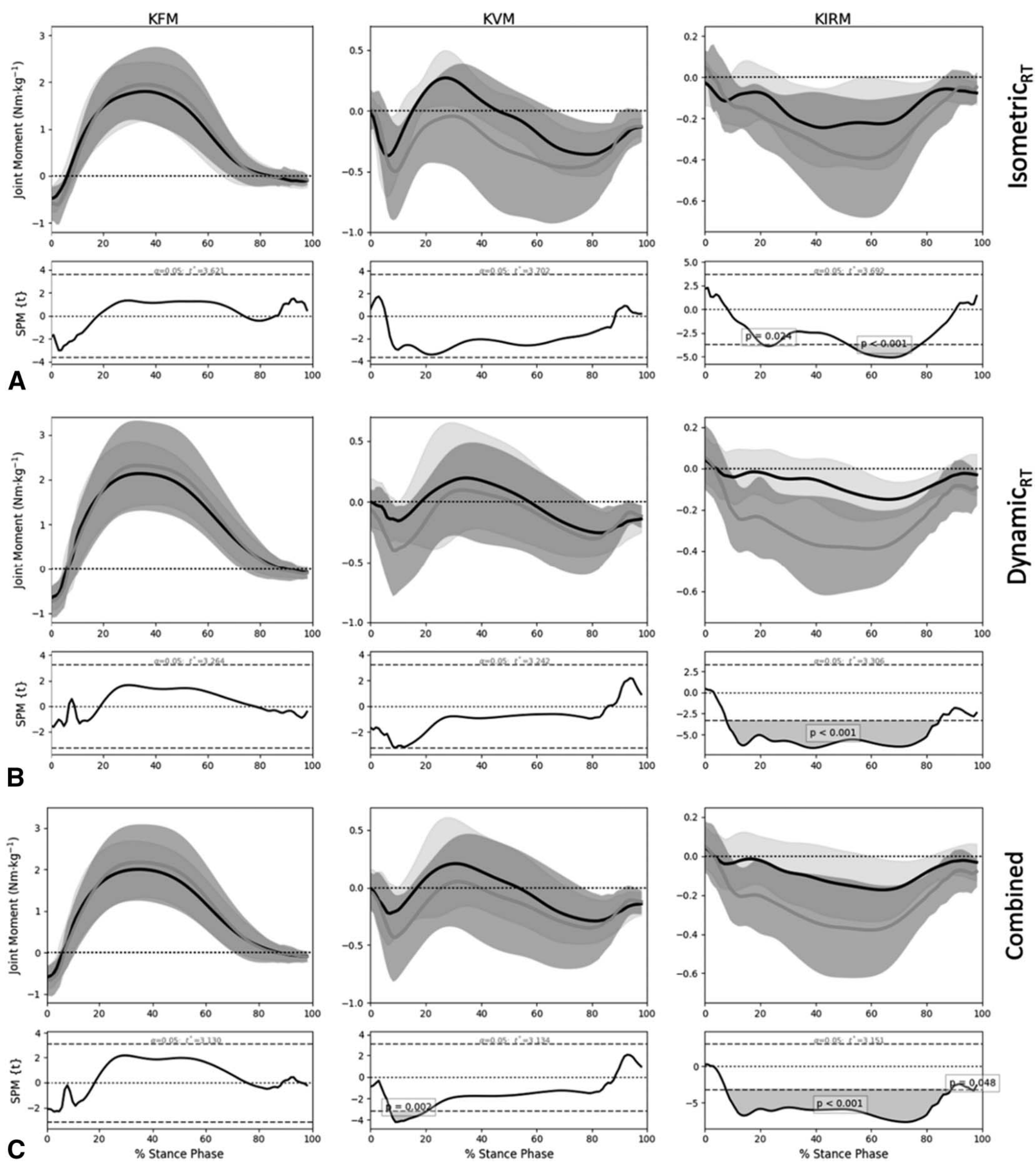

Figure 2. Time-normalized mean and *SD* error clouds and SPM paired t tests for average KMF, KVM, and KIRM plane for (A) isometric$_{RT}$, (B) dynamic$_{RT}$, and (C) combined cohort. Thin black lines show the inference curve with suprathreshold clusters (shaded) and critical threshold (t statistic) as a function of time represented by the dashed line that indicates the random field theory thresholds for significance. KFM = knee flexion moment; KVM = knee valgus moment; KIRM = knee internal rotation moment. Solid red line—pretraining baseline; solid black line—post-training testing.

resistance training intervention demonstrated KVM significantly decreased over the early stance (7.9–21.8%), while KIRM decreased over a majority of the stance phase (8.3–90.5% and 96.2–98.5%). Furthermore, discrete measures during the early stance phase of peak KVM and KIRM decreased in the combined cohort. These findings indicate that increasing single-joint and multijoint strength throughout the kinetic chain may decrease the mechanical demands applied to the knee joint in unplanned sidesteps and potentially facilitate injury resiliency independent of resistance training method in female athletes.

