MARCIE HARRIS-HAYES, PT, DPT, MSCI[1,2] • **TRAVIS J. HILLEN,** MD[3] • **PAUL K. COMMEAN,** BEE[4]
MICHAEL D. HARRIS, PhD[1,2,5] • **MICHAEL J. MUELLER,** PT, PhD, FAPTA[1,3]
JOHN C. CLOHISY, MD[2] • **GRETCHEN B. SALSICH,** PT, PhD[6]

Hip Kinematics During Single-Leg Tasks in People With and Without Hip-Related Groin Pain and the Association Among Kinematics, Hip Muscle Strength, and Bony Morphology

OBJECTIVE: To compare 3-D hip kinematics during the single-leg squat and step-down in patients with hip-related groin pain to those in asymptomatic participants, and to assess relationships among hip kinematics, muscle strength, and bony morphology.

DESIGN: Controlled laboratory cross-sectional study.

METHODS: Forty patients with hip-related groin pain and 40 matched, asymptomatic participants between 18 and 40 years of age participated. A handheld dynamometer was used to assess hip abductor and external rotator strength. An 8-camera motion-analysis system was used to quantify 3-D kinematics during the single-leg squat and step-down. Magnetic resonance imaging was used to quantify bony morphology. The independent *t* test and Mann-Whitney *U* test were used to assess between-group differences. Pearson coefficient correlations were used to assess relationships.

RESULTS: Patients with hip-related groin pain had smaller peak hip flexion angles, smaller knee flexion angles, and lesser squat depth compared to asymptomatic participants during the single-leg squat. Among patients with hip-related groin pain, smaller hip flexion angles during the single-leg squat were associated with hip abductor weakness ($r = 0.47$, $P \leq .01$). Among asymptomatic participants, smaller peak hip flexion angles during the single-leg squat were associated with less acetabular coverage ($r = 0.33$, $P = .04$) and shallow squat depth ($r = 0.48$, $P \leq .01$); a smaller hip internal rotation angle during the step-down was associated with larger femoral neck shaft angle ($r = -0.43$, $P < .01$).

CONCLUSION: Compared to asymptomatic participants, patients with hip-related groin pain had smaller hip and knee flexion angles and shallower squat depth during the single-leg squat. Smaller hip flexion angles were associated with hip abductor weakness among those with hip-related groin pain. *J Orthop Sports Phys Ther 2020;50(5):243-251. Epub 6 Jan 2020. doi:10.2519/jospt.2020.9150*

KEY WORDS: *dysplasia, femoroacetabular impingement, movement*

Hip-related groin pain (HRGP) due to conditions such as femoroacetabular impingement syndrome (FAIS), acetabular dysplasia, and labral tears contributes to substantial pain and activity limitations in young and middle-aged adults.[28] The multifactorial nature of these conditions is unclear. Understanding the role that hip kinematics play in HRGP, in the context of muscle strength and bony morphology, may improve clinicians' ability to tailor appropriate treatment. In particular, high-demand, single-leg tasks may provide an opportunity to detect impaired kinematics that may not occur during gait or bilateral squat. Single-leg tasks, such as the single-leg squat and the step-down, require sufficient neuromuscular perfor-

[1]Program in Physical Therapy, Washington University School of Medicine, St Louis, MO. [2]Department of Orthopaedic Surgery, Washington University School of Medicine, St Louis, MO. [3]Department of Radiology, Washington University School of Medicine, St Louis, MO. [4]Electronic Radiology Lab, Mallinckrodt Institute of Radiology, Washington University School of Medicine, St Louis, MO. [5]Department of Mechanical Engineering and Materials Science, Washington University, St Louis, MO. [6]Program in Physical Therapy, Saint Louis University, St Louis, MO. The study was approved by the Human Research Protection Office at Washington University School of Medicine. Dr Harris-Hayes was supported by grants K23 HD067343 and K12 HD055931 from the National Center for Medical Rehabilitation Research, National Institute of Child Health and Human Development, and National Institute of Neurological Disorders and Stroke, and by grant UL1 RR 024992-01 from the National Center for Research Resources, components of the National Institutes of Health (NIH) and the NIH Roadmap for Medical Research. Additional support was provided by the Program in Physical Therapy at Washington University School of Medicine, Clinical and Translational Science Award grant UL1 TR000448, and Alvin J. Siteman Cancer Center (a National Cancer Institute–designated Cancer Center) grant P30 CA091842. The authors certify that they have no affiliations with or financial involvement in any organization or entity with a direct financial interest in the subject matter or materials discussed in the article. Address correspondence to Dr Marcie Harris-Hayes, Program in Physical Therapy, Washington University School of Medicine, 4444 Forest Park Boulevard, Campus Box 8502, St Louis, MO 63108. E-mail: harrisma@wustl.edu

mance to maintain balance and quality of limb movement through a large and challenging range of motion.[5,12] To better understand the relationships among kinematics, bony morphology, muscle strength, and HRGP, investigations assessing the performance of movement tasks of varying difficulty are needed.

Relationships among hip kinematics, hip muscle strength, and bony morphology have not been established. During daily tasks, hip abductor strength and external rotator (ER) strength play an important role, such as maintaining pelvic position during stance and providing stability to the hip.[17,27] Patients with HRGP have hip muscle weakness,[4,5,8] which may contribute to abnormal hip kinematics; however, evidence to support this relationship is limited. Previous studies that have assessed bony morphology and hip kinematics in patients with HRGP have focused primarily on cam and pincer morphology associated with FAIS,[5,12,16] and few have directly assessed the relationship between bony morphology and hip kinematics.[6,18] The relationship between hip kinematics and femoral version—the relative rotation between the femoral neck and femoral shaft—and the femoral neck shaft angle is unclear.

Our primary goal was to compare 3-D hip kinematics during the single-leg squat and step-down tasks between patients with HRGP and asymptomatic participants. We expected that patients with HRGP would have increased hip adduction and internal rotation (IR) motion during both tasks compared to asymptomatic participants. A secondary purpose was to assess the relationships among hip kinematics, hip muscle strength, and bony morphology among those with HRGP and asymptomatic participants. Regardless of participant group, we hypothesized that larger hip adduction angles would be associated with hip abductor weakness, larger femoral neck shaft angles, and smaller lateral center-edge angles (indicating acetabular dysplasia); that smaller peak hip flexion angles would be associated with a larger alpha angle (indicating cam morphology); and that larger hip IR angles would be associated with ER weakness and larger femoral version angles.

METHODS

The study was approved by the Human Research Protection Office at Washington University School of Medicine, and all participants signed an informed-consent statement prior to participation.

Study Design and Participants

This was a cross-sectional cohort study to investigate mechanical factors associated with HRGP. People with and without HRGP, aged 18 to 40 years, in the St Louis, MO region were recruited from the community, health care clinics, and the Washington University research registry. Participants with HRGP had to report groin or deep hip joint pain that had been present greater than 3 months and was rated, on average, greater than 3/10 (10 is the worst imaginable) on a numeric pain scale. Pain had to be reproduced with the flexion, adduction, internal rotation (FADIR) test. Asymptomatic participants reported no history of hip or current lower extremity pain and were matched to those with HRGP one to one by sex, age (5 years), body mass index (5 kg/m^2), and limb side. Exclusion criteria for both groups were (1) history of hip surgery or fracture, (2) body mass index greater than 30 kg/m^2, (3) contraindication to magnetic resonance imaging, (4) neuromuscular deficits that affected coordination or balance, (5) pregnancy, or (6) screening exam that indicated possible lumbar spine radiculopathy.

Testing Procedures

Prior to testing, participants completed self-report questionnaires, including (1) demographics and medical history, (2) the University of California at Los Angeles activity score,[1,29] (3) the Hip disability and Osteoarthritis Outcome Score,[14] and (4) the Modified Harris Hip Score.[3,20]

Hip Muscle Strength Prior to strength assessment, participants completed a 5-minute warm-up using a stationary bike or treadmill. A microFET3 (Hoggan Scientific, Salt Lake City, UT) handheld dynamometer was used to assess hip muscle strength.[8] Break tests[9,15] were performed to determine maximum force (Newtons). After familiarization, 3 trials using maximal effort were collected.

Hip ER strength was assessed in sitting, with the test hip in 90° of flexion, 0° of abduction, and end-range IR. Hip abductor strength was assessed in sidelying, with the test hip in 15° of abduction, 0° of flexion, and 0° of rotation. For each strength variable, we averaged 3 maximal trials and multiplied the value by the associated moment arm to calculate torque. Because our study included men and women, we normalized torque by weight and height.[2] Test-retest reliability of our methods is good for the abductors (intraclass correlation coefficient [ICC]$_{3,3}$ = 0.94; standard error of measurement [SEM], 0.47 Nm/Nm) and ERs (ICC$_{3,3}$ = 0.89; SEM, 0.39 Nm/Nm).[8]

Hip Joint Kinematics The primary kinematic variables were hip joint angles captured at peak hip flexion for each task.[26] Three-dimensional kinematic data were collected using an 8-camera motion-capture system (Vicon Nexus; Oxford Metrics, Yarnton, UK) sampling at 120 Hz. Retroreflective markers were placed on anatomical landmarks representing the pelvis, thigh, and lower leg.[26] Rigid 4-marker clusters for tracking were placed at the thigh and lower leg. Participants performed the single-leg squat and then the step-down. For each task, the participant performed 2 to 3 practice trials, then 3 trials from which data were collected. Participants rated the pain that they experienced during each trial on a numeric pain-rating scale ranging from 0 (no pain) to 10 (worst pain imaginable).

Single-Leg Squat Participants were instructed to place their arms across their chest, flex the opposite knee to position their foot behind their body, then squat as low as possible.[10,26] For a trial to be valid,

participants had to squat and return to standing without losing balance, while keeping their weight-bearing foot flat on the floor. No specific cues for trunk position were provided.

Step-down Step height was selected according to participant height: 15.2 cm for a height of less than 163 cm, 20.3 cm for a height of 163 to 180 cm, and 25.4 cm for a height greater than 180 cm. Participants were instructed to place their arms across their chest and step forward off the step with their opposite limb, "tap" the floor with their heel, then return. For a trial to be valid, the participant had to lightly tap the floor, as visually assessed by the examiner, and return without losing balance.

Kinematic data were processed by a blinded research assistant, using Visual3D software (C-Motion, Inc, Germantown, MD).[26] Marker trajectories were low-pass filtered using a fourth-order Butterworth filter with a 6-Hz cutoff frequency. We used a 6-degrees-of-freedom model, using the Codamotion model (Charnwood Dynamics Ltd, Rothley, UK), to define the pelvis, and a functional hip joint center[23] and femoral epicondyle markers to define the thigh. To assess squat depth, excursion of a virtual marker, the midpoint between the posterior superior iliac spine markers, was obtained and divided by participant height. We averaged the 3-D joint angles, assessed at peak hip flexion, for each participant. A priori, we chose to analyze motion at peak hip flexion, because positions of hip flexion, combined with hip adduction and IR, may contribute to HRGP. We established our test-retest reliability by performing 2 assessments of the single-leg squat, at a minimum of 2 weeks apart, in 10 asymptomatic participants. Reliability was excellent for hip flexion ($ICC_{3,3}$ = 0.90; SEM, 4.1°) and moderate for hip adduction ($ICC_{3,3}$ = 0.88; SEM, 1.4°) and IR ($ICC_{3,3}$ = 0.86; SEM, 1.4°).

Bony Morphology We have previously published our methods using magnetic resonance imaging to determine measures of bony morphology.[7] Briefly, a 1.5-T magnetic resonance system (MAGNETOM Avanto; Siemens AG, Munich, Germany) was used to acquire 3-D, fat-suppressed gradient-echo sequences centered at the pelvis and distal femora, both acquired in the coronal plane. Standardized procedures were used to optimize participant positioning.[7] The following imaging parameters were used: slice thickness, 0.82 mm; repetition time, 15.96 milliseconds; echo time, 6.2 milliseconds; field of view, 400 mm at the pelvis and distal femora; 512 × 512 matrix.

An independent workstation (LEONARDO; Siemens AG) was used for post-processing to create 2-D pelvic images for femoral version angle, femoral neck shaft angle, alpha angle, and lateral center-edge angle. To obtain images for alpha angles at the 12, 1, 2, and 3 o'clock locations on the femoral head-neck junction, a radial reformat was performed along the femoral neck axis at 30° intervals. For each participant, we used the maximum alpha angle value among the 4 clock-face locations in the analysis. A blinded research assistant completed measurements using Analyze 11.0 software (AnalyzeDirect, Inc, Overland Park, KS). Interrater reliability of our methods has been reported previously[7] and found to be excellent for femoral neck shaft angle ($ICC_{2,1}$ = 0.96; SEM, 1.1°) and femoral version angle ($ICC_{2,1}$ = 0.97; SEM, 1.1°), and to be good for lateral center-edge angle ($ICC_{2,1}$ = 0.86; SEM, 2.0°) and alpha angle ($ICC_{2,1}$ = 0.78; SEM, 2.6°).

Statistical Analysis

The study had a target enrollment of 80 participants. Using preliminary data collected in our lab, an a priori power calculation indicated that a sample size of 40 per group would provide statistical power of at least 0.80 to detect differences in our primary variables, including hip adduction and IR angles during the single-leg squat and hip abductor strength, with effect sizes of at least 0.64 at an alpha of .05 using 2-tailed tests. We used the Kolmogorov-Smirnov test to assess distribution of data and Levene's test to assess equality of variance. Between-group comparisons were performed using independent-samples *t* tests and Mann-Whitney *U* tests for continuous and ordinal data, respectively. Pearson coefficient correlations were used to assess the relationships among kinematics, muscle strength, and bony morphology. A *P* value less than .05 was considered significant.

RESULTS

Between-Group Comparisons

Eighty participants were enrolled. There were no group differences in demographic data (**TABLE 1**). Patients with HRGP demonstrated smaller peak hip flexion angles (68.8° ± 14.6° versus 76.4° ± 16.8°, P = .03), smaller knee flexion angles assessed at peak hip flexion (66.9° ± 8.5° versus 71.2° ± 9.6°, P = .04), and shallower squat depth (9.8% ± 2.2% versus 10.9% ± 2.7%, P = .04) compared to asymptomatic participants during the single-leg squat. There were no differences in hip adduction or IR angles during the single-leg squat and no differences in kinematics during the step-down (**TABLE 2**). Patients with HRGP were weaker compared to asymptomatic participants (**TABLE 2**). There were no differences in measures of bony morphology (**TABLE 2**).

Correlations

Among patients with HRGP (**TABLE 3**), weaker hip abductor strength was associated with smaller hip flexion angles during the single-leg squat (r = 0.47, $P \leq .01$). There were no associations between hip kinematics and muscle strength during the step-down task. Bony morphology was not associated with hip kinematics during either task.

Among asymptomatic participants (**TABLE 4**), there were no associations between hip muscle strength and hip kinematics during the single-leg squat or the step-down. Smaller peak hip flexion angles during the single-leg squat were associated with smaller lateral center-edge angles (r = 0.33, P = .04). Larger femoral

neck shaft angles were associated with smaller hip IR angles during the step-down ($r = -0.43$, $P<.01$).

A Posteriori Assessment

Peak hip flexion angles were similar between those with HRGP who reported pain during the single-leg squat (n = 20) and those who did not (69.7° ± 14.3° versus 68.8° ± 14.5°, respectively; $P = .85$).

DISCUSSION

Patients with HRGP had smaller peak hip flexion angles, smaller knee flexion angles, and shallower squat depth during the single-leg squat compared to asymptomatic participants. We found no differences in step-down kinematics. Despite weakness in hip abductors and ERs, and reporting long pain duration, patients with HRGP had similar hip adduction and rotation angles during both tasks compared to asymptomatic participants. Among those with HRGP, smaller peak hip flexion angles during the single-leg squat were associated with hip abductor weakness.

We are unsure why patients with HRGP had smaller peak hip flexion angles, smaller knee flexion angles, and lesser squat depth compared to asymptomatic participants. Pain during testing did not appear to influence hip flexion angles during the single-leg squat. Hip flexion angles were similar between those with HRGP who reported pain and those who did not. The differences may be associated with other factors, such as hip muscle weakness, adjacent joint kinematics, or other unmeasured variables.

Among patients with HRGP, smaller hip flexion angles were associated with reduced hip abductor strength (**TABLE 3**). Due to the cross-sectional nature of our study, we cannot establish the temporal relationship between hip abductor strength and hip flexion angles. We did not collect muscle activation or kinetic data. Therefore, we cannot draw conclusions regarding muscle activity or joint loading patterns. Hip muscle weakness has been noted among patients with HRGP,[4,5,8] and represents a modifiable target for rehabilitation. We did not assess ankle or trunk kinematics, which may influence hip kinematics. Given the modest relationships noted, other factors, such as fear, anticipation of pain provocation,[25] or poor neuromuscular control, may explain the differences.

Unlike the single-leg squat, peak hip flexion angles during the step-down were similar between groups. The step-down requires hip flexion angles smaller than those required by the single-leg squat (**TABLE 2**). Group differences in peak hip flexion angles might have been observed if participants had been required to go through a greater range of motion. Our findings are in contrast to previous work[16]; however, methodological differences between our study and previous research might explain the conflicting results. We matched patients with HRGP and asymptomatic participants, resulting in 40 in each group. The previous study[16] compared 20 patients with FAIS to 40 asymptomatic participants. Hip flexion values in patients with FAIS in the previous study[16] might have approached those of asymptomatic participants if more patients had been enrolled. Patients with HRGP in our study had varied bony morphology; however, exploration of a subset comparing patients with FAIS to participants without impingement morphology (n = 8 pairs) showed a similar trend to our reported findings for hip flexion. Our testing methods likely resulted in a more challenging task by using a higher step height, analyzing kinematics at larger hip and knee flexion angles, and potentially shifting the participant's center of mass superoanteriorly by placing the arms across the chest instead of at the side.

TABLE 1 Demographic Characteristics for Both Groups and Descriptive Data Reporting Pain and Patient-Reported Outcome Measures in Participants With Hip-Related Groin Pain[a]

	HRGP (n = 40)	Control (n = 40)	*P* Value
Sex, n			...
Female	33	33	
Male	7	7	
Age, y	28.2 ± 4.9	27.6 ± 5.5	.62[b]
Body mass index, kg/m^2	24.1 ± 3.0	24.0 ± 2.5	.88[b]
UCLA activity score[cd]	9 (3-10)	10 (4-10)	.15[e]
Pain duration, y[d]	2 (0.4-13)	...	...
HOOS[f]			
Pain subscale	75.4 ± 14.7	...	...
Symptoms subscale	71.9 ± 17.1	...	...
ADL subscale	89.9 ± 11.2	...	...
Sport/rec subscale	72.5 ± 21.4	...	...
QoL subscale	58.7 ± 21.7	...	...

Abbreviations: ADL, function in activities of daily living; HOOS, Hip disability and Osteoarthritis Outcome Score; HRGP, hip-related groin pain; QoL, quality of life; sport/rec, function in sports and recreation; UCLA, University of California at Los Angeles.
[a]*Values are mean ± SD unless otherwise indicated.*
[b]*Independent-samples t tests were used.*
[c]*Participants were asked to rate their activity level over the previous 6 months (1, wholly inactive, dependent on others; 10, regularly participates in impact sports such as jogging, tennis, skiing, acrobatics, ballet, heavy labor, or backpacking).*
[d]*Values are median (range).*
[e]*The Mann-Whitney U test was performed. One control participant did not complete the UCLA activity score.*
[f]*Patient-reported outcome measure (100, no disability).*

Each of these methodological differences could have influenced hip kinematics.