Both resistance training methods decreased variables associated with ACL strain during unplanned sidesteps in female athletes. Increasing single-joint and multijoint lower limb maximum strength has previously been shown to mitigate the mechanical demands applied to the knee joint loading during athletic tasks (13) and reduce ACL injury rates in athletic populations (31,32,49), supporting the notion for a continuous and progressive resistance training exposure in female athletes to better mitigate the mechanical demands during high-impact activities. However, previous studies investigating the effects of an isolated resistance training intervention on knee joint loading during unplanned sidesteps demonstrated contrasting findings. In fact, KVM increased during unplanned sidestepping tasks by 11–50%, indicating a potentially elevated ACL risk after improvements in lower limb strength (12,23). Both studies concluded that increases in lower limb strength capacity might heighten ACL loading during unplanned sidesteps. Potential discrepancies in resistance training methodologies and sidestep protocols across studies may have moderated the results. Another explanation for these conflict results, other than between-study methodological differences, may be attributed to the difference between the athlete's ability to express force in a standardized test (e.g., back squat 1RM, isometric midthigh pull, or isokinetic test) and their ability to express force in a controlled and coordinated pattern during unplanned sidesteps (22). The current cohort of subjects continued with their sports-specific training throughout the intervention, which may have afforded them the opportunity to learn to utilize the increased strength within the skill of unplanned sidestepping, resulting in adequately (re)calibrated motor skills (26). In other words, athletes may need to be exposed to motor skill training that allows them to translate improved maximum strength into calibrated movement strategies (9). More research is warranted about how different resistance interventions in isolation and in combination with other training modalities (e.g., motor skill training) may change the mechanical demands applied to the knee joint during unplanned sidesteps.

Interestingly, peak and continuous JP_{KNEE} remained unchanged for both groups ($p = 0.43–0.86$). The combined negative joint power represents the net rate, amount, and timing of energy dissipation of all muscles and ligaments around a joint (50). The current results indicate that knee joint power remained unchanged during unplanned sidesteps, despite decreased KVM and KIRM. Analysis of peak joint moments in single planes have recently been described as 'likely overly reductionistic' to infer ACL risk as they fail to account for either the rate or the timings of multiplanar joint demands (43). As such, quantifying maximum strength or even the relative contribution of a specific muscle group with modeling approaches during a high-impact activity in addition to isolated joint kinetics (i.e., joint moments or power) may potentially help to individualize training intervention with the goal to increase injury resiliency (27). We speculate that subjects in this study demonstrated lower relative knee joint demands following the resistance training interventions due to the increased lower limb strength capacity and the improved ability to mitigate mechanical demands. In other words, although the absolute mechanical demands applied to the knee joint may have remained unchanged (i.e., JP_{KNEE}), the increased capacity of the tissue and joint to withstand or execute the task resulted in a lower relative demand. Understanding the interplay of single-joint and multijoint strength on the relative mechanical demands of single muscle groups during athletic movements can inform practitioners how to better individualize training and facilitate long-term athlete development.

Knee joint kinetics were not statistically different between $isometric_{RT}$ and $dynamic_{RT}$ training groups during unplanned sidesteps ($p = 0.23–0.98$). Interestingly, the $dynamic_{RT}$ group showed a moderate effect for decreased peak KVM after the intervention ($g = 0.61$; 95% CI = 0.06, 1.14), excluding the null, compared with a small effect in the $isometric_{RT}$ group ($g = 0.45$; 95% CI = −0.24, 1.13). Peak KIRM decreased in both groups, but the change in the effect size magnitude was almost double in the $dynamic_{RT}$ ($g = 1.38$; 95% CI = 0.79, 1.97) compared with the $isometric_{RT}$ ($g = 0.72$; 95% CI = 0.02, 1.42) group. Although not a benefit per se, this may indicate a larger benefit from dynamic resistance training exercises throughout the entire range of motion compared with isometric training at specific joint angles. Indirect support can be found in previous research demonstrating improved athletic performance (e.g., CMJ height) and isokinetic strength after $isometric_{RT}$ at multiple joint angles (6,8,19). The current $isometric_{RT}$ intervention utilized only 1 joint angle at each joint (e.g., ISO_{SQUAT} training was conducted at 130–140° knee joint flexion). This may have limited a transfer to unplanned sidesteps, despite the moderate-to-large increases in maximum strength at sidestep-specific joint angles (see Table 2). Targeting multiple specific joint ranges may have elicited more beneficial changes to mitigate the mechanical demands applied to the knee joint, considering the knee joint flexion ranges between 110 and 160° from the initial contact to weight acceptance. Based on the current data increasing strength throughout the entire range may be more effective in mitigating knee joint loading during more complex motor skills compared with isometric training at joint ranges that are associated with peak joint moments. We speculate that an integrative approach, combining both dynamic and isometric resistance training at specific joint angles, may further facilitate athletic development and injury resiliency. Considering the regions of accentuated force production in various strength exercises and during athletic activities may help practitioners design specific interventions.