There were no group differences in hip adduction or rotation angles during either task. Previous work also found no differences in hip adduction between asymptomatic participants and those with FAIS.[16] There were large standard deviations relative to group means, suggesting that people in both groups had a wide range of movement patterns. It is possible that abnormal kinematics, such as excessive hip adduction, exists in a subgroup of people,[22,26] despite presence or absence of pain, and may precede injury. However, to our knowledge, the relationship between hip kinematics and pain onset has not been studied prospectively.

Among asymptomatic participants, hip kinematics were associated with bony morphology, but not hip muscle strength (**TABLE 4**). Less acetabular coverage was associated with smaller peak hip flexion angles during the single-leg squat, and larger femoral neck shaft angles were associated with smaller hip IR angles at peak hip flexion during the step-down. In contrast, Souza and Powers[24] reported no association between femoral neck shaft angle and hip IR angles during running in asymptomatic women. Differences may be due to the tasks assessed. We did not find a correlation between hip kinematics and cam morphology or femoral version during either task. We were surprised to observe relationships between bony morphology and kinematics among asymptomatic participants but not among patients with HRGP. Our sample was relatively small, and bony morphology values may not represent the variability of a larger population. In future, larger studies may provide insight to the relationship between bony morphology and hip kinematics.

Limitations

Our patient sample represents a heterogeneous population. While all patients reported long duration of deep hip joint and/or anterior groin pain, the source of their symptoms may vary. To be enrolled, the patient's history had to be consistent with HRGP, and the groin pain had to be reproduced with the FADIR test. Given that the FADIR test is sensitive but not specific,[21] we collected history information and performed screening tests to rule out pain referred from other sources. It is possible that groin pain may be due to other anatomical entities, such as iliopsoas-related groin pain.[28] Fourteen participants (10 with HRGP and 4 who were asymptomatic) had cam morphology (alpha angle greater than 60°) or pincer morphology (lateral center-edge angle greater than 40°), and 3 (1 with HRGP and 2 who were asymptomatic) had acetabular dysplasia (lateral center-edge angle less than 20°). We did not perform additional diagnostic imaging to determine whether a labral tear or chondral lesion was present. Our ultimate goal, to be pursued in a larger, prospective study, is to better understand the interaction of the multiple factors associated with

TABLE 2 Between-Group Differences in Hip Kinematics, Muscle Strength, and Bony Morphology

	HRGP[a]	Control[a]	*P* Value[b]
Kinematics[c]			
Single-leg squat			
Hip flexion angle, deg	68.8 ± 14.6	76.4 ± 16.8	.03
Hip adduction angle, deg	18.6 ± 6.7	18.6 ± 6.9	.98
Hip IR angle, deg	3.8 ± 7.5	1.7 ± 8.6	.25
Knee flexion angle, deg	66.9 ± 8.5	71.2 ± 9.6	.04
Knee adduction angle, deg	3.3 ± 4.8	1.9 ± 6.9	.28
Knee IR angle, deg	2.4 ± 6.8	1.5 ± 7.4	.60
Squat depth, % height	9.8 ± 2.2	10.9 ± 2.7	.04
Time to complete motion, s	3.1 ± 1.0	2.9 ± 0.9	.42
Step-down			
Hip flexion angle, deg	57.1 ± 12.5	59.7 ± 9.8	.30
Hip adduction angle, deg	23.4 ± 5.9	23.3 ± 6.2	.94
Hip IR angle, deg	6.5 ± 6.7	5.4 ± 8.1	.52
Knee flexion angle, deg	69.7 ± 8.1	73.0 ± 6.4	.05
Knee adduction angle, deg	5.0 ± 5.0	4.0 ± 6.6	.44
Knee IR angle, deg	2.9 ± 6.6	2.3 ± 7.7	.72
Time to complete motion, s	4.0 ± 1.0	3.8 ± 1.1	.29
Muscle strength[d]			
Hip external rotators	3.5 ± 0.8	4.2 ± 1.1	<.01
Hip abductors	6.9 ± 2.0	8.9 ± 1.7	<.01
Bony morphology, deg[e]			
FNSA	135.4 ± 4.5	133.7 ± 4.7	.13
Femoral version[f]	9.1 ± 9.3	10.5 ± 7.5	.45
Maximum alpha angle	53.7 ± 7.7	51.7 ± 8.6	.32
LCEA	30.3 ± 6.4	30.8 ± 6.0	.76

Abbreviations: FNSA, femoral neck-shaft angle; HRGP, hip-related groin pain; IR, internal rotation; LCEA, lateral center-edge angle.
[a]*Values are mean ± SD; n = 40 for both groups.*
[b]*Independent-samples t tests were used.*
[c]*Extracted at the peak hip flexion angle.*
[d]*Muscle torque was normalized by body weight × height × 100.*
[e]*n = 38 for both groups. Due to technical issues, magnetic resonance imaging data were not available for 3 participants; therefore, we included only those matched pairs for which we had imaging data for both participants.*
[f]*Larger values indicate femoral anteversion.*

TABLE 3 Associations Among Hip Kinematics, Hip Muscle Strength, and Bony Morphology Variables Among Patients With Hip-Related Groin Pain

	Hip FA	Hip AA	Hip IRA	Knee FA	Knee AA	Knee IRA	Hip ERS	Hip AS	FNSA	FV	MA	LCEA	Squat Depth
Single-leg squat task													
Hip FA[a]	1	0.05	−0.24	0.28	0.13	0.14	0.23	0.47	−0.14	0.02	0.07	−0.20	0.30
P value		.76	.13	.08	.42	.39	.16	<.01	.41	.91	.69	.24	.07
Hip AA[a]		1	0.21	−0.13	−0.12	0.36	−0.07	−0.10	0.01	−0.07	−0.17	0.08	0.03
P value			.20	.42	.45	.02	.68	.54	.95	.66	.30	.62	.88
Hip IRA[a]			1	−0.14	0.41	−0.11	−0.11	−0.23	0.04	0.17	−0.06	0.11	−0.07
P value				.41	<.01	.49	.51	.16	.81	.32	.72	.51	.67
Knee FA[a]				1	0.21	0.36	0.21	0.12	−0.13	0.28	0.07	−0.46	0.89
P value					.20	.02	.20	.47	.45	.08	.66	<.01	<.01
Knee AA[a]					1	0.43	0.28	0.26	−0.09	−0.09	0.34	−0.10	0.39
P value						<.01	.05	.10	.58	.59	.04	.54	.01
Knee IRA[a]						1	0.02	0.14	−0.13	−0.12	0.29	−0.07	0.44
P value							.93	.39	.43	.48	.08	.67	<.01
Strength													
Hip ERS[b]							1	0.50	0.10	0.07	0.09	−0.29	0.29
P value								<.01	.56	.69	.59	.08	.06
Hip AS[b]								1	0.13	−0.20	0.10	−0.09	0.14
P value									.42	.23	.54	.61	.38
Morphology													
FNSA									1	−0.13	−0.07	−0.32	−0.16
P value										.43	.67	.05	.35
FV[c]										1	−0.26	−0.01	0.12
P value											.12	.94	.47
MA											1	−0.21	0.04
P value												.21	.82
LCEA												1	−0.52
P value													<.01
Single-leg squat depth													1
Step-down task													
Hip FA[a]	1	0.24	−0.17	0.47	−0.13	0.02	−0.10	0.21	0.14	0.06	0.00	−0.03	
P value		.13	.31	<.01	.45	.89	.53	.20	.41	.74	.98	.85	
Hip AA[a]		1	0.07	0.06	−0.14	−0.23	0.00	0.14	0.22	0.12	−0.29	−0.12	
P value			.68	.71	.40	.17	.98	.40	.19	.47	.08	.48	
Hip IRA[a]			1	−0.22	0.73	0.03	0.41	−0.01	−0.24	0.24	−0.11	0.14	
P value				.19	<.01	.85	.39	.97	.15	.16	.95	.40	
Knee FA[a]				1	0.07	0.32	0.31	0.36	0.20	0.15	0.19	−0.50	
P value					.67	.05	.05	.02	.23	.38	.27	<.01	
Knee AA[a]					1	0.37	0.30	0.19	−0.09	0.12	0.19	0.03	
P value						.02	.06	.24	.61	.47	.26	.85	
Knee IRA[a]						1	0.08	0.31	−0.03	−0.21	0.40	−0.09	
P value							.63	.05	.86	.21	.01	.58	

Abbreviations: AA, adduction angle; AS, abductor strength; ERS, external rotator strength; FA, flexion angle; FNSA, femoral neck-shaft angle; FV, femoral version; IRA, internal rotation angle; LCEA, lateral center-edge angle; MA, maximum alpha angle.

[a]*Extracted at the peak hip flexion angle.*

[b]*Muscle torque was normalized by body weight × height × 100.*

[c]*Larger values indicate femoral anteversion.*

TABLE 4 Associations Among Hip Kinematics, Hip Muscle Strength, and Bony Morphology Variables Among Asymptomatic Participants

	Hip FA	Hip AA	Hip IRA	Knee FA	Knee AA	Knee IRA	Hip ERS	Hip AS	FNSA	FV	MA	LCEA	Squat Depth
Single-leg squat task													
Hip FA[a]	1	0.25	−0.39	0.41	0.21	0.04	−0.04	0.03	−0.03	−0.03	−0.07	0.33	0.48
P value		.13	.01	.01	.19	.82	.80	.84	.85	.87	.65	.04	<.01
Hip AA[a]		1	−0.25	−0.10	−0.05	−0.37	−0.02	0.09	0.20	0.09	0.15	0.05	0.05
P value			.12	.54	.74	.02	.91	.57	.22	.61	.35	.75	.75
Hip IRA[a]			1	0.07	0.58	0.19	0.20	−0.11	−0.31	0.15	0.15	−0.05	0.04
P value				.65	<.01	.25	.21	.52	.06	.36	.35	.78	.81
Knee FA[a]				1	0.39	0.17	0.35	0.05	−0.15	0.17	0.07	−0.11	0.91
P value					.01	.29	.03	.75	.36	.31	.69	.51	<.01
Knee AA[a]					1	0.25	0.21	0.05	−0.52	−0.01	−0.01	0.18	0.44
P value						.12	.19	.76	.01	.97	.96	.28	<.01
Knee IRA[a]						1	0.04	0.04	−0.15	−0.02	−0.24	−0.20	0.09
P value							.82	.81	.37	.89	.14	.21	.60
Strength													
Hip ERS[b]							1	0.53	−0.01	−0.04	0.35	−0.39	0.31
P value								<.01	.94	.82	.03	.01	.05
Hip AS[b]								1	0.01	0.04	0.29	−0.29	0.05
P value									.95	.81	.07	.07	.76
Morphology													
FNSA									1	−0.02	−0.14	−0.11	−0.16
P value										.91	.40	.51	.33
FV[c]										1	0.20	−0.04	0.13
P value											.22	.79	.44
MA											1	−0.19	0.11
P value												.24	.53
LCEA												1	−0.01
P value													.93
Single-leg squat depth													1
Step-down task													
Hip FA[a]	1	0.54	−0.56	0.09	−0.30	−0.06	−0.23	0.05	0.23	−0.03	−0.10	0.21	
P value		<.01	<.01	.58	.06	.73	.15	.76	.15	.85	.55	.19	
Hip AA[a]		1	−0.45	−0.22	−0.49	−0.32	−0.21	−0.04	0.23	0.12	0.00	−0.04	
P value			<.01	.17	<.01	.05	.19	.81	.16	.48	.99	.82	
Hip IRA[a]			1	−0.08	0.74	0.14	0.18	−0.17	−0.43	0.08	−0.06	0.08	
P value				.61	<.01	.39	.26	.30	<.01	.63	.70	.61	
Knee FA[a]				1	0.15	0.17	0.19	−0.01	−0.02	0.18	−0.05	−0.10	
P value					.35	.29	.24	.94	.91	.27	.79	.54	
Knee AA[a]					1	0.22	0.30	0.06	−0.54	−0.12	−0.04	0.21	
P value						.18	.06	.70	<.01	.48	.79	.19	
Knee IRA[a]						1	−0.02	0.02	−0.26	−0.07	−0.07	−0.12	
P value							.90	.92	.12	.68	.66	.48	

Abbreviations: AA, adduction angle; AS, abductor strength; ERS, external rotator strength; FA, flexion angle; FNSA, femoral neck-shaft angle; FV, femoral version; IRA, internal rotation angle; LCEA, lateral center-edge angle; MA, maximum alpha angle.

[a]*Extracted at the peak hip flexion angle.*

[b]*Muscle torque was normalized by body weight × height × 100.*

[c]*Larger values indicate femoral anteversion.*

HRGP. We therefore designed our study to be inclusive of hip joint conditions.

Our small sample of 40 patients with HRGP limits our ability to adequately assess multifactorial relationships among patient characteristics (sex, body mass index, age, etc), hip kinematics, muscle strength, bony morphology, and patient-reported activity limitations (Hip disability and Osteoarthritis Outcome Score, Modified Harris Hip Score). Our study provides preliminary data to assist in designing a larger study to better assess these relationships. Strength assessment was limited to the hip abductors and ERs. Other lower extremity muscles may play a role in hip kinematics.[11,13,19] We do not know whether our kinematic reliability measures are generalizable to the symptomatic group, because we completed reliability testing among asymptomatic participants only. Research investigating movement variability across a number of trials for specific tasks, instead of averaging all trials, may provide further insight to group differences in movement.

CONCLUSION

Compared to asymptomatic participants, patients with HRGP had smaller peak hip flexion angles, smaller knee flexion angles, and shallower squat depth during the single-leg squat. Smaller hip flexion angles during the single-leg squat were associated with hip abductor weakness among those with HRGP. ◉

KEY POINTS

FINDINGS: Patients with hip-related groin pain (HRGP) had smaller peak hip flexion angles, smaller knee flexion angles, and shallower squat depth during the single-leg squat compared to those without symptoms. Smaller hip flexion angles were associated with hip abductor weakness among those with HRGP.

IMPLICATIONS: Abnormal lower extremity movement patterns and muscle weakness may be appropriate targets for rehabilitation among patients with HRGP.

CAUTION: The patients with HRGP who were included in this study represent a heterogeneous sample, including different hip pain conditions such as femoroacetabular impingement syndrome and acetabular dysplasia.

STUDY DETAILS

AUTHOR CONTRIBUTIONS: All authors contributed to the study design, data analysis, interpretation, and manuscript preparation, including final approval. Dr Harris-Hayes takes responsibility for the integrity of the work as a whole, from inception to the finished article. She also provided study materials and patients, obtained funding, and collected and assembled data. Dr Hillen and Paul K. Commean also collected and assembled data. Dr Mueller also obtained funding. Dr Clohisy also provided study materials and patients.

DATA SHARING: Data may be available on reasonable request.

PATIENT AND PUBLIC INVOLVEMENT: Patients were not involved in the design, recruitment, or conduct of the study.

REFERENCES

1. Amstutz HC, Thomas BJ, Jinnah R, Kim W, Grogan T, Yale C. Treatment of primary osteoarthritis of the hip. A comparison of total joint and surface replacement arthroplasty. *J Bone Joint Surg Am*. 1984;66:228-241.
2. Bazett-Jones DM, Cobb SC, Joshi MN, Cashin SE, Earl JE. Normalizing hip muscle strength: establishing body-size-independent measurements. *Arch Phys Med Rehabil*. 2011;92:76-82. https://doi.org/10.1016/j.apmr.2010.08.020
3. Byrd JW, Jones KS. Prospective analysis of hip arthroscopy with 2-year follow-up. *Arthroscopy*. 2000;16:578-587. https://doi.org/10.1053/jars.2000.7683
4. Casartelli NC, Maffiuletti NA, Item-Glatthorn JF, et al. Hip muscle weakness in patients with symptomatic femoroacetabular impingement. *Osteoarthritis Cartilage*. 2011;19:816-821. https://doi.org/10.1016/j.joca.2011.04.001
5. Diamond LE, Dobson FL, Bennell KL, Wrigley TV, Hodges PW, Hinman RS. Physical impairments and activity limitations in people with femoroacetabular impingement: a systematic review. *Br J Sports Med*. 2015;49:230-242. https://doi.org/10.1136/bjsports-2013-093340
6. Farkas GJ, Cvetanovich GL, Rajan KB, Espinoza Orías AA, Nho SJ. Impact of femoroacetabular impingement morphology on gait assessment in symptomatic patients. *Sports Health*. 2015;7:429-436. https://doi.org/10.1177/1941738115592827
7. Harris-Hayes M, Commean PK, Patterson JD, Clohisy JC, Hillen TJ. Bony abnormalities of the hip joint: a new comprehensive, reliable and radiation-free measurement method using magnetic resonance imaging. *J Hip Preserv Surg*. 2014;1:62-70. https://doi.org/10.1093/jhps/hnu009
8. Harris-Hayes M, Mueller MJ, Sahrmann SA, et al. Persons with chronic hip joint pain exhibit reduced hip muscle strength. *J Orthop Sports Phys Ther*. 2014;44:890-898. https://doi.org/10.2519/jospt.2014.5268
9. Kendall FP, McCreary EK, Provance PG, Rodgers MM, Romani WA. *Muscles: Testing and Function With Posture and Pain*. 5th ed. Baltimore, MD: Lippincott Williams & Wilkins; 2005.
10. Khuu A, Foch E, Lewis CL. Not all single leg squats are equal: a biomechanical comparison of three variations. *Int J Sports Phys Ther*. 2016;11:201-211.
11. Kierkegaard S, Mechlenburg I, Lund B, Søballe K, Dalgas U. Impaired hip muscle strength in patients with femoroacetabular impingement syndrome. *J Sci Med Sport*. 2017;20:1062-1067. https://doi.org/10.1016/j.jsams.2017.05.008
12. King MG, Lawrenson PR, Semciw AI, Middleton KJ, Crossley KM. Lower limb biomechanics in femoroacetabular impingement syndrome: a systematic review and meta-analysis. *Br J Sports Med*. 2018;52:566-580. https://doi.org/10.1136/bjsports-2017-097839
13. Kivlan BR, Carcia CR, Christoforetti JJ, Martin RL. Comparison of range of motion, strength, and hop test performance of dancers with and without a clinical diagnosis of femoroacetabular impingement. *Int J Sports Phys Ther*. 2016;11:527-535.
14. Klässbo M, Larsson E, Mannevik E. Hip disability and osteoarthritis outcome score. An extension of the Western Ontario and McMaster Universities Osteoarthritis Index. *Scand J Rheumatol*. 2003;32:46-51. https://doi.org/10.1080/03009740310000409
15. Krause DA, Schlagel SJ, Stember BM, Zoetewey JE, Hollman JH. Influence of lever arm and stabilization on measures of hip abduction and adduction torque obtained by hand-held dynamometry. *Arch Phys Med Rehabil*. 2007;88:37-42. https://doi.org/10.1016/j.apmr.2006.09.011
16. Lewis CL, Loverro KL, Khuu A. Kinematic differences during single-leg step-down between individuals with femoroacetabular impingement syndrome and individuals without hip pain. *J Orthop Sports Phys Ther*. 2018;48:270-279. https://doi.org/10.2519/jospt.2018.7794
17. Neumann DA. Kinesiology of the hip: a focus on muscular actions. *J Orthop Sports Phys Ther*. 2010;40:82-94. https://doi.org/10.2519/jospt.2010.3025
18. Ng KCG, Lamontagne M, Jeffers JRT,

Grammatopoulos G, Beaulé PE. Anatomic predictors of sagittal hip and pelvic motions in patients with a cam deformity. *Am J Sports Med*. 2018;46:1331-1342. https://doi.org/10.1177/0363546518755150
19. Park SK, Kobsar D, Ferber R. Relationship between lower limb muscle strength, self-reported pain and function, and frontal plane gait kinematics in knee osteoarthritis. *Clin Biomech (Bristol, Avon)*. 2016;38:68-74. https://doi.org/10.1016/j.clinbiomech.2016.08.009
20. Potter BK, Freedman BA, Andersen RC, Bojescul JA, Kuklo TR, Murphy KP. Correlation of Short Form-36 and disability status with outcomes of arthroscopic acetabular labral debridement. *Am J Sports Med*. 2005;33:864-870. https://doi.org/10.1177/0363546504270567
21. Reiman MP, Goode AP, Cook CE, Hölmich P, Thorborg K. Diagnostic accuracy of clinical tests for the diagnosis of hip femoroacetabular impingement/labral tear: a systematic review with meta-analysis. *Br J Sports Med*. 2015;49:811. https://doi.org/10.1136/bjsports-2014-094302
22. Schmidt E, Harris-Hayes M, Salsich GB. Dynamic knee valgus kinematics and their relationship to pain in women with patellofemoral pain compared to women with chronic hip joint pain. *J Sport Health Sci*. 2019;8:486-493. https://doi.org/10.1016/j.jshs.2017.08.001
23. Schwartz MH, Rozumalski A. A new method for estimating joint parameters from motion data. *J Biomech*. 2005;38:107-116. https://doi.org/10.1016/j.jbiomech.2004.03.009
24. Souza RB, Powers CM. Predictors of hip internal rotation during running: an evaluation of hip strength and femoral structure in women with and without patellofemoral pain. *Am J Sports Med*. 2009;37:579-587. https://doi.org/10.1177/0363546508326711
25. Tucker K, Larsson AK, Oknelid S, Hodges P. Similar alteration of motor unit recruitment strategies during the anticipation and experience of pain. *Pain*. 2012;153:636-643. https://doi.org/10.1016/j.pain.2011.11.024
26. Vasiljevic D, Salsich GB, Snozek D, et al. Three dimensional kinematics of visually classified lower extremity movement patterns during a single leg squat among people with chronic hip joint pain. *Physiother Theory Pract*. 2018:1-9. https://doi.org/10.1080/09593985.2018.1491081
27. Ward SR, Winters TM, Blemker SS. The architectural design of the gluteal muscle group: implications for movement and rehabilitation. *J Orthop Sports Phys Ther*. 2010;40:95-102. https://doi.org/10.2519/jospt.2010.3302
28. Weir A, Brukner P, Delahunt E, et al. Doha agreement meeting on terminology and definitions in groin pain in athletes. *Br J Sports Med*. 2015;49:768-774. https://doi.org/10.1136/bjsports-2015-094869
29. Zahiri CA, Schmalzried TP, Szuszczewicz ES, Amstutz HC. Assessing activity in joint replacement patients. *J Arthroplasty*. 1998;13:890-895. https://doi.org/10.1016/s0883-5403(98)90195-4

EARN CEUs With *JOSPT*'s Read for Credit Program

JOSPT's **Read for Credit (RFC)** program invites readers to study and analyze selected *JOSPT* articles and successfully complete online exams about them for continuing education credit. To participate in the program:

1. Go to **www.jospt.org** and click on **Read for Credit** in the top blue navigation bar that runs throughout the site.
2. Log in to read and study an article and to pay for the exam by credit card.
3. When ready, click **Take Exam** to answer the exam questions for that article.
4. Evaluate the RFC experience and receive a personalized certificate of continuing education credits.

The RFC program offers you 2 opportunities to pass the exam. You may review all of your answers—including your answers to the questions you missed. You receive **0.2 CEUs**, or 2 contact hours, for each exam passed.

JOSPT's website maintains a history of the exams you have taken and the credits and certificates you have been awarded in **My CEUs** and **Your Exam Activity**, located in the right rail of the Read for Credit page listing available exams.

[EDITORIAL]

Patients as Partners in Research: There Is Plenty of Help for Researchers

ALISON M. HOENS, *MSc, BScPT*
Department of Physical Therapy, University of British Columbia, Vancouver, Canada
Centre for Health Evaluation and Outcomes Sciences, University of British Columbia, Vancouver, Canada
Arthritis Research Canada, Milan Ilich Arthritis Research Centre, Richmond, Canada

JOLETTA BELTON, *MSc*
Special Features Editor
Endless Possibilities Initiative, Fraser, CO
Retrain Pain Foundation, Mamaroneck, NY

ALEX SCOTT, *PT, PhD*
Special Features Editor
Department of Physical Therapy, University of British Columbia, Vancouver, Canada

CLARE L. ARDERN, *PT, PhD*
Editor-in-Chief
Division of Physiotherapy, Karolinska Institute, Stockholm, Sweden

J Orthop Sports Phys Ther 2020;50(5):219-221. doi:10.2519/jospt.2020.0104

Thank you to all who read and responded to our call to action in our first editorial in this series about engaging patients as research team partners.[3] We are delighted with the positive response! The first editorial in the series focused on *why* researchers should engage patient partners on research teams. In this, the second editorial in the series, we concentrate on *how* to engage patient partners.

Researchers who have had limited opportunity or have not yet had the opportunity to work with patient partners on a research team may worry about how to "do it right." Common concerns include

1. When and how to invite patient partners into a study
2. How patient partners can contribute to research
3. If, when, and how to offer payment for patient partners' contributions
4. How to document patient partners' role in manuscripts

The following sections highlight a sample of resources researchers can use to address their concerns and authentically engage patients as partners in research.

Deciding Whether Researchers and Patients Are Ready for Partnership

How do you know if you are "ready" for patient partnership in research? Clinical Trials Ontario has developed 2 decision aids, one for researchers[7] and another for patients.[8] These interactive online tools lead users through a step-by-step decision tree to help all parties decide when it is right to partner on research.

How to Engage Patient Partners

The Action Catalogue (http://actioncatalogue.eu/) helps researchers identify and select their preferred method for engaging partners who are not already part of a research team. Researchers choose from a list of 32 criteria (eg, intent, level of engagement, skills, number of participants, budget, duration, roles, etc) and 57 evidence-based methods that support inclusive engagement.

The interactive map tool, developed by the George & Fay Yee Centre for Healthcare Innovation,[10] provides ideas for how to engage patients (and other stakeholders) in different phases of the research cycle.

How Patient Partners Can Contribute: Defining Roles

Researchers need to collaborate with patient partners to define how each will contribute to a research project. Defining the patient partner's role should balance the needs of the project with the knowledge, experience, and skills of the patient partner. Every partnership is different, so patient partner roles cannot be predetermined by researchers if meaningful engagement is to occur.

For example, the first step in the research cycle is to establish the research question. The patient perspective regarding the research question can enhance the relevance and meaningfulness of research. Patient partners can (1) help identify the research question to be studied or (2) verify or help refine a question prespecified by the researchers.

One resource to guide the discussion regarding potential roles within each phase of the research cycle has been proposed by Izabela Szelest and has been included in a publication by the Can-SOLVE CKD Network.[5] Another informative resource that illustrates the complementary roles of patient partners and researchers throughout the research cycle is outlined by Moss et al[12] (**FIGURE**).

The guiding principle when defining the patient partner's role is "meaningful engagement." Components of the "Workbook to Guide the Development of a Patient Engagement In Research (PEIR) Plan"[13] can help the research team ensure that engagement is beneficial for and valued by all research team members.

How Patient Partners Can Contribute: Recruiting, Orienting, and Training

Including at least 2 patient partners who reflect some diversity in the patient population (consider sex, age, condition/disease severity, geographical location, etc) can help to mitigate token patient engagement. A practical guide is "Patient Engagement: Heard and Valued."[15]

There are abundant training resources for patient partners and for researchers, including those hosted on the US-based INSPIRE Research Portal (http://inspireresearch.org/), UK-based INVOLVE training support,[16] and Canadian-based, patient-oriented primary health care online modules.[1]

Budgeting for Patient Partners' Contributions to Research

Respectfully engaging patient partners in research includes consideration of reimbursement for out-of-pocket expenses such as travel and parking, and compensation for time, effort, and expertise.[14]

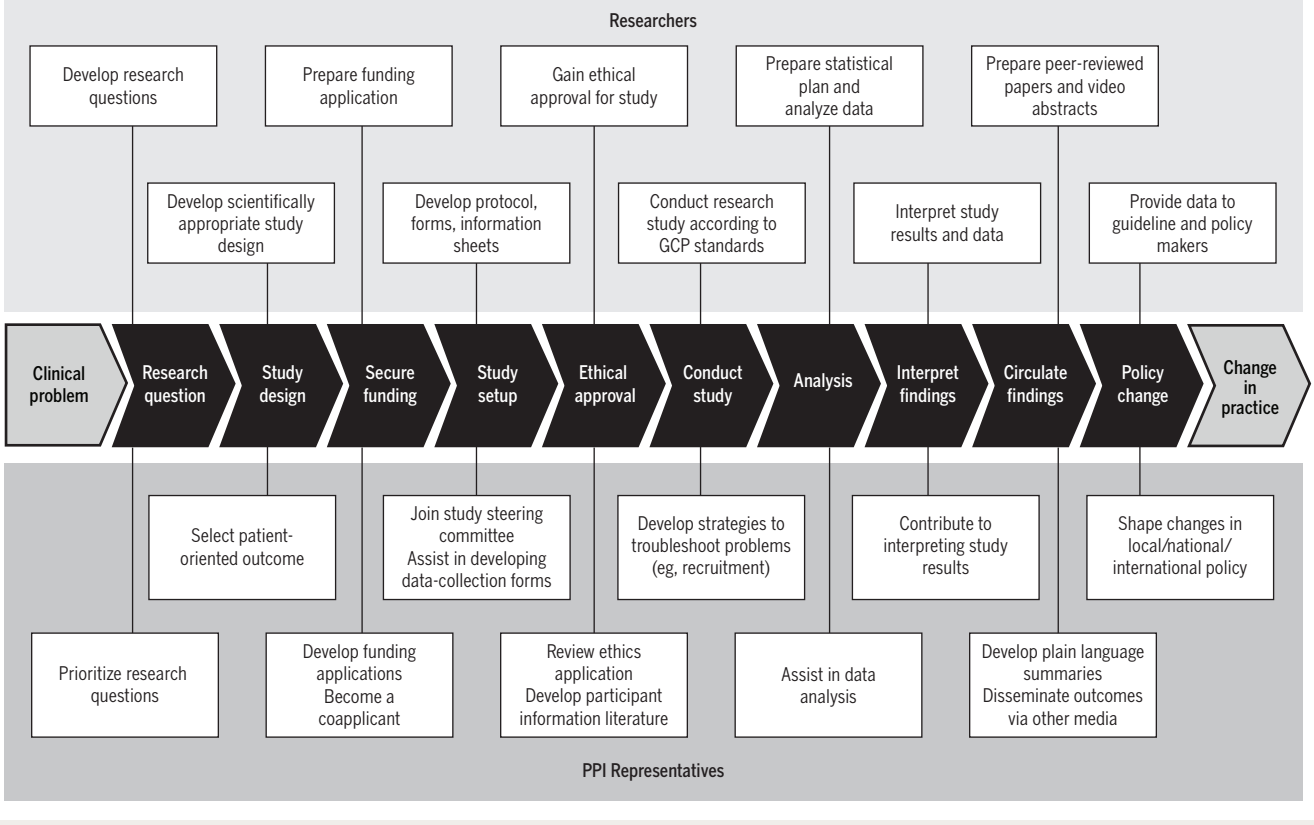

FIGURE. Patients and researchers can collaborate at every stage of the research process. Examples of complementary roles that can be assigned to patients and the public are illustrated. Abbreviations: GCP, good clinical practice; PPI, patient and public involvement. Reprinted with permission from Moss et al.[12] ©2016 Royal College of Obstetricians and Gynaecologists

"Should Money Come Into It? A Tool for Deciding Whether to Pay Patient-Engagement Participants"[6] can help researchers propose appropriate remuneration for patient partners. This report provides a decision tool and questions for researchers and patient partners to consider in the decision-making process.

If the decision is to proceed with compensation, helpful tools to assist in budgeting include the website "budgeting for engagement"[9] and the report "Peer Payment Standards for Short-term Engagements."[2] Collectively, these tools can provide an evidence-informed and respectful foundation for developing the budget for a grant application.

Documenting Patient Partnership in Research

JOSPT requires authors to include a statement about how (if at all) patient partners were involved in the research. Two resources to guide researchers on what to report, how to report, and how much detail to include are the GRIPP2 reporting checklists[17] and the article "Framework for Advancing the Reporting of Patient Engagement in Rheumatology Research Projects."[11]

Summary: Demystifying Patient Partnership in Research

If including patients as equal partners in health care research is increasingly regarded as "the right thing to do,"[3] then it is important that researchers and patients "do it right." The research community should be aware of, use, and share resources that support best practices in this domain. In this editorial, we highlighted a selection of resources to help researchers and to demystify patient partnerships in research.

We encourage researchers to approach local organizations that specialize in patient engagement in research when planning a research project (eg, the Patient-Centered Outcomes Research Institute [https://www.pcori.org/], the website "Strategy for patient-oriented research,"[4] and INVOLVE [https://www.invo.org.uk/]).

If you have additional resources, suggestions, questions, or stories about partnering with patients in research, please reach out to us via e-mail (jospt@jospt.org) or our social media channels (@JOSPT).

REFERENCES

1. BC SUPPORT Unit. Patient-Oriented Research Training and Learning – Primary Health Care (PORTL-PHC) online modules (for all stakeholders). Available at: https://bcsupportunit.ca/resources/patient-oriented-research-training-and-learning-primary-health-care-portl-phc-online. Accessed January 22, 2020.
2. Becu A, Allan L. Peer Payment Standards for Short-term Engagements. Vancouver, Canada: BC Centre for Disease Control; 2018.
3. Belton J, Hoens A, Scott A, Ardern CL. Patients as partners in research: it's the right thing to do. *J Orthop Sports Phys Ther*. 2019;49:623-626. https://doi.org/10.2519/jospt.2019.0106
4. Canadian Institutes of Health Research. Strategy for patient-oriented research. Available at: https://cihr-irsc.gc.ca/e/41204.html. Accessed January 22, 2020.
5. Can-SOLVE CKD Network. Engaging Patients in the Research Process: A Toolkit for Project Leads. Vancouver, Canada: Can-SOLVE CKD Network; 2017.
6. The Change Foundation. Should Money Come Into It? A Tool for Deciding Whether to Pay Patient-Engagement Participants. Toronto, Canada: The Change Foundation; 2015.
7. Clinical Trials Ontario. Investigator decision aid. Available at: https://www.ctontario.ca/patients-public/resources-for-engaging-patients/investigator-decision-aid/. Accessed January 22, 2020.
8. Clinical Trials Ontario. Patient decision aid. Available at: https://www.ctontario.ca/patients-public/resources-for-engaging-patients/patient-decision-aid/. Accessed January 22, 2020.
9. George & Fay Yee Centre for Healthcare Innovation. Budgeting for engagement. Available at: https://chimb.ca/sub-sites/1-patient-engagement/?page=79-budgeting-for-engagement. Accessed January 22, 2020.
10. George & Fay Yee Centre for Healthcare Innovation. The interactive map tool. Available at: https://chimb.ca/sub-sites/1-patient-engagement?page=75-how-to-engage#. Accessed January 22, 2020.
11. Hamilton CB, Leese JC, Hoens AM, Li LC. Framework for advancing the reporting of patient engagement in rheumatology research projects. *Curr Rheumatol Rep*. 2017;19:38. https://doi.org/10.1007/s11926-017-0666-4
12. Moss N, Daru J, Lanz D, Thangaratinam S, Khan KS. Involving pregnant women, mothers and members of the public to improve the quality of women's health research. *BJOG*. 2017;124:362-365. https://doi.org/10.1111/1471-0528.14419
13. PEIRS Project Team. Workbook to Guide the Development of a Patient Engagement In Research (PEIR) Plan. Richmond, Canada: Arthritis Research Canada; 2018. Available at: https://www.arthritisresearch.ca/wp-content/uploads/2018/06/PEIR-Plan-Guide.pdf
14. Richards DP, Jordan I, Strain K, Press Z. Patient partner compensation in research and health care: the patient perspective on why and how. *Patient Exp J*. 2018;5:art 2. https://doi.org/10.35680/2372-0247.1334
15. Snow B, Tweedie K, Pederson A, Shrestha H, Bachmann L. Patient Engagement: Heard and Valued—A Handbook for Meaningful Engagement of Patients That Have Not Traditionally Been Heard in Healthcare Planning. Surrey, Canada: Fraser Health Authority; 2013.
16. Staley K, Hanley B, Faulkner A. Developing Training and Support for Public Involvement in Research. Eastleigh, UK: INVOLVE Coordinating Centre; 2012.
17. Staniszewska S, Brett J, Simera I, et al. GRIPP2 reporting checklists: tools to improve reporting of patient and public involvement in research. *Res Involv Engagem*. 2017;3:13. https://doi.org/10.1186/s40900-017-0062-2

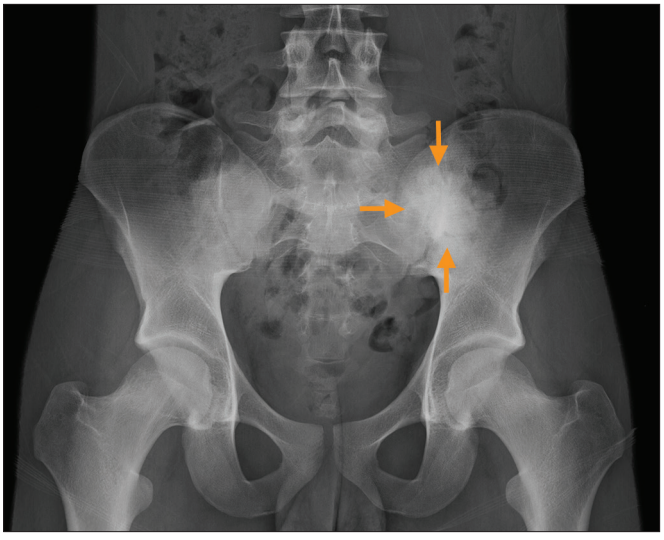

FIGURE 1. Anteroposterior radiograph of the pelvis demonstrating a large sclerotic lesion over the superior aspect of the left sacroiliac joint.

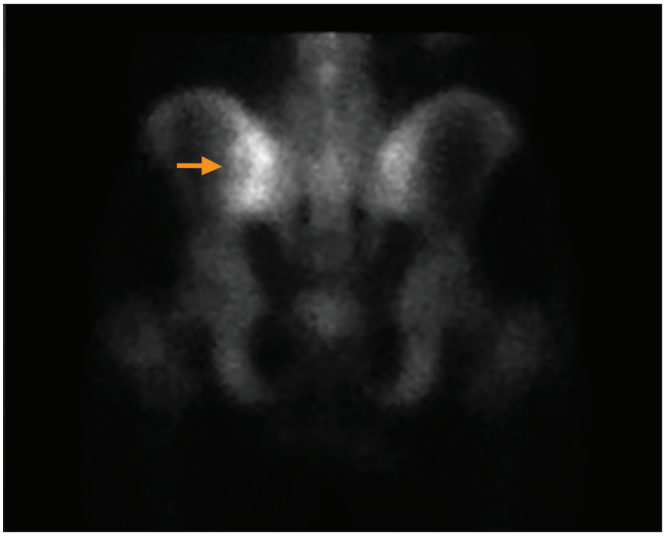

FIGURE 2. Posterior-view bone scan demonstrating increased uptake of the radiotracer involving the medial aspect of the left iliac bone.