We undertook an embedded study within the high-performance training program of elite female athletes, and therefore, limitations were present and should be considered when interpreting the results. First, 6 dropouts (2 in $dynamic_{RT}$ and 4 in $isometric_{RT}$) increased the likelihood of a type 1 error and potentially inflated effect sizes, limiting the detection of between-group differences. Furthermore, the wide CIs demonstrate the uncertainty in evaluating the true average effect of both intervention groups and warrant a cautious interpretation of the current findings. The individual change in peak and continuous knee joint power for both interventions is presented in Supplemental Digital Content 1 (see Figures 2, 3, and 4, http://links.lww.com/JSCR/A532). Second, by combining the groups, there is a potential risk of losing information or masking differences that might be present if the study transitions from a pilot investigation to a fully powered study comparing isometric and dynamic resistance training. Next, training intensity in the isometric training group was not strictly monitored during the intervention period, introducing potential variability in subject effort level. Finally, the individualized set distribution of both training interventions may have contributed to the wide heterogeneity of results.

Practical Applications

A 4-week individualized single-joint and multijoint lower limb resistance training intervention incorporating isometric or dynamic exercises significantly reduced knee joint kinetics associated with ACL injury risk during unplanned sidesteps in elite female athletes. These findings highlight the need for practitioners to recognize maximum strength as a modifiable risk factor, challenging the perspective that female athletes' increased injury risk is solely due to innate and nonmodifiable biological factors. As such, increasing lower body maximum strength may enable athletes to succeed despite being in potentially biomechanically compromised positions associated with ACL injury risk during high-impact activities. While no between-group changes in knee joint kinetics were found, we hypothesize that dynamic resistance training offers advantages in reducing ACL injury-associated mechanical joint demands in the long run. However, isometric resistance training may induce less fatigue than $dynamic_{RT}$, enabling its integration into training phases, focusing on skill development while maintaining the protective benefits of resistance training. This study highlights the benefits of increasing maximum strength with isometric and dynamic resistance training to reduce ACL injury risk factors among elite female athletes.