Diagnosis of Ewing's Sarcoma After a Fall

JEREMY D. HOUSER, DPT, OCS, *Department of Applied Medicine and Rehabilitation, Indiana State University, Terre Haute, IN.*
SCOTT D. CAROW, DPT, DSc, OCS, SCS, *Department of Applied Medicine and Rehabilitation, Indiana State University, Terre Haute, IN.*

A 21-year-old male Army basic trainee was evaluated in a direct-access physical therapy clinic for left-sided low back pain. Symptoms began 1 week earlier after falling backward and landing on his left buttock during a 13-mile loaded march. He described his pain as unrelenting, even at night. Past medical history was unremarkable. There were no other constitutional symptoms.

Upon examination, active range of motion of the lumbar spine was full and pain free in flexion, and slightly painful at the end ranges of extension. Visual inspection of the lumbar spine revealed a marble-sized mass along the lower left paraspinals that was pain free and mobile on palpation. Given the acute traumatic injury, unrelenting night pain in the lower back, and unusual soft tissue mass, radiographs were ordered (**FIGURE 1**). Additionally, with the suspicion of stress fracture, the clinic-specific protocol included referral for a bone scan (**FIGURE 2**). The radiographic finding of a sclerotic lesion at the sacroiliac joint, coincident with increased uptake on the bone scan, prompted referral for a computed tomography scan of the pelvis. Computed tomography, done 6 days later, characterized an infiltrative soft tissue mass (**FIGURE 3**, available at www.jospt.org). The therapist immediately contacted an orthopaedic surgeon, who recommended that the physical therapist order immediate magnetic resonance imaging (STAT MRI) (**FIGURE 4**, available at www.jospt.org). The patient underwent a tissue biopsy and subsequently was diagnosed with Ewing's sarcoma. The patient was transferred to a cancer treatment facility for further management.

Two of the most common clinical characteristics of Ewing's sarcoma are localized bone pain and a palpable mass.[1] This case illustrates the importance of comprehensive screening, including "red flag questions," as well as basic skills, including visual inspection and palpation, which contributed to timely intervention. *J Orthop Sports Phys Ther 2020;50(5):276. doi:10.2519/jospt.2020.9109*

Reference
1. Fragkandrea I, Nixon JA, Panagopoulou P. Signs and symptoms of childhood cancer: a guide for early recognition. *Am Fam Physician*. 2013;88:185-192.

STEVEN J. KAMPER, PhD[1]

Risk of Bias and Study Quality Assessment: Linking Evidence to Practice

J Orthop Sports Phys Ther 2020;50(5):277-279. doi:10.2519/jospt.2020.0702

Evidence-based practice requires use of the best available evidence, which implies that some evidence is better than other evidence. Better evidence comes from research findings that are at lower risk of bias. Recalling an earlier Evidence in Practice article,[2] bias means that the results of the study do not reflect the true effect of an intervention. A biased study can overestimate (or underestimate) the size of an effect or association.

Sorting the good from the bad when it comes to research evidence requires assessment of the methods and results of the study. There are several tools available to help the reader assess study quality or risk of bias. Study quality and risk of bias are overlapping but subtly different concepts. Risk of bias is how likely it is that the study findings are biased, whereas study quality is a broader concept that includes risk of bias among other features, such as generalizability[4] and appropriate reporting. The items included in risk of bias assessment tools are more narrowly focused, whereas those in study quality tools cover more ground.

Study quality and risk of bias assessment tools both aim to help the reader assess how likely it is that the results of a study are true, and, therefore, the extent to which the study should inform clinical decisions.

Measuring Risk of Bias and Study Quality

Researchers have developed checklists, scales, and domain-based tools that identify indicators (criteria) of study quality and potential bias.

- Checklist: a set of criteria that identify study features that indicate study quality or risk of bias. Checklists should not be summed to produce a total score.
- Scale: a set of criteria that are summed to produce a total score.
- Domain-based tool: a list of types of bias (domains); assessors make judgments about the risk of each type of bias.

The principles underlying measurement of study quality and risk of bias are no different from those measuring clinical outcomes.[3,5] When using any tool to assess study quality or risk of bias, we are most concerned about reliability (whether different people have the same scores on the scale/checklist) and validity (whether the tool actually measures risk of bias). Not all tools have been tested for reliability and validity. Place more faith in established and well-known tools to guide your assessment.

Assessment Tools

Different study quality and risk of bias tools apply to different study designs, because certain types of bias may or may not be relevant depending on the research question. For example, identification of, measurement of, and statistical adjustment for confounders are critical for prognostic studies, but not for randomized clinical trials (RCTs). Intention-to-treat analysis is an important feature of RCTs, but is not relevant to diagnostic studies. The tool used to measure study quality or risk of bias must match the study design.

Measurement of study quality is best developed for treatment-effectiveness studies. The most common tools are the Physiotherapy Evidence Database (PEDro) scale and the Cochrane risk of bias tool. The former is commonly used as a scale and the latter is a domain-based tool. The PEDro scale includes a list of study features that are marked as present, absent, or unclear, and the number of "present" items is summed to represent the study quality score. The Cochrane risk of bias tool includes a list of types of bias (domains), and the rater judges whether the study is at risk (high, low, or unclear) of bias. The PEDro scale and Cochrane risk of bias tool identify many of the same study features: both include items related to randomization, concealed allocation, blinding, and appropriate reporting of results. While both tools were developed using robust methods,[1,6,7] there is no strong evidence that either is more reliable and valid than the other.

While numerous assessment tools are available for most study types, they generally include similar items, and there is typically no consensus as to which is preferred. This is because the most important features that denote study quality and lead to bias are well recognized.

[1]School of Public Health, University of Sydney, Camperdown, Australia; Centre for Pain, Health and Lifestyle, Australia.

Some well-accepted tools for study types include the Quality In Prognostic Studies (QUIPS) tool for observational studies investigating prognostic factors, the Quality Assessment of Diagnostic Accuracy Studies-revised (QUADAS-2) for diagnosis studies, and A MeaSurement Tool to Assess systematic Reviews-revised (AMSTAR-2) for systematic reviews (**TABLE**).

Reporting Guidelines

Cousins of study quality assessment tools are reporting guidelines, although they are not designed to assess risk of bias. Reporting guidelines help authors ensure that their articles include sufficient information for readers to judge the quality and applicability of their research. The items often overlap with those in study quality checklists, but they serve a different purpose. Because reporting guidelines focus on what appears in the manuscript (rather than the design of the study), they are often also used by journal editors to improve research articles during peer review. There are specific guidelines for different study designs. The best known include the CONsolidated Standards Of Reporting Trials (CONSORT) statement for RCTs, the STrengthening the Reporting of OBservational studies in Epidemiology (STROBE) statement for observational studies, and the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement for systematic reviews. The Enhancing the QUAlity and Transparency Of health Research (EQUATOR)

TABLE Items in Study Quality Tools

Study Type	Cochrane Risk of Bias Tool	PEDro Scale	QUIPS	QUADAS-2	AMSTAR-2
RCTs	• Selection bias • Attrition bias • Performance bias • Detection bias • Reporting bias • Other bias	• Eligibility • Randomization • Concealed allocation • Group comparability • Participant blinding • Therapist blinding • Assessor blinding • Intention-to-treat analysis • Loss to follow-up • Statistical comparisons • Point and variability measures			
Prognosis			• Participation • Attrition • Prognostic factor measurement • Confounder measurement • Outcome measurement • Analysis and reporting		
Diagnostic tests				• Patient selection • Index test • Reference standard • Flow and timing	
Systematic reviews					• Research question • A priori protocol • Inclusion criteria • Comprehensive search • Justification of exclusions • Duplicate study selection • Duplicate data extraction • Included study description • Risk of bias assessment • Impact of bias on interpretation • Impact of bias on synthesis • Appropriate meta-analysis • Funding sources • Heterogeneity • Publication bias • Conflicts of interest

Abbreviations: AMSTAR-2, A MeaSurement Tool to Assess systematic Reviews-revised; PEDro, Physiotherapy Evidence Database; QUADAS-2, Quality Assessment of Diagnostic Accuracy Studies-revised; QUIPS, Quality In Prognostic Studies; RCT, randomized clinical trial.

network (https://www.equator-network.org/) keeps an up-to-date repository of reporting guidelines.

Application

Sifting out the poor-quality research and paying attention to the good is a requirement of evidence-based practice. The key to assessing quality is understanding how and to what extent bias may impact study findings. Recognize which types of bias are most relevant to the study in question, judge the extent to which bias should impact confidence in the study findings, and decide when the risk of bias is so great that the results should be ignored altogether. Systematic reviews can be a useful resource, because most reviews report risk of bias or study quality assessments of the included studies.

Study quality and risk of bias assessment tools can help the reader understand how much confidence one should place in the findings of a study. However, the reader must select the right tool for the job, and proper application requires an understanding of the principles that underpin the items in the tool.

REFERENCES

1. Higgins JP, Altman DG, Gøtzsche PC, et al. The Cochrane Collaboration's tool for assessing risk of bias in randomised trials. *BMJ*. 2011;343:d5928. https://doi.org/10.1136/bmj.d5928
2. Kamper SJ. Bias: linking evidence with practice. *J Orthop Sports Phys Ther*. 2018;48:667-668. https://doi.org/10.2519/jospt.2018.0703
3. Kamper SJ. Fundamentals of measurement: linking evidence to practice. *J Orthop Sports Phys Ther*. 2019;49:114-115. https://doi.org/10.2519/jospt.2019.0701
4. Kamper SJ. Generalizability: linking evidence to practice. *J Orthop Sports Phys Ther*. 2020;50:45-46. https://doi.org/10.2519/jospt.2020.0701
5. Kamper SJ. Reliability and validity: linking evidence to practice. *J Orthop Sports Phys Ther*. 2019;49:286-287. https://doi.org/10.2519/jospt.2019.0702
6. Maher CG, Sherrington C, Herbert RD, Moseley AM, Elkins M. Reliability of the PEDro scale for rating quality of randomized controlled trials. *Phys Ther*. 2003;83:713-721. https://doi.org/10.1093/ptj/83.8.713
7. Verhagen AP, de Vet HC, de Bie RA, et al. The Delphi list: a criteria list for quality assessment of randomized clinical trials for conducting systematic reviews developed by Delphi consensus. *J Clin Epidemiol*. 1998;51:1235-1241. https://doi.org/10.1016/s0895-4356(98)00131-0

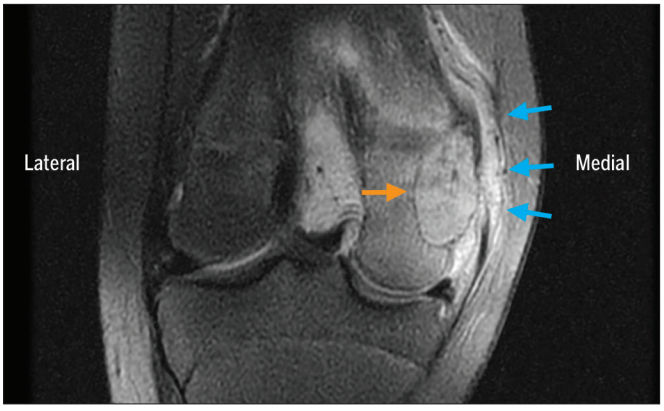

FIGURE 3. Coronal T2-weighted magnetic resonance image of the right knee showing a 2.1 × 1.5 × 2.9-cm bony lesion on the medial femur (orange arrow). Additionally, the magnetic resonance image revealed a partial medial collateral ligament rupture and effusion (blue arrows).

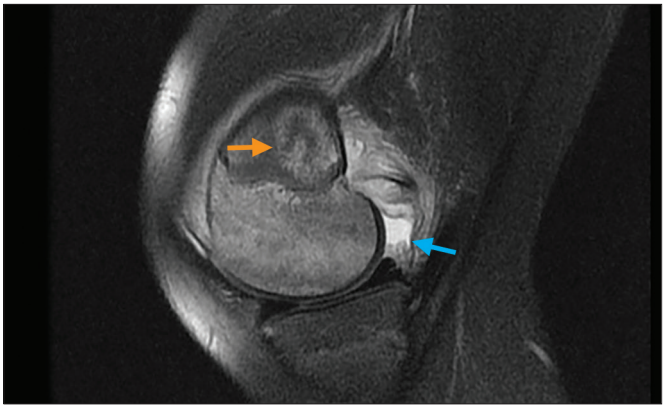

FIGURE 4. Sagittal T2-weighted magnetic resonance image of the right knee demonstrating a bony lesion at the medial femur (orange arrow). Joint effusion can also be visualized (blue arrow).

Chondroblastoma of the Distal Femur in an Adolescent

RYAN KASER, PT, DPT, *ProActive Physical Therapy Specialists, Prineville, OR.*
WILLIAM J. GARCIA, PT, DPT, OCS, FAAOMPT, *California State University, Sacramento, CA.*
RICARDO MORALES, PT, *Sutter Medical Foundation, Yuba City, CA.*

An 11-year-old female was referred to physical therapy by her pediatrician, due to a 3-month history of right medial knee pain. She denied a specific injury; however, she reported that her symptoms started after playing volleyball with family. Her worst pain occurred in the morning and with walking. She denied significant night pain, and general health screening was noncontributory. The patient's medical diagnosis was Osgood-Schlatter disease, based on radiographs obtained at the initial pediatrician consultation (**FIGURES 1** and **2**, available at www.jospt.org).

On physical examination, an antalgic gait pattern was observed, along with erythema and effusion at the knee. Knee active range of motion was significantly limited (30°-90°), and passive range of motion revealed an empty end feel. Valgus stress testing was inconclusive. Palpation reproduced pain along the medial collateral ligament, medial joint line, and femoral condyle. Initial hypotheses included suprapatellar bursitis, medial collateral ligament sprain, or meniscus injury; Osgood-Schlatter disease was not suspected, based on presentation. Based on tissue irritability, a negative red flag screen, and pending magnetic resonance imaging (MRI) ordered by the pediatrician, initial treatment focused on symptom modulation.

An MRI scan was obtained 2 weeks after starting physical therapy and revealed a bony lesion near the medial condyle of the right femur and damage to medial joint structures (**FIGURES 3** and **4**).[2] Osteosarcoma was suspected; therefore, she was referred to an oncologist and physical therapy was suspended.

Pathology after open biopsy and curettage of the lesion revealed a chondroblastoma.[1,3] The mass was removed 1 week after MRI, and the patient returned to physical therapy for 10 weeks. Upon discharge from physical therapy, she returned to normal function. One year later, the chondroblastoma recurred, requiring additional surgery. A chondroblastoma is a rare, benign bone tumor found in the epiphysis or apophysis of long bones in individuals 10 to 25 years of age.[1,3] Recurrence can occur in 8% to 20% of patients, commonly within 2 to 3 years of surgery.[1] *J Orthop Sports Phys Ther 2020;50(5):275. doi:10.2519/jospt.2020.9021*

References
1. van der Geest IC, van Noort MP, Schreuder HW, Pruszczynski M, de Rooy JW, Veth RP. The cryosurgical treatment of chondroblastoma of bone: long-term oncologic and functional results. *J Surg Oncol*. 2007;96:230-234. https://doi.org/10.1002/jso.20804
2. Wang F, Li J, Yu D, Wang Q. Chondroblastoma of the distal femoral metaphysis: a case report with emphasis on imaging findings and differential diagnosis. *Medicine (Baltimore)*. 2018;97:e0336. https://doi.org/10.1097/MD.0000000000010336
3. Xiong Y, Lang Y, Yu Z, et al. The effects of surgical treatment with chondroblastoma in children and adolescents in open epiphyseal plate of long bones. *World J Surg Oncol*. 2018;16:14. https://doi.org/10.1186/s12957-018-1314-9

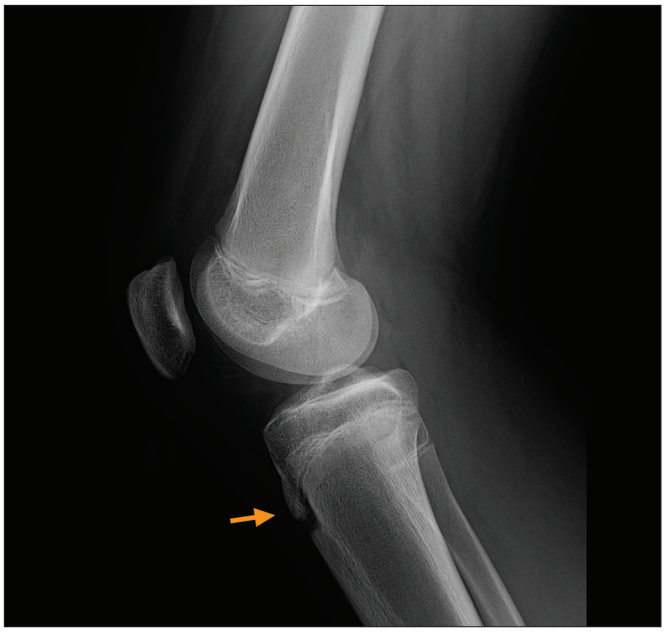

FIGURE 1. Lateral-view radiograph of the right knee. A slightly prominent tibial tubercle (arrow) was suspected to represent early onset of Osgood-Schlatter disease or a normal variant, per radiologist report.

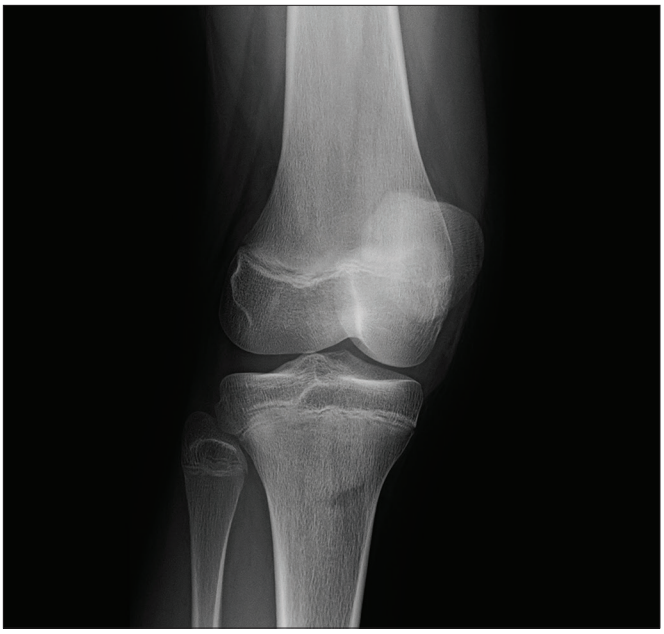

FIGURE 2. Internal rotation–view radiograph of the right knee. No acute abnormalities were found.

RASMUS ØSTERGAARD NIELSEN, PT, PhD[1,2] • IAN SHRIER, MD, PhD[3] • MARTÍ CASALS, MSc, PhD[4,5] • ALBERTO NETTEL-AGUIRRE, MSc, PhD[6-8] MERETE MØLLER, PT, PhD[9] • CAROLINE BOLLING, PT, PhD[10] • NATALIÁ F.N. BITTENCOURT, PT, PhD[10,11] • BEN CLARSEN, PT, PhD[12,29] NIELS WEDDERKOPP, MD, PhD[13,14] • TORBJØRN SOLIGARD, MSc, PhD[6,15] • TOOMAS TIMPKA, MD, PhD[16,17] • CAROLYN A. EMERY, PT, PhD[6-8] ROALD BAHR, MD, PhD[12] • JENNY JACOBSSON, PT, PhD[16,17] • ROD WHITELEY, PT, PhD[18] • ÖRJAN DAHLSTRÖM, PhD[16,19] NICOL VAN DYK, PT, PhD[28] • BABETTE M. PLUIM, MD, PhD[10,20,21] • EMMANUEL STAMATAKIS, MSc, PhD[22] • LUZ PALACIOS-DERFLINGHER, MSc, PhD[6,8] MORTEN W. FAGERLAND, MSc, PhD[12] • KARIM M. KHAN, MD, PhD[23,24] • CLARE L. ARDERN, PT, PhD[25-27] • EVERT VERHAGEN, PhD[10]

Statement on Methods in Sport Injury Research From the First METHODS MATTER Meeting, Copenhagen, 2019

SYNOPSIS: High-quality sports injury research can facilitate sports injury prevention and treatment. There is scope to improve how our field applies best-practice methods—methods matter (greatly!). The first METHODS MATTER meeting, held in January 2019 in Copenhagen, Denmark, was the forum for an international group of researchers with expertise in research methods to discuss sports injury methods. We discussed important epidemiological and statistical topics within the field of sports injury research. With this opinion document, we provide the main take-home messages that emerged from the meeting. Meeting participants agreed that the definition of sport injury depends on the research question and context. It was considered essential to be explicit about the goal of the research effort and to use frameworks to illustrate the assumptions that underpin measurement and the analytical strategy. Complex systems were discussed to illustrate how potential risk factors can interact in a nonlinear way. This approach is often a useful alternative to identifying single risk factors. Investigating changes in exposure status over time is important when analyzing sport injury etiology, and analyzing recurrent injury, subsequent injury, or injury exacerbation remains challenging. The choice of statistical model should consider the research question, injury measure (eg, prevalence, incidence), type and granularity of injury data (categorical or continuous), and study design. Multidisciplinary collaboration will be a cornerstone for future high-quality sport injury research. Working outside professional silos in a diverse, multidisciplinary team benefits the research process, from the formulation of research questions and designs to the statistical analyses and dissemination of study results in implementation contexts. This article has been copublished in the *British Journal of Sports Medicine* and the *Journal of Orthopaedic & Sports Physical Therapy*. *J Orthop Sports Phys Ther 2020;50(5):226-233. doi:10.2519/jospt.2020.9876*

Sports injury researchers have powerful statistical software packages at their disposal to help answer increasingly sophisticated questions posed by coaches, clinicians, and athletes. New statistical approaches, etiological and causal frameworks, and complex systems theory continue to be developed and refined—a gift and a challenge in equal measure. This ongoing development of methodological approaches allows for high-quality analyses that advance the broad field of sports injury research to improve clinical care, injury treatment, and injury prevention.[79]

Two decades ago, in general medical journals, the proportion of published

[1]Section for Sport Science, Department of Public Health, Aarhus University, Aarhus, Denmark. [2]Research Unit for General Practice in Aarhus, Aarhus, Denmark. [3]Centre for Clinical Epidemiology, Lady Davis Institute, Jewish General Hospital, McGill University, Montreal, Canada. [4]Sport and Physical Activity Studies Center, Faculty of Medicine, University of Vic-Central University of Catalonia, Barcelona, Spain. [5]Medical Department, Futbol Club Barcelona, Barça Innovation Hub, Barcelona, Spain. [6]Sport Injury Prevention Research Centre, Faculty of Kinesiology, University of Calgary, Calgary, Canada. [7]Department of Pediatrics, Cumming School of Medicine, University of Calgary, Calgary, Canada. [8]Department of Community Health Sciences, Cumming School of Medicine, University of Calgary, Calgary, Canada. [9]Department of Sports Science and Clinical Biomechanics, University of Southern Denmark, Odense, Denmark. [10]Amsterdam Collaboration on Health & Safety in Sports, Department of Public and Occupational Health, Amsterdam Movement Sciences, Amsterdam University Medical Centers-Vrije Universiteit Amsterdam, Amsterdam, the Netherlands. [11]Sports Physical Therapy Department, Minas Tênis Clube and Uni-BH University Center, Belo Horizonte, Brazil. [12]Oslo Sports Trauma Research Center, Norwegian School of Sport Sciences, Oslo, Norway. [13]Department of Orthopaedic Surgery, Hospital of South West Jutland, Esbjerg, Denmark. [14]Department of Regional Health Research, University of Southern Denmark, Odense, Denmark. [15]Medical and Scientific Department, International Olympic Committee, Lausanne, Switzerland. [16]Athletics Research Center, Linköping University, Linköping, Sweden. [17]Swedish Athletics Association, Stockholm, Sweden. [18]Aspetar Orthopaedic and Sports Medicine Hospital, Doha, Qatar. [19]Department of Behavioral Sciences and Learning, Linköping University, Linköping, Sweden. [20]Medical Department, Royal Netherlands Lawn Tennis Association, Amstelveen, the Netherlands. [21]Section Sports Medicine, Faculty of Health Sciences, University of Pretoria, Pretoria, South Africa. [22]Charles Perkins Centre, School of Health Sciences, The University of Sydney, Camperdown, Australia. [23]Department of Family Practice and School of Kinesiology, University of British Columbia, Vancouver, Canada. [24]*British Journal of Sports Medicine*, London, United Kingdom. [25]Division of Physiotherapy, Department of Neurobiology, Care Sciences and Society, Karolinska Institute, Stockholm, Sweden. [26]Sport and Exercise Medicine Research Centre, La Trobe University, Melbourne, Australia. [27]*Journal of Orthopaedic & Sports Physical Therapy*, Alexandria, VA. [28]High Performance Unit, Irish Rugby Football Union, Dublin, Ireland. [29]Department of Health Promotion, Norwegian Institute of Public Health, Bergen, Norway. The *British Journal of Sports Medicine* provided an unrestricted grant for the event that was used to offset hotel meeting room rental and meal costs at the event in Copenhagen. Karim Khan is Editor-in-Chief, *British Journal of Sports Medicine* and Clare Ardern is Editor-in-Chief, *Journal of Orthopaedic & Sports Physical Therapy*. The other authors certify that they have no affiliations with or financial involvement in any organization or entity with a direct financial interest in the subject matter or materials discussed in the article. Address correspondence to Rasmus Østergaard Nielsen, Section for Sport Science, Department of Public Health, Aarhus University, Bartholins Allé 2, Building 1260, 132, 8000 Aarhus C, Denmark. E-mail: roen@ph.au.dk

articles with questionable application of statistical methods reportedly ranged from 39% to 90%.[2] Researchers made so many basic statistical errors that the late Professor Douglas Altman, a former Director of the Centre for Statistics in Medicine in Oxford, declared that the level of inappropriate use of statistical techniques in biomedical research was a scandal.[1] In the future, it is therefore essential that similar or even worse findings than those in biomedical research 2 decades ago are not repeated in the present sports injury research context. After all, methods matter![79]

"How often do we discuss epidemiology, causality, and statistical sciences in sports injury research?" you may ask. To the best of our knowledge, no specific community or forum exists on epidemiology or statistics in sports injury research. Training new researchers to conduct methodologically robust sports injury research is often limited and inadequate, and researchers, both experienced and inexperienced, often employ traditional methods that may not be ideal for their type of data and research question. This limited focus on methodology inspired the first "METHODS MATTER" meeting for a group of representative researchers. The goal was to discuss epidemiological and statistical topics within the field of sports injury research. With this opinion document, we provide readers of sports injury research a summary of discussions and the main take-home messages that emerged from the first METHODS MATTER meeting. An overview of these take-home messages is provided in the **TABLE**.

METHODS

The first METHODS MATTER meeting was held in Copenhagen, Denmark on January 29 and 30, 2019. Thirty-one researchers from 13 countries were invited and 25 researchers from 11 countries attended. The agenda consisted of 6 preselected topics: (1) injury definition, (2) sports injury data and statistical modeling, (3) complex systems thinking and computational modeling, (4) longitudinal data analyses, (5) recurrent and subsequent injuries, and (6) causality.

In each session, the key elements were introduced by 2 or 3 presentations, after which a discussion followed on the content of the presentations and other topics that emerged (for the meeting invitation, title of presentations, and book of abstracts, see the **SUPPLEMENTARY FILE**). Each session-specific discussion was guided by a scientific facilitator and a moderator. The facilitator was a content expert who ensured that everyone had a chance to contribute to the discussion. The facilitator encouraged discussions around the table and aimed to provide a concise 2-minute summary at the end of each session. The moderator kept time.

After the meeting, each facilitator drafted a summary of the session that was circulated to the presenters and moderator associated with that topic for review. Authors R.O.N. and E.V. merged the 6 documents and drafted the introduction, methods, and conclusion, which were then distributed to all authors for a first round of feedback. After revisions, the full-text manuscript was circulated twice for final comments and suggestions for improvement prior to submission.

The attendees agreed on certain issues (eg, an injury definition depends on a range of factors) and were challenged by other issues (eg, how to best analyze recurrent events). Consequently, this manuscript should not be regarded as a consensus statement. We hope it will serve as a tool for sports science researchers dealing with the complexity of sport injury epidemiology, causality, sports biostatistics, and other methodological issues.

Our views and take-home messages are presented under the following 8 headings: (1) No universal sports injury definition is necessary; (2) Be explicit about the goal of your research: are you describing, predicting, or drawing a causal inference? (3) Frameworks can guide researchers; (4) Analyzing longitudinal data; (5) Which statistical model should I choose? (6) Dealing with recurrent or subsequent injury; (7) Complex systems; and (8) Need for multidisciplinary collaborations.

No Universal Sport Injury Definition Is Necessary

Injury consensus statements across sports use different definitions of sport injury,[24,25,40,46,57,58,60,74,77] in part because the definition depends on the context.[17,22,76] Researchers planning a sports injury study need to consider a range of operational injury definitions. These can be roughly divided into broad categories with respect to time loss from sports, such as any physical complaint, which includes non–time-loss injuries, and more narrow definitions (eg, unavailable for competition). Studies that use a broader definition often have greater statistical power because more injuries are captured. However, collecting detailed injury data using a broad definition may be resource demanding, require criteria that are more subjective, and capture a number of injuries with minimal consequences (eg, cuts and bruises). In contrast, narrow definitions are generally based on more objective criteria and filter out less severe cases. Associations may exist for a broader definition when none exist for a narrow definition, or vice versa.

Traditionally, measures such as prevalence proportion or incidence rate are reported in sports injury studies.[54] At the METHODS MATTER meeting, we discussed the outcomes of injury severity and injury burden.[6,23] Currently, there is no consensus on the definition of injury burden or on how to operationalize burden in statistical analyses. Creating a composite burden score (eg, the severity score from the Oslo Sports Trauma Research Center questionnaire) from different outcome measures to collapse a complex phenomenon into one number should be considered with caution. This approach risks omitting important information (eg, the difference between prevention and treatment). Still, the

idea of injury burden is appealing, as it aims to provide more information on the consequences of an injury beyond the classical measures of prevalence and incidence.

Recording sports injury events in practice is also contingent on who identifies the event (ie, whether it is researchers, athletes, coaches and managers, clinicians, or combinations of these). For instance, loyalty or toughness may encourage athletes, coaches, and medical staff to downplay injury symptoms or hasten return to sport.

The choice of sports injury definition should also be guided by the research question. For example, studies of workload and injury risk have typically recorded only noncontact injuries, based on an assumption that workload is unrelated to contact injuries.[32] On the other hand, studies of overuse injuries in general require broad definitions, as athletes often continue to participate in training and competition despite being injured.[5,18] In addition, we need to consider how to capture a sports injury when it originates from sport, from an activity of daily living, or from a combination of the two. A continued discussion on these (and other) aspects related to injury definitions is needed.

Be Explicit About the Goal of Your Research: Are You Describing, Predicting, or Drawing a Causal Inference?

In causal inference, "…being explicit about the goal of the analysis is a prerequisite for good science,"[27] and we recommend the practice for sports injury researchers as well. For such clarification, a 3-fold classification of the research goal, which was published recently,[28] may be used:

1. Description: for instance, describe injury risk or rate over time in a group of athletes
2. Prediction: for instance, examine which athletes are more likely to sustain in-

TABLE Take-Home Messages and Recommendations From the First METHODS MATTER Meeting

Topic	Opinions and Recommendations
No universal sports injury definition is necessary	1. There is no need for a single, universally accepted definition of sport injury 2. Choosing an injury definition is a balancing act between a range of factors, such as level of pain/injury severity, number of cases, research question, and ease of reporting. As these factors are often competing, we encourage researchers to match their choice of definition to the study purpose, setting, and design
Be explicit about the goal of your research: are you describing, predicting, or drawing a causal inference?	3. Be explicit about the research goal (eg, description, prediction, or causal inference) 4. To ensure that sports injury researchers report the goal of their research in their publications, we recommend coordinated action by sports science and medicine journals. For instance, the author guidelines could state that authors should explicitly describe their research goal 5. Define the terms used in research (eg, prediction, causation). Standard language that clinicians and researchers understand will improve evidence transparency and quality
Frameworks can guide researchers	6. Clearly outline your assumptions. Specifying your theoretical framework and/or drawing a causal diagram when dealing with a causal question is generally very helpful to the reader
Analyzing longitudinal data	7. As sports injury occurrence is likely a highly dynamic process, investigating changes over time is important. Consequently, sports injury researchers are recommended to embrace the options that longitudinal data offer
Which statistical approach should I choose?	8. The choice of the statistical analytical approach depends on various factors, including, but not limited to, research question, injury measure (eg, prevalence, incidence), type of injury data (categorical or numerical/continuous), and study design
Dealing with recurrent or subsequent injury	9. There is no consensus on what constitutes a "healed" injury 10. There is no consensus on the recommended statistical approach to analyze recurrent injury data, subsequent injury data, or data on injury exacerbation 11. As no consensus on what constitutes a recurrent injury, subsequent injury, or injury exacerbation should exist, classifications of recurrent injury, subsequent injury, and injury exacerbation should be clearly defined in each manuscript
Sports injuries are complex and contextual	12. Researchers require at least a basic understanding of what complex systems entail and how to interpret the results to better use complex system analysis in sports science 13. Statistical modeling and systems-based modeling approaches that recognize nonlinear complex interactions complement traditional biostatistical and epidemiological methods 14. Approaches that combine qualitative and quantitative methods may help investigators better understand how nonlinear complex interactions underpin most sports injuries
Need for multidisciplinary teams and collaborations	15. Collaboration bridges gaps between statisticians, epidemiologists, sports injury researchers, athletes, and clinical experts 16. Involve statisticians, epidemiologists, and practitioners early when designing a study, not after data have been collected 17. Working in diverse, multidisciplinary teams should help to better formulate research questions, identify an appropriate study design, ensure appropriate and legally acceptable data acquisition, conduct correct statistical analyses, make proper interpretation of study results, and disseminate them in suitable implementation contexts 18. Stakeholders in sports injury research are encouraged to intensify their investments in statistical, epidemiological, and methodological education in our field, such as multisite and interdisciplinary collaborations, training reviewers, providing online opportunities, exchanging trainees, developing (and extending) guidelines, and including methods content in regular scientific meetings

jury than others—in plain language, this translates to identifying/predicting "who" is at high risk of getting injured

3. Causal inference: for instance, examine the causal effect of an exposure on sports injury—in layman's terms, this translates to examining "why" or "how" an injury occurs using intrinsic and extrinsic causes of injury

When identifying the research goal, it is important to understand that every true causal factor (if it is well measured) is a predictor (although sometimes a weak one), but not every predictor is a causal factor.[45,67] As an example, American football players wearing a shirt with an animal logo had a lower risk of concussion than players who wore shirts without an animal logo.[71] Here, the "who" question (prediction) was addressed through an animal logo variable that is not a causal factor (most likely, changing one's jersey will not change risk of concussion).

If the sports injury researcher is aiming to investigate the causal effect of body weight (or another causal question) on sports injury occurrence, he or she is dealing with a "why" question. In this case, concepts such as confounding, effect-measure modification, and mediation should be given careful attention and consideration, as the etiology of sports injury is likely to be multifactorial.[43] If the goal is prediction, attention to subgroup differences may be needed, depending on the research question of interest.

At the METHODS MATTER meeting, there was discussion about whether the terms "why" and "how" cover the same concept. We did not reach agreement. Clinicians, coaches, and athletes should be aware that some sports injury researchers use the "why" and "how" terms interchangeably. Some may consider "why" and "how" to cover different aspects (eg, etiology and mechanisms, respectively[7]), and others may avoid using the terms altogether.

Frameworks Can Guide Researchers

Researchers should be encouraged to disclose the underlying assumptions of their analyses. Sports injury frameworks help to illustrate the assumptions underpinning who- or why-related questions. The fundamental rationale and theoretical basis that a sports injury occurs if the load applied to a body structure exceeds its capacity to withstand the load[30] led to different frameworks about the causal relationship between workload and injury, with slightly different assumptions.[7-9,49,81] For example, a dynamic model of etiology in sport injury was presented in 2007, in which the authors argued that "exposure is a combination of both possessing a risk factor and then participating (to a greater or lesser degree) with the risk factor."[43]

In a sports injury setting, if the aim is to assess causality, directed acyclic graphs (DAGs) and other causal diagrams can help illustrate which variables to include and adjust for in a statistical analysis. It has been recommended that sports injury researchers include DAGs in their publications.[69,72] Directed acyclic graphs are useful to understand when to adjust for confounding variables,[42,66] when an effect is mediated through another variable, and when adjusting for a variable introduces new bias rather than minimizing bias. This is important when trying to investigate the average/direct/indirect/total causal effect of a certain causal factor in sports injury occurrence.[41,47] For additional information on DAGs, we refer readers to other published literature.[69]

Analyzing Longitudinal Data

Longitudinal data may be viewed as multiple records (eg, injury status) on 1 or more athletes over time. New technologies make access to such data easier, but they carry the price of in-depth considerations when analyzing the data.[26] Irrespective of the size of the data set, researchers must ensure that they collect appropriate data (in an appropriate manner) to answer specific and clear research questions, and that they employ correct statistical tools to handle such data.[13] Athletes often change their training schedule and characteristics. In the 1970s, general methodologists of science insisted that it was impossible to measure how health-related exposures and outcomes changed over time.[20] Researchers interested in the study of change were encouraged to frame their questions in other ways.[20] Later, this was identified as poor advice.[20]

As sports injury occurrence is a highly dynamic process,[43] investigating changes over time is important. Consequently, sports injury researchers are recommended to embrace the options that longitudinal data offer. For instance, longitudinal data permit the calculation of metrics that quantify absolute or relative changes in training load.[50,51] When studying change over time, time-varying exposures (eg, change in training load) and time-varying outcomes (eg, change in injury status) are 2 essential concepts.[80] The open question remains: "Which approach is suitable for which question and data?" There are many options (eg, time-to-event methods,[50] g-methods,[64] survival trees,[83] classification and regression trees with repeated events,[16] and generalized linear mixed models[12]). The most suitable approach for the research question should be given greater consideration in sport injury research in the future. At best, sports injury epidemiologists and sports biostatisticians should be included when deciding on the analytical approach.[13]

Although the advantage of large-scale longitudinal data must be highlighted, these data also carry challenges, including (1) handling dependencies in these data due to the repeated measures on each individual, (2) missing data, which are often substantial in these studies, (3) censoring,[50] (4) competing risk,[51] and (5) understanding the complexity of the statistical analyses required to take full advantage of the many opportunities longitudinal data provide. Ignoring these challenges when fitting models may lead to biased estimates and misinterpretation of results.[13,50,51,80]

Which Statistical Approach Should I Choose?