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References

1. Agel J, Arendt EA, Bershadsky B. Anterior cruciate ligament injury in National Collegiate Athletic Association basketball and soccer: A 13-year review. *Am J Sports Med* 33: 524–530, 2005.
2. Agel J, Rockwood T, Klossner D. Collegiate ACL injury rates across 15 sports: National Collegiate Athletic Association injury surveillance system data update (2004-2005 through 2012-2013). *Clin J Sport Med* 26: 518–523, 2016.
3. Augustsson SR, Ageberg E. Weaker lower extremity muscle strength predicts traumatic knee injury in youth female but not male athletes. *BMJ Open Sport Exerc Med* 3: e000222, 2017.
4. Besier TF, Lloyd DG, Cochrane JL, Ackland TR. External loading of the knee joint during running and cutting maneuvers. *Med Sci Sports Exerc* 33: 1168–1175, 2001.
5. Besier TF, Sturnieks DL, Alderson JA, Lloyd DG. Repeatability of gait data using a functional hip joint centre and a mean helical knee axis. *J Biomech* 36: 1159–1168, 2003.
6. Bimson L, Langdown LP, Fisher J, Steele J. Six weeks of knee extensor isometric training improves soccer related skills in female soccer players. *J Trainology* 6: 52–56, 2017.
7. Bisesti BA, Lawrence MA, Koch AJ, Carlson LA. Comparison of knee moments and landing patterns during a lateral cutting maneuver: Shod vs. barefoot. *J Strength Cond Res* 29: 3075–3078, 2015.
8. Bogdanis GC, Tsoukos A, Methenitis SK, Selima E, Veligekas P, Terzis G. Effects of low volume isometric leg press complex training at two knee angles on force-angle relationship and rate of force development. *Eur J Sport Sci* 19: 345–353, 2019.
9. Brand MT, de Oliveira RF. Recalibration in functional perceptual-motor tasks: A systematic review. *Hum Mov Sci* 56: 54–70, 2017.
10. Brown SR, Hume PA, Lorimer AV, Brughelli M, Besier TF. An individualised approach to assess the sidestep manoeuvre in male rugby union athletes. *J Sci Med Sport* 23: 1086–1092, 2020.
11. Bruton MR, O'Dwyer N, Adams R. Sex differences in the kinematics and neuromuscular control of landing: Biological, environmental and sociocultural factors. *J Electromyogr Kinesiol* 23: 747–758, 2013.
12. Cochrane JL, Lloyd DG, Besier TF, Elliot B, Doyle T, Ackland TR. Training affects knee kinematics and kinetics in cutting maneuvers in sport. *Med Sci Sports Exerc* 42: 1535–1544, 2010.
13. Czasche MB, Goodwin JE, Bull AMJ, Cleather DJ. Effects of an 8-week strength training intervention on tibiofemoral joint loading during landing: A cohort study. *BMJ Open Sport Exerc Med* 4: e000273, 2018.
14. Dai B, Herman D, Liu H, Garrett WE, Yu B. Prevention of ACL injury, part I: Injury characteristics, risk factors, and loading mechanism. *Res Sports Med* 20: 180–197, 2012.
15. Davies WT, Ryu JH, Graham-Smith P, Goodwin JE, Cleather DJ. Stronger subjects select a movement pattern that may reduce anterior cruciate ligament loading during cutting. *J Strength Cond Res* 36: 1853–1859, 2022.
16. Dello Iacono A, Padulo J, Bešlija T, Halperin I. Barbell hip-thrust exercise: Test-retest reliability and correlation with isokinetic performance. *J Strength Cond Res* 35: 659–667, 2021.
17. Dempsey AR, Lloyd DG, Elliott BC, Steele JR, Munro BJ. Changing sidestep cutting technique reduces knee valgus loading. *Am J Sports Med* 37: 2194–2200, 2009.
18. Fleck SJ, Falkel JE. Value of resistance training for the reduction of sports injuries. *Sports Med* 3: 61–68, 1986.
19. Folland JP, Hawker K, Leach B, Little T, Jones DA. Strength training: Isometric training at a range of joint angles versus dynamic training. *J Sports Sci* 23: 817–824, 2005.
20. Havens KL, Sigward SM. Joint and segmental mechanics differ between cutting maneuvers in skilled athletes. *Gait Posture* 41: 33–38, 2015.
21. Hewett TE, Myer GD, Ford KR, et al. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: A prospective study. *Am J Sports Med* 33: 492–501, 2005.
22. Holsbeeke L, Ketelaar M, Schoemaker MM, Gorter JW. Capacity, capability, and performance: Different constructs or three of a kind? *Arch Phys Med Rehabil* 90: 849–855, 2009.
23. Jamison ST, McNeilan RJ, Young GS, Givens D, Best T, Chaudhari AMW. Randomized controlled trial of the effects of a trunk stabilization program on trunk control and knee loading. *Med Sci Sports Exerc* 44: 1924–1934, 2012.
24. Jones PA, Herrington L, Graham-Smith P. Braking characteristics during cutting and pivoting in female soccer players. *J Electromyogr Kinesiol* 30: 46–54, 2016.
25. Kadlec D, Jordan MJ, Snyder L, Alderson J, Nimphius S. Test re-test reliability of single and multijoint strength properties in female Australian footballers. *Sports Med Open* 7: 5, 2021.
26. Kadlec D, Miller-Dicks M, Nimphius S. Training for "worst-case" scenarios in sidestepping: Unifying strength and conditioning and perception–action approaches. *Sports Med Open* 9: 22, 2023.
27. Kipp K. Joint and pull phase specific relative effort in weightlifting and simulated training effects. *Sports Biomech* 0: 1–13, 2021.
28. Kordi M, Folland JP, Goodall S, et al. Cycling-specific isometric resistance training improves peak power output in elite sprint cyclists. *Scand J Med Sci Sports* 30: 1594–1604, 2020.
29. Kubo K, Ohgo K, Takeishi R, et al. Effects of isometric training at different knee angles on the muscle-tendon complex in vivo. *Scand J Med Sci Sports* 16: 159–167, 2006.
30. Lakens D. Calculating and reporting effect sizes to facilitate cumulative science: A practical primer for t-tests and ANOVAs. *Front Psychol* 4: 863, 2013.
31. Lauersen JB, Andersen TE, Andersen LB. Strength training as superior, dose-dependent and safe prevention of acute and overuse sports injuries: A systematic review, qualitative analysis and meta-analysis. *Br J Sports Med* 52: 1557–1563, 2018.
32. Lauersen JB, Bertelsen DM, Andersen LB. The effectiveness of exercise interventions to prevent sports injuries: A systematic review and meta-analysis of randomised controlled trials. *Br J Sports Med* 48: 871–877, 2014.
33. Lum D, Barbosa TM. Brief review: Effects of isometric strength training on strength and dynamic performance. *Int J Sports Med* 40: 363–375, 2019.
34. Malone S, Hughes B, Doran DA, Collins K, Gabbett TJ. Can the workload-injury relationship be moderated by improved strength, speed and repeated-sprint qualities? *J Sci Med Sport* 22: 29–34, 2019.
35. Maniar N, Schache AG, Cole MH, Opar DA. Lower-limb muscle function during sidestep cutting. *J Biomech* 82: 186–192, 2019.
36. Maniar N, Schache AG, Sritharan P, Opar DA. Non-knee-spanning muscles contribute to tibiofemoral shear as well as valgus and rotational joint reaction moments during unanticipated sidestep cutting. *Sci Rep* 8: 2501, 2018.
37. McBride JM, Triplett-McBride T, Davie A, Newton RU. A comparison of strength and power characteristics between power lifters, Olympic lifters, and sprinters. *J Strength Cond Res* 13: 58–66, 1999.
38. Nimphius S. Exercise and sport science failing by design in understanding female athletes. *Int J Sports Physiol Perform* 14: 1157–1158, 2019.
39. Nimphius S, McBride JM, Rice PE, Goodman-Capps CL, Capps CR. Comparison of quadriceps and hamstring muscle activity during an isometric squat between strength-matched men and women. *J Sports Sci Med* 18: 101–108, 2019.