Injury data are often classified as a dichotomous outcome (ie, an athlete is

either injured or not injured) or as different categorical states that each athlete can inhabit over time. However, other ways of collecting and handling injury data exist, as (1) athletes often move between various states of injury severity, (2) athletes can have more than one injury, or (3) researchers are interested in other injury-related outcomes. This reality may be better reflected in injury data of greater detail and granularity, which can end up being categorical or numerical.[51] The type and granularity of injury data have a substantial impact when choosing the statistical approach. For instance, log-binomial regression or logistic regression requires a dichotomous injury outcome, whereas linear regression requires numerical/continuous data. In addition to the type of injury data, the type of injury outcome measures (eg, prevalence proportion or incidence rate) has implications when choosing statistical models as well.

Different statistical approaches continue to be integrated in the field, including data imputation, time-to-event analysis, longitudinal data, and clustered data, among others. Machine-learning approaches to data, of which prediction is the main goal, are also being considered.[19,28,35] Whether the analyses of interest are descriptive or inferential (the latter can be subdivided into prediction or causal inference), authors should use appropriate terms, concepts, and methods accordingly.[67] Study design and outcomes of interest will play an important role in deciding the appropriate analytic approaches beyond the classical regression techniques.

A common analytical approach is the generalized linear model.[82] This approach requires independence between observations of the injury/outcome. However, these assumptions may be violated in some situations, such as clustered studies (outcomes of individuals within a cluster may be more similar than those of individuals between clusters) or longitudinal studies (repeated measures of the same athletes are analogous to clustering in an individual). Ignoring nonindependence of data when fitting the model may lead to incorrect estimation of standard errors and erroneous conclusions often due to overstated statistical significance. The 2 following techniques are often used to account for correlated data of any type: (1) adding a "random effect" to account for clustering (eg, generalized linear mixed models, frailty models), or (2) incorporating a correlation structure for the observations (eg, generalized estimating equations).

There is a special interest in recurrent event data. The simplest approach to analysis in this setting is to count the events observed within a given period. These counts are usually assumed to follow a Poisson distribution.[14] Where the variance of the counts (rates) is not the same as the mean (ie, data do not follow a Poisson distribution), a quasi-Poisson or a negative binomial distribution is an alternative choice.[10,11] Another way of looking at recurrent event data is to model the time to event. In this case, the time to event of all individuals may not be fully observed, as this may be subject to censoring (eg, dropout from the study before complete follow-up).

Analyzing data in a "competing risk" setting (when other outcomes may preclude the outcome of primary interest and/or change the probability of the outcome of interest) may be important, as athletes may sustain multiple injuries over time.[4,51] Some suggested methods to analyze data in the face of these challenges include competing risk models,[4,51] multistate models,[4] and recurrent event models with a time-dependent covariate.[31,56,78]

Dealing With Recurrent or Subsequent Injury

There is wide recognition that a subsequent injury can be correlated to a previous injury. When analyzing subsequent injury, the terms *repeat*, *recurrent*, *exacerbation*, or *multiple* are often used interchangeably. To avoid confusion, authors should clearly define their terminology in each manuscript. For example, the answer to "When is an injury considered healed?" depends on the research question, and multistate models might provide a framework for researchers and clinicians to help decide on the appropriate categorization.[70] Importantly, models and frameworks should be transparent, valid, and demonstrate clinical utility for the end user. Here, valid and reliable assessment of injury data over time is important. Momentary assessment was discussed as a tool to record information on recurrent injury, including occurrence day and recovery day (however defined).[15,36-39,48]

Competing risks and analysis of recurrent events are major challenges in sport injury research,[3,4,62,65] and there is considerable uncertainty about how to handle these. Methods like the Aalen-Johansen estimator could be a useful alternative to the Kaplan-Meier estimator in survival analyses when dealing with competing risks.[51] Extra precaution should be taken when analyzing small data sets, as these may introduce additional bias and overfitting.

Sports Injuries Are Complex and Contextual

As with most health conditions, it is likely that linear and nonlinear complex interactions underpin most sports injuries.[9,44,63] A complex systems approach to sports injuries tries to understand how relationships between the multitude of direct and indirect risk factors result in different paths to being injured.[9,33,59] Further, athletes act within an ecological context where other determinants of risk may be important to take into account. For instance, the finding that the quality of communication between medical staff and team managers in professional soccer clubs was correlated with injury rates expands the understanding of injury mechanisms because failed communication could lead to inappropriate workloads for some athletes.[21,61] The outcomes of studies performed in the ecological context can immediately be used

for sports safety promotion interventions and programs.[75] To further improve consistency and relevance in recommendations, research approaches that include complex systems models or are ecological are needed to effectively engage stakeholders and qualitatively derive relevant questions to measure quantitatively.

Need for Multidisciplinary Teams and Collaborations

The presentations and discussions at the METHODS MATTER meeting from various methodology-oriented peers were sometimes contentious but occurred in a relaxed and friendly atmosphere, where open critique was encouraged. To reduce the risk of having the use of statistical techniques in sports injury research referred to as a scandal,[1] we discussed the next steps. Here are 3 considerations regarding multidisciplinary collaborations:

- Collaboration is key to bridging gaps between statisticians, researchers, and clinical content experts. Developing objectives, design, data acquisition, analyses, interpretation, and dissemination in the most appropriate implementation context requires collaborative approaches.
- Different presentations of the same research project to different statisticians, data scientists, or injury methodologists will often be met with different recommendations regarding methods.
- Researchers must collaborate more with the statistical community and invest in statistical education in our field (eg, multicenter and interdisciplinary collaborations, reviewer training, online opportunities, trainee exchanges, guidelines, methodological content in meetings).

The next steps in collaboration include ongoing contribution to educational editorials and reviews to accompany those previously published in the *Journal of Orthopaedic & Sports Physical Therapy*, *British Journal of Sports Medicine*, and other journals.[29,34,49-55,68,72,73,79]

CONCLUSION

The general sentiment at the METHODS MATTER meeting was that defining sport injury depends on the research question and context. It is essential that researchers are explicit about the goal of any research effort (eg, description, prediction, or causal inference) and that they use frameworks to illustrate assumptions underpinning the analytical strategy. Modeling of complex systems was brought forward to illustrate how the description of interaction between risk factors can be an alternative to identifying isolated risk factors.

Investigating changes in exposure status over time is important when analyzing sport injury etiology, even though analyzing recurrent injury, subsequent injury, or injury exacerbation remains challenging. Finally, the choice of statistical model should consider the research question, injury measure (eg, prevalence, incidence), type of injury data (categorical or continuous), and study design. The view at the meeting was that multidisciplinary collaboration will be the cornerstone for future high-quality sport injury science. Working beyond professional silos in a diverse, multidisciplinary team benefits the research process. It promotes better research questions, more appropriate study design, and more rigorous statistical analysis. Collaboration also promotes dissemination of study results—a step toward implementation!

STUDY DETAILS

AUTHOR CONTRIBUTIONS: Drs Nielsen and Verhagen drafted the introduction and the methods. Drs Clarsen, Bahr, and Ardern drafted the "No Universal Sports Injury Definition Is Necessary" section. Drs Emery, Wedderkopp, Nettel-Aguirre, Palacios-Derflingher, and Casals drafted the "Which Statistical Approach Should I Choose?" section. Drs Verhagen, Bittencourt, Timpka, Whiteley, and Bolling drafted the "Sports Injuries Are Complex and Contextual" section. Drs Fagerland, van Dyk, Jacobsson, and Møller drafted the "Analyzing Longitudinal Data" section. Drs van Dyk, Soligard, Verhagen, Dahlström, and Shrier drafted the "Dealing With Recurrent or Subsequent Injury" section. Drs Palacios-Derflingher, Khan, Shrier, Wedderkopp, Bahr, and Stamatakis drafted the "Be Explicit About the Goal of Your Research: Are You Describing, Predicting, or Drawing a Causal Inference?" section and the "Frameworks Can Guide Researchers" section. All authors drafted the "Need for Multidisciplinary Teams and Collaborations" section. The content of these sections was merged by Drs Verhagen and Nielsen. All authors revised the article for important intellectual content.

DATA SHARING: There are no data in this manuscript.

PATIENT AND PUBLIC INVOLVEMENT: Patient partners were not involved in this project.

REFERENCES

1. Altman DG. The scandal of poor medical research. *BMJ*. 1994;308:283-284. https://doi.org/10.1136/bmj.308.6924.283
2. Altman DG. Statistical reviewing for medical journals. *Stat Med*. 1998;17:2661-2674. https://doi.org/10.1002/(sici)1097-0258(19981215)17:23<2661::aid-sim33>3.0.co;2-b
3. Andersen PK, Geskus RB, de Witte T, Putter H. Competing risks in epidemiology: possibilities and pitfalls. *Int J Epidemiol*. 2012;41:861-870. https://doi.org/10.1093/ije/dyr213
4. Andersen PK, Keiding N. Interpretability and importance of functionals in competing risks and multistate models. *Stat Med*. 2012;31:1074-1088. https://doi.org/10.1002/sim.4385
5. Bahr R. No injuries, but plenty of pain? On the methodology for recording overuse symptoms in sports. *Br J Sports Med*. 2009;43:966-972. https://doi.org/10.1136/bjsm.2009.066936
6. Bahr R, Clarsen B, Ekstrand J. Why we should focus on the burden of injuries and illnesses, not just their incidence. *Br J Sports Med*. 2018;52:1018-1021. https://doi.org/10.1136/bjsports-2017-098160
7. Bahr R, Krosshaug T. Understanding injury mechanisms: a key component of preventing injuries in sport. *Br J Sports Med*. 2005;39:324-329. https://doi.org/10.1136/bjsm.2005.018341
8. Bertelsen ML, Hulme A, Petersen J, et al. A framework for the etiology of running-related injuries. *Scand J Med Sci Sports*. 2017;27:1170-1180. https://doi.org/10.1111/sms.12883

9. Bittencourt NFN, Meeuwisse WH, Mendonça LD, Nettel-Aguirre A, Ocarino JM, Fonseca ST. Complex systems approach for sports injuries: moving from risk factor identification to injury pattern recognition—narrative review and new concept. *Br J Sports Med*. 2016;50:1309-1314. https://doi.org/10.1136/bjsports-2015-095850
10. Bolker BM, Brooks ME, Clark CJ, et al. Generalized linear mixed models: a practical guide for ecology and evolution. *Trends Ecol Evol*. 2009;24:127-135. https://doi.org/10.1016/j.tree.2008.10.008
11. Booth JG, Casella G, Friedl H, Hobert JP. Negative binomial loglinear mixed models. *Stat Model*. 2003;3:179-191. https://doi.org/10.1191/1471082X03st058oa
12. Burton P, Gurrin L, Sly P. Extending the simple linear regression model to account for correlated responses: an introduction to generalized estimating equations and multi-level mixed modelling. *Stat Med*. 1998;17:1261-1291. https://doi.org/10.1002/(sici)1097-0258(19980615)17:11<1261::aid-sim846>3.0.co;2-z
13. Casals M, Finch CF. Sports biostatistician: a critical member of all sports science and medicine teams for injury prevention. *Inj Prev*. 2017;23:423-427. https://doi.org/10.1136/injuryprev-2016-042211
14. Casals M, Langohr K, Carrasco JL, Rönnegård L. Parameter estimation of Poisson generalized linear mixed models based on three different statistical principles: a simulation study. *Stat Oper Res Trans*. 2015;39:281-308.
15. Chéron C, Leboeuf-Yde C, Le Scanff C, et al. Leisure-time sport and overuse injuries of extremities in children age 6–13, a 2.5 years prospective cohort study: the CHAMPS-study DK. *BMJ Open*. 2017;7:e012606. https://doi.org/10.1136/bmjopen-2016-012606
16. Chipman HA, George EI, McCulloch RE. BART: Bayesian additive regression trees. *Ann Appl Stat*. 2010;4:266-298. https://doi.org/10.1214/09-AOAS285
17. Clarsen B, Bahr R. Matching the choice of injury/illness definition to study setting, purpose and design: one size does not fit all! *Br J Sports Med*. 2014;48:510-512. https://doi.org/10.1136/bjsports-2013-093297
18. Clarsen B, Myklebust G, Bahr R. Development and validation of a new method for the registration of overuse injuries in sports injury epidemiology: the Oslo Sports Trauma Research Centre (OSTRC) Overuse Injury Questionnaire. *Br J Sports Med*. 2013;47:495-502. https://doi.org/10.1136/bjsports-2012-091524
19. Claudino JG, de Oliveira Capanema D, de Souza TV, Serrão JC, Machado Pereira AC, Nassis GP. Current approaches to the use of artificial intelligence for injury risk assessment and performance prediction in team sports: a systematic review. *Sports Med Open*. 2019;5:28. https://doi.org/10.1186/s40798-019-0202-3
20. Cronbach LJ, Furby L. How we should measure "change": or should we? *Psychol Bull*. 1970;74:68-80. https://doi.org/10.1037/h0029382
21. Ekstrand J, Lundqvist D, Davison M, D'Hooghe M, Pensgaard AM. Communication quality between the medical team and the head coach/manager is associated with injury burden and player availability in elite football clubs. *Br J Sports Med*. 2019;53:304-308. https://doi.org/10.1136/bjsports-2018-099411
22. Finch CF. An overview of some definitional issues for sports injury surveillance. *Sports Med*. 1997;24:157-163. https://doi.org/10.2165/00007256-199724030-00002
23. Fuller CW. Injury risk (burden), risk matrices and risk contours in team sports: a review of principles, practices and problems. *Sports Med*. 2018;48:1597-1606. https://doi.org/10.1007/s40279-018-0913-5
24. Fuller CW, Ekstrand J, Junge A, et al. Consensus statement on injury definitions and data collection procedures in studies of football (soccer) injuries. *Br J Sports Med*. 2006;40:193-201. https://doi.org/10.1136/bjsm.2005.025270
25. Fuller CW, Molloy MG, Bagate C, et al. Consensus statement on injury definitions and data collection procedures for studies of injuries in rugby union. *Br J Sports Med*. 2007;41:328-331. https://doi.org/10.1136/bjsm.2006.033282
26. Gunn JE, Shah SN. Big data and opportunities for injury surveillance. *Inj Prev*. 2016;22 suppl 1:i3-i5. https://doi.org/10.1136/injuryprev-2015-041789
27. Hernán MA. The C-word: scientific euphemisms do not improve causal inference from observational data. *Am J Public Health*. 2018;108:616-619. https://doi.org/10.2105/AJPH.2018.304337
28. Hernán MA, Hsu J, Healy B. A second chance to get causal inference right: a classification of data science tasks. *CHANCE*. 2019;32:42-49. https://doi.org/10.1080/09332480.2019.1579578
29. Hjerrild M, Videbaek S, Theisen D, Malisoux L, Oestergaard Nielsen R. How (not) to interpret a non-causal association in sports injury science. *Phys Ther Sport*. 2018;32:121-125. https://doi.org/10.1016/j.ptsp.2018.05.009
30. Hreljac A. Etiology, prevention, and early intervention of overuse injuries in runners: a biomechanical perspective. *Phys Med Rehabil Clin N Am*. 2005;16:651-667. https://doi.org/10.1016/j.pmr.2005.02.002
31. Huang X, Wolfe RA. A frailty model for informative censoring. *Biometrics*. 2002;58:510-520. https://doi.org/10.1111/j.0006-341x.2002.00510.x
32. Hulin BT. The never-ending search for the perfect acute:chronic workload ratio: what role injury definition? *Br J Sports Med*. 2017;51:991-992. https://doi.org/10.1136/bjsports-2016-097279
33. Hulme A, Finch CF. From monocausality to systems thinking: a complementary and alternative conceptual approach for better understanding the development and prevention of sports injury. *Inj Epidemiol*. 2015;2:31. https://doi.org/10.1186/s40621-015-0064-1
34. Hulme A, Thompson J, Nielsen RO, Read GJM, Salmon PM. Towards a complex systems approach in sports injury research: simulating running-related injury development with agent-based modelling. *Br J Sports Med*. 2019;53:560-569. https://doi.org/10.1136/bjsports-2017-098871
35. James G, Witten D, Hastie T, Tibshirani R. *An Introduction to Statistical Learning: With Applications in R*. New York, NY: Springer; 2013.
36. Jespersen E, Holst R, Franz C, Rexen CT, Klakk H, Wedderkopp N. Overuse and traumatic extremity injuries in schoolchildren surveyed with weekly text messages over 2.5 years. *Scand J Med Sci Sports*. 2014;24:807-813. https://doi.org/10.1111/sms.12095
37. Jespersen E, Holst R, Franz C, Rexen CT, Wedderkopp N. Seasonal variation in musculoskeletal extremity injuries in school children aged 6–12 followed prospectively over 2.5 years: a cohort study. *BMJ Open*. 2014;4:e004165. https://doi.org/10.1136/bmjopen-2013-004165
38. Johansen B, Wedderkopp N. Comparison between data obtained through real-time data capture by SMS and a retrospective telephone interview. *Chiropr Osteopat*. 2010;18:10. https://doi.org/10.1186/1746-1340-18-10
39. Junge T, Runge L, Juul-Kristensen B, Wedderkopp N. Risk factors for knee injuries in children 8 to 15 years: the CHAMPS study DK. *Med Sci Sports Exerc*. 2016;48:655-662. https://doi.org/10.1249/MSS.0000000000000814
40. King DA, Gabbett TJ, Gissane C, Hodgson L. Epidemiological studies of injuries in rugby league: suggestions for definitions, data collection and reporting methods. *J Sci Med Sport*. 2009;12:12-19. https://doi.org/10.1016/j.jsams.2007.12.001
41. Mansournia MA, Altman DG. Inverse probability weighting. *BMJ*. 2016;352:i189. https://doi.org/10.1136/bmj.i189
42. Mansournia MA, Etminan M, Danaei G, Kaufman JS, Collins G. Handling time varying confounding in observational research. *BMJ*. 2017;359:j4587. https://doi.org/10.1136/bmj.j4587
43. Meeuwisse WH, Tyreman H, Hagel B, Emery C. A dynamic model of etiology in sport injury: the recursive nature of risk and causation. *Clin J Sport Med*. 2007;17:215-219. https://doi.org/10.1097/JSM.0b013e3180592a48
44. Mendiguchia J, Alentorn-Geli E, Brughelli M. Hamstring strain injuries: are we heading in the right direction? *Br J Sports Med*. 2012;46:81-85. https://doi.org/10.1136/bjsm.2010.081695
45. Moons KG, Royston P, Vergouwe Y, Grobbee DE, Altman DG. Prognosis and prognostic research: what, why, and how? *BMJ*. 2009;338:b375. https://doi.org/10.1136/bmj.b375
46. Mountjoy M, Junge A, Alonso JM, et al. Consensus statement on the methodology of injury and illness surveillance in FINA (aquatic sports). *Br J Sports Med*. 2016;50:590-596. https://doi.org/10.1136/bjsports-2015-095686
47. Naimi AI, Cole SR, Kennedy EH. An introduction to g methods. *Int J Epidemiol*. 2017;46:756-762. https://doi.org/10.1093/ije/dyw323

48. Nauta J, Jespersen E, Verhagen E, van Mechelen W, Wedderkopp N. Upper extremity injuries in Danish children aged 6–12, mechanisms, and risk factors. *Scand J Med Sci Sports*. 2017;27:93-98. https://doi.org/10.1111/sms.12617
49. Nielsen RO, Bertelsen ML, Møller M, et al. Training load and structure-specific load: applications for sport injury causality and data analyses. *Br J Sports Med*. 2018;52:1016-1017. https://doi.org/10.1136/bjsports-2017-097838
50. Nielsen RO, Bertelsen ML, Ramskov D, et al. Time-to-event analysis for sports injury research part 1: time-varying exposures. *Br J Sports Med*. 2019;53:61-68. https://doi.org/10.1136/bjsports-2018-099408
51. Nielsen RO, Bertelsen ML, Ramskov D, et al. Time-to-event analysis for sports injury research part 2: time-varying outcomes. *Br J Sports Med*. 2019;53:70-78. https://doi.org/10.1136/bjsports-2018-100000
52. Nielsen RO, Bertelsen ML, Verhagen E, et al. When is a study result important for athletes, clinicians and team coaches/staff? *Br J Sports Med*. 2017;51:1454-1455. https://doi.org/10.1136/bjsports-2017-097759
53. Nielsen RO, Chapman CM, Louis WR, et al. Seven sins when interpreting statistics in sports injury science. *Br J Sports Med*. 2018;52:1410-1412. https://doi.org/10.1136/bjsports-2017-098524
54. Nielsen RO, Debes-Kristensen K, Hulme A, et al. Are prevalence measures better than incidence measures in sports injury research? *Br J Sports Med*. 2019;53:396-397. https://doi.org/10.1136/bjsports-2017-098205
55. Nielsen RØ, Malisoux L, Møller M, Theisen D, Parner ET. Shedding light on the etiology of sports injuries: a look behind the scenes of time-to-event analyses. *J Orthop Sports Phys Ther*. 2016;46:300-311. https://doi.org/10.2519/jospt.2016.6510
56. Olesen AV, Parner ET. Correcting for selection using frailty models. *Stat Med*. 2006;25:1672-1684. https://doi.org/10.1002/sim.2298
57. Orchard JW, Newman D, Stretch R, Frost W, Mansingh A, Leipus A. Methods for injury surveillance in international cricket. *Br J Sports Med*. 2005;39:e22. https://doi.org/10.1136/bjsm.2004.012732
58. Orchard JW, Ranson C, Olivier B, et al. International consensus statement on injury surveillance in cricket: a 2016 update. *Br J Sports Med*. 2016;50:1245-1251. https://doi.org/10.1136/bjsports-2016-096125
59. Philippe P, Mansi O. Nonlinearity in the epidemiology of complex health and disease processes. *Theor Med Bioeth*. 1998;19:591-607. https://doi.org/10.1023/a:1009979306346
60. Pluim BM, Fuller CW, Batt ME, et al. Consensus statement on epidemiological studies of medical conditions in tennis, April 2009. *Br J Sports Med*. 2009;43:893-897. https://doi.org/10.1136/bjsm.2009.064915
61. Pol R, Hristovski R, Medina D, Balague N. From microscopic to macroscopic sports injuries. Applying the complex dynamic systems approach to sports medicine: a narrative review. *Br J Sports Med*. 2019;53:1214-1220. https://doi.org/10.1136/bjsports-2016-097395
62. Putter H, Fiocco M, Geskus RB. Tutorial in biostatistics: competing risks and multi-state models. *Stat Med*. 2007;26:2389-2430. https://doi.org/10.1002/sim.2712
63. Quatman CE, Quatman CC, Hewett TE. Prediction and prevention of musculoskeletal injury: a paradigm shift in methodology. *Br J Sports Med*. 2009;43:1100-1107. https://doi.org/10.1136/bjsm.2009.065482
64. Richardson TS, Rotnitzky A. Causal etiology of the research of James M. Robins. *Stat Sci*. 2014;29:459-484. https://doi.org/10.1214/14-Sts505
65. Satagopan JM, Ben-Porat L, Berwick M, Robson M, Kutler D, Auerbach AD. A note on competing risks in survival data analysis. *Br J Cancer*. 2004;91:1229-1235. https://doi.org/10.1038/sj.bjc.6602102
66. Shakiba M, Mansournia MA, Salari A, Soori H, Mansournia N, Kaufman JS. Accounting for time-varying confounding in the relationship between obesity and coronary heart disease: analysis with G-estimation: the ARIC Study. *Am J Epidemiol*. 2018;187:1319-1326. https://doi.org/10.1093/aje/kwx360
67. Shmueli G. To explain or to predict? *Stat Sci*. 2010;25:289-310. https://doi.org/10.1214/10-STS330
68. Shrier I. Understanding causal inference: the future direction in sports injury prevention. *Clin J Sport Med*. 2007;17:220-224. https://doi.org/10.1097/JSM.0b013e3180385a8c
69. Shrier I, Platt RW. Reducing bias through directed acyclic graphs. *BMC Med Res Methodol*. 2008;8:70. https://doi.org/10.1186/1471-2288-8-70
70. Shrier I, Steele RJ, Zhao M, et al. A multistate framework for the analysis of subsequent injury in sport (M-FASIS). *Scand J Med Sci Sports*. 2016;26:128-139. https://doi.org/10.1111/sms.12493
71. Smoliga JM, Zavorsky GS. Team logo predicts concussion risk: lessons in protecting a vulnerable sports community from misconceived, but highly publicized epidemiologic research. *Epidemiology*. 2017;28:753-757. https://doi.org/10.1097/EDE.0000000000000694
72. Stovitz SD, Verhagen E, Shrier I. Distinguishing between causal and non-causal associations: implications for sports medicine clinicians. *Br J Sports Med*. 2019;53:398-399. https://doi.org/10.1136/bjsports-2017-098520
73. Stovitz SD, Verhagen E, Shrier I. Misinterpretations of the 'p value': a brief primer for academic sports medicine. *Br J Sports Med*. 2017;51:1176-1177. https://doi.org/10.1136/bjsports-2016-097072
74. Timpka T, Alonso JM, Jacobsson J, et al. Injury and illness definitions and data collection procedures for use in epidemiological studies in athletics (track and field): consensus statement. *Br J Sports Med*. 2014;48:483-490. https://doi.org/10.1136/bjsports-2013-093241
75. Timpka T, Ekstrand J, Svanström L. From sports injury prevention to safety promotion in sports. *Sports Med*. 2006;36:733-745. https://doi.org/10.2165/00007256-200636090-00002
76. Timpka T, Jacobsson J, Bickenbach J, Finch CF, Ekberg J, Nordenfelt L. What is a sports injury? *Sports Med*. 2014;44:423-428. https://doi.org/10.1007/s40279-014-0143-4
77. Turner M, Fuller CW, Egan D, et al. European consensus on epidemiological studies of injuries in the thoroughbred horse racing industry. *Br J Sports Med*. 2012;46:704-708. https://doi.org/10.1136/bjsports-2011-090312
78. Ullah S, Gabbett TJ, Finch CF. Statistical modelling for recurrent events: an application to sports injuries. *Br J Sports Med*. 2014;48:1287-1293. https://doi.org/10.1136/bjsports-2011-090803
79. Verhagen E, Stovitz SD, Mansournia MA, Nielsen RO, Shrier I. *BJSM* educational editorials: methods matter. *Br J Sports Med*. 2018;52:1159-1160. https://doi.org/10.1136/bjsports-2017-097998
80. Windt J, Ardern CL, Gabbett TJ, et al. Getting the most out of intensive longitudinal data: a methodological review of workload–injury studies. *BMJ Open*. 2018;8:e022626. https://doi.org/10.1136/bmjopen-2018-022626
81. Windt J, Gabbett TJ. How do training and competition workloads relate to injury? The workload–injury aetiology model. *Br J Sports Med*. 2017;51:428-435. https://doi.org/10.1136/bjsports-2016-096040
82. Yergens DW, Dutton DJ, Patten SB. An overview of the statistical methods reported by studies using the Canadian community health survey. *BMC Med Res Methodol*. 2014;14:15. https://doi.org/10.1186/1471-2288-14-15
83. Zhou Y, McArdle JJ. Rationale and applications of survival tree and survival ensemble methods. *Psychometrika*. 2015;80:811-833. https://doi.org/10.1007/s11336-014-9413-1

ANU M. RÄISÄNEN, PT, PhD[1] • **TANJA KULMALA,** PT, MHSc[2] • **JARI PARKKARI,** MD, PhD[3,4] • **TOMMI VASANKARI,** MD, PhD[2]
PEKKA KANNUS, MD, PhD[2,4] • **TRON KROSSHAUG,** PhD[5] • **URHO M. KUJALA,** MD, PhD[6]
ARI HEINONEN, PT, PhD[6] • **JOHANNA VESANTO,** PT, MHSc[6] • **KATI PASANEN,** PT, PhD[1,3,7,8]

There Is No Relationship Between Lower Extremity Alignment During Unilateral and Bilateral Drop Jumps and the Risk of Knee or Ankle Injury: A Prospective Study

OBJECTIVE: To investigate the association between lower extremity alignment during unilateral and bilateral drop jump tests and the risk of acute noncontact knee or ankle injuries in young team sport athletes.

DESIGN: Prospective cohort study.

METHODS: A 2-dimensional video analysis was used to measure the frontal plane knee projection angle in the single-leg vertical drop jump (VDJ) and the bilateral VDJ in young team sport athletes. Out of the 364 athletes (187 male, 177 female), 189 played basketball and 175 played floorball.

RESULTS: Six male athletes sustained knee injuries and 23 sustained ankle injuries. Frontal plane knee projection angle in the single-leg VDJ or the bilateral VDJ was not associated with ankle injuries among male athletes. No statistical analysis was performed for the knee injuries. Among female athletes, 28 sustained knee and 41 sustained ankle injuries. Frontal plane knee projection angle during the single-leg VDJ or the bilateral VDJ was not a risk factor for knee or ankle injuries.

CONCLUSION: Lower extremity alignment during unilateral and bilateral drop jump tests was not associated with future noncontact knee or ankle injuries among young team sport athletes. The findings should be interpreted cautiously due to the small number of injuries. *J Orthop Sports Phys Ther 2020;50(5):267-274. doi:10.2519/jospt.2020.9247*

KEY WORDS: *landing, movement control, risk factors, screening tool, valgus*

Noncontact ankle and knee injuries are common in team sports requiring frequent directional changes, accelerations, and decelerations.[12,13,15,32] These injuries can have substantial negative effects on the future health of athletes, including predisposing them to osteoarthritis in the injured joint.[50,52] To improve injury prevention practices, it is important to identify modifiable risk factors.

Controlling lower extremity alignment during athletic tasks is an essential component of movement. Insufficient capability to control medial and lateral knee motion can increase the mechanical loads experienced by soft tissue structures, including the knee ligaments.[19,26,56] There is conflicting evidence as to whether poor lower extremity alignment (ie, knee moving toward valgus) during single-leg and bilateral landing tasks is a risk factor for knee injury.[6,22,23,37,38]

In elite female soccer players, increased knee valgus during a bilateral landing may reduce the risk of ankle injuries.[37] Because acute noncontact ankle injuries are common in team sports,[15] exploring the relationship between lower extremity alignment during drop jump landings and ankle injuries is warranted. Landing on 1 leg from a jump has recently attracted research focus. Unilateral and bilateral landings differ in their joint angles,[9,35,39] joint moments,[56] muscle activation,[39] and energy dissipation strategies.[56] Therefore, the injury risk profiles of athletes may differ across landing tasks.[9]

There is a need to move from laboratory-identified injury risk factors to techniques that can be implemented into clinical practice.[1] Two-dimensional (2-D) video analysis methods are suitable for quantifying frontal plane knee motions.[28,30,33] The equipment is portable

[1]Sport Injury Prevention Research Centre Faculty of Kinesiology, University of Calgary, Calgary, Canada. [2]UKK Institute for Health Promotion Research, Tampere, Finland. [3]Tampere Research Center of Sport Medicine, UKK Institute for Health Promotion Research, Tampere, Finland. [4]Tampere University Hospital, Tampere, Finland. [5]Oslo Sports Trauma Research Center, Norwegian School of Sport Sciences, Oslo, Norway. [6]Faculty of Sport and Health Sciences, University of Jyväskylä, Jyväskylä, Finland. [7]Alberta Children's Hospital Research Institute, University of Calgary, Calgary, Canada. [8]McCaig Institute for Bone and Joint Health, Cumming School of Medicine, University of Calgary, Calgary, Canada. The study was approved by the Ethics Committee of Pirkanmaa Hospital District (ETL code R10169). This study was financially supported by the Finnish Ministry of Education and Culture and the Competitive State Research Financing of the Expert Responsibility Area of Tampere University Hospital (grants 9N053, 9S047, and 9T046). The authors certify that they have no affiliations with or financial involvement in any organization or entity with a direct financial interest in the subject matter or materials discussed in the article. Address correspondence to Dr Anu M. Räisänen, Sport Injury Prevention Research Centre, Faculty of Kinesiology, University of Calgary, 2500 University Drive NW, Calgary, AB T2N 1N4 Canada. E-mail: Anu.raisanen@ucalgary.ca

and easy to set up and use in a clinical or field setting.

We aimed to investigate whether frontal plane knee projection angle (FPKPA) during the single-leg vertical drop jump (VDJ) and bilateral VDJ was associated with increased risk of acute noncontact knee and ankle injuries in young basketball and floorball athletes.

METHODS

Study Design and Participants

This study is part of a large prospective cohort study.[41] Teams from the 2 highest youth league levels from 3 basketball and 3 floorball clubs were invited to participate. The inclusion criteria were being 21 years of age or younger, an official team member, and free from injury at baseline. Athletes were considered to be injury free if they did not report injuries in the baseline questionnaire and were able to fully participate in baseline testing. Athletes entered the study during the preseason of 2011, 2012, and 2013 (**FIGURE 1**). After baseline testing at the UKK Institute for Health Promotion Research (Tampere, Finland), injury registration continued until the end of April 2014. The average ± SD follow-up time was 16.9 ± 9.5 months, with 56% of athletes completing at least 12 months, 18% completing at least 24 months, and 14% completing 36 months of injury registration.

Ethical approval was granted by the Ethics Committee of Pirkanmaa Hospital District (ETL code R10169). Informed written consent was obtained from each participant or from the legal guardians of athletes younger than 18 years of age. The rights of participants were protected throughout the study.

Unilateral and Bilateral VDJ Procedures

Baseline measurements of standing height (centimeters), weight (kilograms), and leg dominance (preferred leg to kick a ball) were recorded. Each athlete completed a questionnaire about the lower extremity time-loss injuries they had sustained during the previous 12 months.[41]

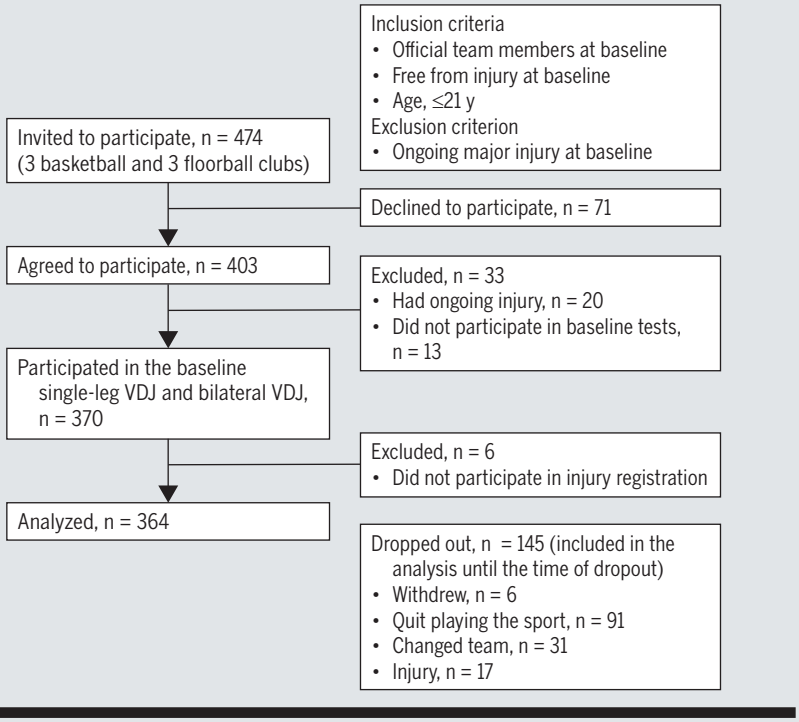

FIGURE 1. Flow of participants. Abbreviation: VDJ, vertical drop jump.

The single-leg VDJ and bilateral VDJ test procedures are based on the work of Stensrud and colleagues.[48] Participants wore shorts and indoor shoes, and female participants wore sports bras. For the 2-D video analysis, square pieces of sports tape were placed on the right and left tibial tuberosity and right and left anterior superior iliac spine (ASIS). As a standardized warm-up, athletes performed a series of double-leg squats (2 × 8), followed by squat jumps (2 × 5). Participants familiarized themselves with the tests by performing 2 to 3 practice repetitions prior to testing. For each test, participants performed 2 or 3 valid trials, the mean value of which was calculated for each leg.

In the single-leg VDJ, athletes stood on a 10-cm box in a unilateral stance, dropped off the box on the weight-bearing leg, and performed a maximal vertical jump on the same leg. Athletes were instructed to jump as high as possible and attempt to touch an overhead target at an unobtainable height, reaching with both hands and landing unilaterally. A trial was invalid when the athlete jumped instead of dropping off the box, touched the contralateral leg to the floor, reached with only 1 hand, or clearly lost balance or fell during the test. For the bilateral VDJ, athletes dropped off a 30-cm box and landed on both feet, then performed a maximal vertical jump, reaching toward the overhead goal.

Two-Dimensional Video Analysis

Each trial was recorded with a high-definition digital video camera (HXR-NX70E; Sony, Tokyo, Japan) positioned on a tripod at a distance of 7 m.[41] A single investigator (J.V.), blinded to the participant's injury status, analyzed the video footage using Java-based computer software (ImageJ; National Institutes of Health, Bethesda, MD). From the initial landing, knee flexion was visually assessed, based on the lowest point of pelvis height.[6,48] From this frame, the FPKPA was calculated as the intersection of a line created by the ASIS and knee joint

center and the line created by the knee joint center and the ankle joint center.[6,7,21] Neutral alignment was considered 0°, positive values represented valgus alignment, and negative values represented varus alignment.

Injury and Exposure Registration

A team coach or another designated team member recorded all acute noncontact lower extremity injuries that resulted in an athlete being unable to fully participate in training or match play for at least 24 hours.[18] We analyzed knee and ankle injuries. A noncontact injury was an injury occurring without direct contact to the injured body part. For injury registration, the study physicians contacted the team coach or designate on a weekly basis by phone or e-mail. Next, each injured athlete was contacted for a standardized phone interview to record the injury time, place, cause, type, location, and time loss. To report exposure, the team coach or designate recorded the athlete's participation in team practices and games, and e-mailed the records to the study group at the end of each month.