40. O'Kane JW, Neradilek M, Polissar N, Sabado L, Tencer A, Schiff MA. Risk factors for lower extremity overuse injuries in female youth soccer players. *Orthop J Sports Med* 5: 2325967117733963, 2017.
41. Oranchuk DJ, Storey AG, Nelson AR, Cronin JB. Isometric training and long-term adaptations: Effects of muscle length, intensity, and intent: A systematic review. *Scand J Med Sci Sports* 29: 484–503, 2019.
42. Pataky TC, Robinson MA, Vanrenterghem J. Vector field statistical analysis of kinematic and force trajectories. *J Biomech* 46: 2394–2401, 2013.
43. Robinson MA, Sharir R, Rafeeuddin R, Vanrenterghem J, Donnelly CJ. The non-sagittal knee moment vector identifies 'at risk' individuals that the knee abduction moment alone does not. *Sports Biomech* 22: 80–90, 2023.
44. Roy A. Estimating correlation coefficient between two variables with repeated observations using mixed effects model. *Biom J* 48: 286–301, 2006.
45. Suchomel TJ, Nimphius S, Bellon CR, Stone MH. The importance of muscular strength: Training considerations. *Sports Med* 48: 765–785, 2018.
46. Vanrenterghem J, Venables E, Pataky T, Robinson MA. The effect of running speed on knee mechanical loading in females during side cutting. *J Biomech* 45: 2444–2449, 2012.
47. Walden M, Krosshaug T, Bjorneboe J, Andersen TE, Faul O, Hagglund M. Three distinct mechanisms predominate in non-contact anterior cruciate ligament injuries in male professional football players: A systematic video analysis of 39 cases. *Br J Sports Med* 49: 1452–1460, 2015.
48. Warneke K, Hillebrecht M, Wirth K, Schiemann S, Keiner M. Correlation between isometric maximum strength and one repetition maximum in the calf muscle in extended and bended knee joint. *Int J Appl Sports Sci* 34: 61–71, 2022.
49. Weir G, Alderson JA, Elliott BC, et al. A 2-yr biomechanically informed ACL injury prevention training intervention in female field hockey players. *Transl J Am Coll Sports Med* 4: 206–214, 2019.
50. Winter DA. *Biomechanics and Motor Control of Human Movement* (4th ed.). Hoboken, NJ: Wiley, 2009.