Statistical Methods

Analyses were performed in SPSS (SPSS Statistics 25; IBM Corporation, Armonk, NY), with the exception of the Cox regression models (R Version 3.5.1, package coxme[49]; R Foundation for Statistical Computing, Vienna, Austria). Initially, body mass index,[45] age,[47] sport,[40] number of acute lower extremity injuries during the previous year,[51,55] and level of play[11,12,43] (defined as playing at the highest adult league level at least once) were considered to be potential confounders. Considering previous research and the characteristics of the study cohort, potential confounders were rated by importance, and 1 or 2 confounders for each injury type for male and female participants were entered into the Cox regression models, following the recommendation of not exceeding 10 events per independent variable.[42] Leg was the unit of analysis. Team and leg were used as random effects. Because the rates of and risk factors for knee and ankle injuries differ between sexes, we performed separate analyses for male and female athletes.

RESULTS

Complete baseline test data and injury data were obtained from 364 athletes. Baseline characteristics by sex are described in **TABLE 1**. In the single-leg VDJ, the FPKPA could not be calculated in 19 athletes for 1 (n = 15) and 2 (n = 4) legs, due to the ASIS markers not being visible during the initial landing or the athlete landing with too much rotation to determine the ankle joint center. For the bilateral VDJ, the FPKPA could not be calculated in 20 athletes for 1 (n = 13) or 2 (n = 7) legs, due to the ASIS markers not being visible.

During the follow-up, 176 acute noncontact lower extremity injuries were registered. A total of 112 (31%) athletes sustained at least 1 noncontact lower extremity injury. The ankle was the body part with the highest percentage of injuries (49%), followed by the knee (22%) and the hip (9%). The severity of knee and ankle injuries[18] is reported in **TABLE 2**.

Noncontact Knee Injuries

Six male athletes sustained 7 knee injuries: 3 meniscus injuries, 2 hyperextension injuries, 1 lateral collateral ligament sprain, and 1 patellar subluxation. Mean FPKPA in the single-leg VDJ was 9.4° ± 11.0° for the injured group and 5.4° ± 5.2° for the uninjured group. Distribution of FPKPA values for the single-leg VDJ is presented in **FIGURE 2**. In the bilateral VDJ, mean ± SD FPKPA was 1.7° ± 9.3° for the injured group and 2.8° ± 8.1° for the uninjured group. Distribution of FPKPA values for the bilateral VDJ is presented in **FIGURE 3**. Due to the small number of knee injuries, it was not possible to perform statistical analysis of knee injury risk factors among male athletes.

Twenty-eight female athletes sustained 31 noncontact knee injuries: 17 anterior cruciate ligament ruptures, 2 medial collateral ligament sprains, 1 meniscus injury, 1 lateral collateral ligament sprain, 1 bone

TABLE 1 Basic Characteristics of the Athletes[a]

Characteristic	Male (n = 187)	Female (n = 177)
Age, y	16.0 ± 1.6	15.5 ± 2.0
Height, cm	178.5 ± 8.1	167.4 ± 6.2
Weight, kg	68.9 ± 10.7	60.8 ± 8.3
Body mass index, kg/m^2	21.5 ± 2.6	21.7 ± 2.7
Time playing the sport, y	8.1 ± 3.1	6.3 ± 2.5

[a]*Values are mean ± SD.*

TABLE 2 Severity of Noncontact Knee and Ankle Injuries[a]

	Minimal (1-3 d)	Mild (4-7 d)	Moderate (8-28 d)	Severe (>28 d)	Total
Male					
Knee	1	2	0	4	7
Ankle	5	11	7	5	28
Female					
Knee	2	1	8	20	31
Ankle	14	9	18	17	58

[a]*Values are number of injuries.*

bruise, 1 knee distortion, 1 hyperextension injury, and 7 minor knee injuries for which the athlete did not seek medical attention. The mean ± SD FPKPA for the single-leg VDJ was 7.4° ± 5.2° in the injured group and 7.5° ± 5.0° in the uninjured group. The mean FPKPA for the bilateral VDJ was 5.1° ± 10.9° in the injured group and 8.1° ± 8.4° in the uninjured group. The distribution of FPKPAs is presented in **FIGURES 4** and **5**. The FPKPA for both the single-leg VDJ and the bilateral VDJ was not associated with risk of knee injury in female athletes (**TABLE 3**).

Noncontact Ankle Injuries

Twenty-three male athletes sustained 28 noncontact ankle injuries: 26 lateral ligament sprains, 1 medial ligament sprain, and 1 bone bruise. Mean FPKPA for the single-leg VDJ was 4.7° ± 5.2° in the injured group and 5.7° ± 5.5° in the uninjured group. The mean FPKPA for the bilateral VDJ was 0.8° ± 9.0° in the injured group and 3.0° ± 8.0° in the uninjured group. The FPKPA was not associated with ankle injuries in male athletes (**TABLE 3**).

Forty-one female athletes sustained 58 ankle injuries: 54 lateral ligament sprains, 2 medial ligament sprains, 1 syndesmosis ligament sprain, and 1 ankle fracture. The mean FPKPA for the single-leg VDJ was 6.5° ± 5.6° in the injured group and 7.8° ± 4.7° in the uninjured group. The mean ± SD FPKPA for the bilateral VDJ was 6.5° ± 5.6° in the injured group and 8.2° ± 8.7° in the uninjured group. There was no association between FPKPA and new ankle injury (**TABLE 3**).

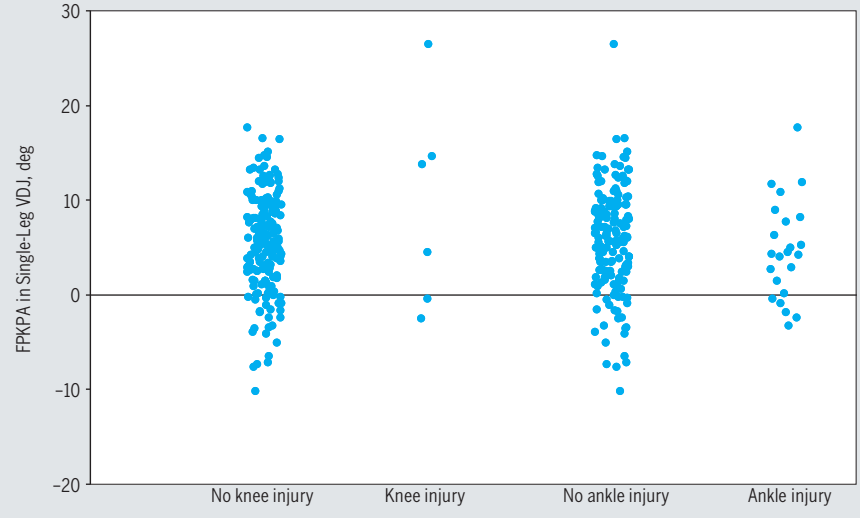

FIGURE 2. Distribution of FPKPAs in the single-leg VDJ for injured and uninjured male athletes. Abbreviations: FPKPA, frontal plane knee projection angle; VDJ, vertical drop jump.

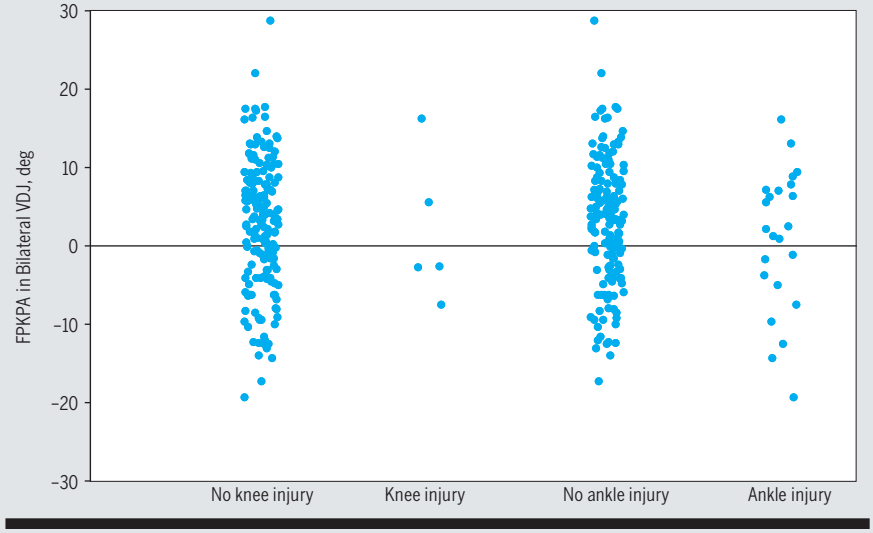

FIGURE 3. Distribution of FPKPAs in the bilateral VDJ for injured and uninjured male athletes. Abbreviations: FPKPA, frontal plane knee projection angle; VDJ, vertical drop jump.

DISCUSSION

There was no association between FPKPA at the initial landing for the single-leg VDJ or bilateral VDJ, and no association between FPKPA and the risk of noncontact knee injury or ankle injury in youth male and female floorball and basketball players.

Previous studies using 2-D analysis of the single-leg VDJ have focused on female athletes[6,38] and reported significant differences between injured and uninjured athletes. However, comparisons between studies are difficult to make, due to the differences in study methods. In our study, the FPKPAs for the single-leg VDJ and bilateral VDJ in injured and uninjured players overlap. The tests failed to separate the athletes into 2 distinctly different groups, as one would expect if test performance were associated with injury risk.[2]

The premise of functional movement tests, such as the single-leg VDJ and bilateral VDJ, is to identify athletes who are at high risk of injury.[4,16,17] If an entire team could be easily screened using simple field tests, injury prevention efforts could focus on high-risk athletes, for whom injury prevention programs are the best prophylactic.[34] However, our study does not support the use of the single-leg VDJ or the bilateral VDJ to screen for high-risk athletes. A screening test with high sensitivity to identify ath-

letes who are most likely to get injured is crucial.[53] A screening test with high specificity would ensure that only a few athletes who are not at high risk would be incorrectly categorized as high risk.

Hewett and colleagues[22] reported a significant association between the bilateral VDJ performance and increased risk of anterior cruciate ligament injury, with acceptable specificity and sensitivity. However, this has not been repeated in later studies on adult[23] or adolescent[24] female athletes. Even with acceptable specificity and sensitivity, the results of the injured and uninjured players overlap.[2] Considering the multifactorial nature of sport injuries,[29] identifying who will get injured based on a dynamic movement task seems unattainable. However, assessing the drop jump performance can provide useful information for the clinician, athlete, and coach.

Instead of large-scale screenings, the drop jump tests could be used to identify maladaptive movement patterns, to assess the results of movement retraining protocols,[20] and to assess the athlete's readiness to return to play.[3] In the clinical setting, observation of movement quality in drop jumps can be a suitable method to assess the athlete's movement patterns.[10,36,48] Future studies could use video analysis methods to explore the possibility to set return-to-play guidelines using the single-leg VDJ and the bilateral VDJ, among other dynamic movement tasks.

The FPKPA in VDJ tests was not associated with the risk of ankle injuries. Our decision to study ankle injuries was based on a previous finding that poor lower extremity alignment during the bilateral VDJ was associated with a lower risk of ankle injuries.[37] Therefore, we were interested in knowing whether this surprising finding could be reproduced in a younger cohort. Limitations in ankle function, such as limited ankle dorsiflexion range of motion, contribute to frontal plane[46] and sagittal plane[14] kinematics during landings. However, measuring the FPKPA alone during landing tasks does not seem to provide valuable information about ankle function. It is possible that the limitations in ankle function that contribute to landing kinematics do not increase the risk of ankle injuries and, rather, contribute to the increased risk of knee injuries.[27] If the ankle does not adequately help to attenuate energy, then the knee must absorb more energy, which could make the knee more susceptible to injury.

We included basketball and floorball players, as frequent directional changes are typical in both sports. In floorball, jumping is very infrequent, and one could expect floorball players to have a reduced ability to control lower extremity alignment during landing tasks when compared to basketball players, who are exposed to frequent jumping. However, youth basketball players may have greater knee valgus angles in a bilateral drop jump than youth floorball players.[25] Therefore, combining data from floorball and basketball athletes is unlikely to be a major source of bias.

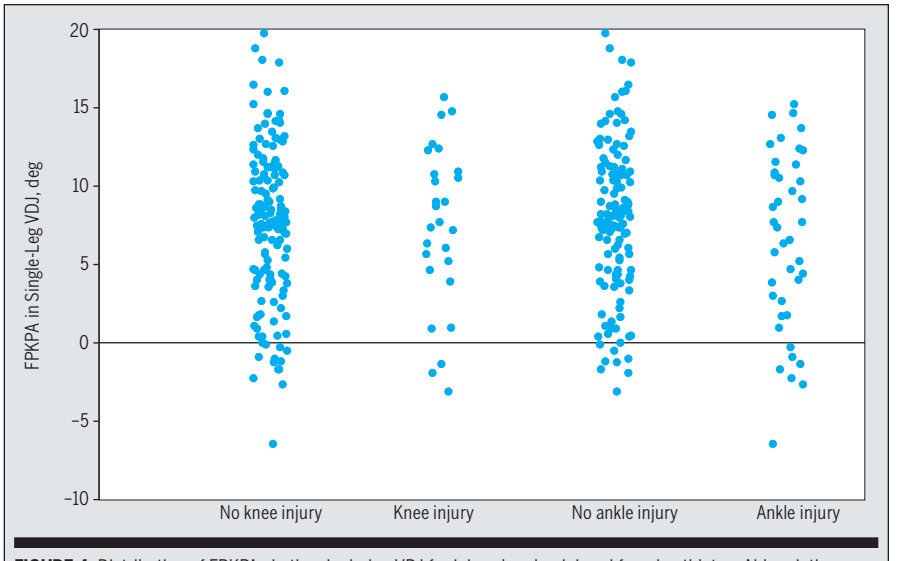

FIGURE 4. Distribution of FPKPAs in the single-leg VDJ for injured and uninjured female athletes. Abbreviations: FPKPA, frontal plane knee projection angle; VDJ, vertical drop jump.

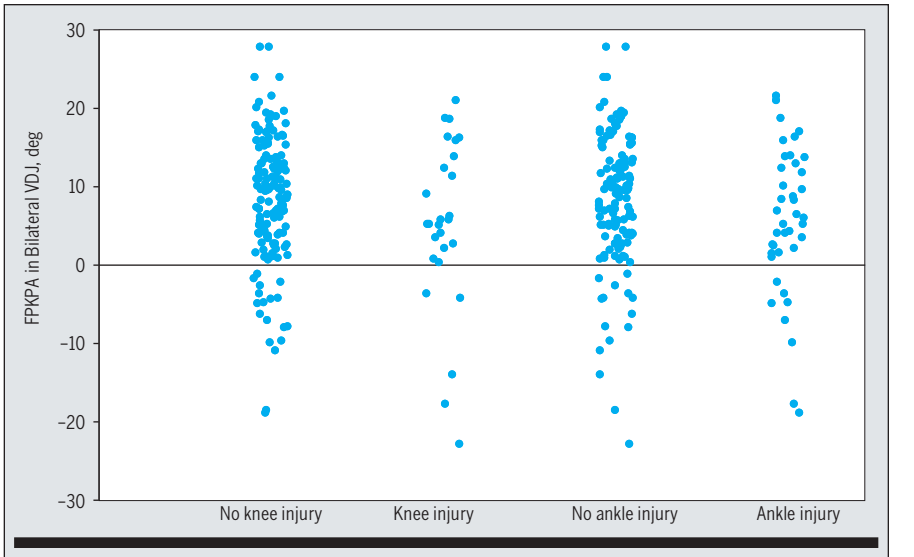

FIGURE 5. Distribution of FPKPAs in the bilateral VDJ for injured and uninjured female athletes. Abbreviations: FPKPA, frontal plane knee projection angle; VDJ, vertical drop jump.

Strengths and Limitations

We studied a large cohort with weekly prospective injury collection over a 3-year period. A single investigator, blinded to injury status, completed the video analysis. The 2-D video analysis method has been previously validated against 3-D motion analysis and is suitable for measuring movements occurring primarily in the frontal plane.[28] Despite the fact that transverse plane motions cannot be measured with a single-camera setup, the 2-D video analysis method is useful for measuring lower extremity alignment during functional tasks.[8,31,33,48,54]

A limitation is the small number of injuries and possibility of type II error. Fifty-six percent of the athletes completed at least a 12-month follow-up, and 32% were followed for a longer period. For a risk factor study, 12 months might be considered a short follow-up; during a longer follow-up, we would expect a greater proportion of athletes to sustain injury, increasing the statistical power. However, the athlete's performance of dynamic tasks, such as a drop jump, could change over a long follow-up. Future studies should consider longer follow-up periods to account for repeated testing and possibly combining FPKPA with trunk lateral motion.

Some athletes rotated their body during the initial landing as they prepared for the maximal jump. Trunk rotation can affect the values of the FPKPA. Rotation could have contributed to the large range of FPKPAs that we observed in the drop jumps. The ASIS markers were not always visible during greater knee flexion angles. For these reasons, we chose to exclude the data of some players from the injury risk analysis. To assess whether the excluded individuals were at higher risk, we compared the proportions of the excluded athletes in the injured and uninjured groups and did not detect significant differences.

We used the ASIS to mark the line from the center of the knee joint to the hip.[6,7,38] Because the ASIS is located more laterally than the hip joint center, our definition of zero alignment differed slightly from the standard definition, which uses the hip joint center for marker placement. As a result, our study measured higher knee valgus degrees compared with those of studies that used the hip joint center to measure frontal plane projection angles.

We used the mean of valid trials instead of the greatest FPKPA. Previous studies have used visual observation of functional tasks to rate the movement based on the poorest performance.[44,48] It is possible that using the mean may disguise the poorer performances of the task, which could bias the risk analysis. Focusing on lower extremity alignment alone and not considering the kinetic chain perspective may not comprehensively assess injury risk.[5-7] In future studies, the FPKPA should be combined with measures to assess the control of other body parts, such as the trunk or the pelvis.

CONCLUSION

Frontal plane knee projection angle during unilateral and bilateral drop jumps should not be used as a screening tool to identify youth athletes at high risk of knee or ankle injury. These results need to be interpreted with caution due to the limited number of injuries. ◉

KEY POINTS

FINDINGS: Frontal plane lower extremity alignment during the single-leg or the bilateral vertical drop jump was not associated with an increased risk of acute noncontact knee or ankle injury in young team sport athletes.

IMPLICATIONS: Two-dimensional video analysis of lower extremity alignment in the single-leg or the bilateral drop jump should not be used to screen athletes for increased risk of knee or ankle injury.

CAUTION: Due to the small number of injuries, the association between frontal plane alignment and lower extremity injury might have been underestimated. Future meta-analyses may present evidence to support these findings.

TABLE 3 Hazard Ratios for Frontal Plane Knee Projection Angle Derived From Separate Cox Regression Models for Single-Leg and Bilateral VDJs

	Male[ab]	Female[b]	
	Ankle Injuries	Ankle Injuries[c]	Knee Injuries[d]
Single-leg VDJ	0.96 (0.90, 1.02)	0.98 (0.93, 1.03)	0.99 (0.94, 1.05)
Bilateral VDJ	0.97 (0.93, 1.01)	1.01 (0.98, 1.04)	0.99 (0.96, 1.02)

Abbreviation: VDJ, vertical drop jump.
[a]*Adjusted for age. Due to the small number of male athletes with knee injuries (n = 6), it was not possible to analyze knee injury risk factors among male athletes.*
[b]*Values in parentheses are 95% confidence interval.*
[c]*Adjusted for the number of previous injuries and playing at the elite level at least once.*
[d]*Adjusted for the number of previous injuries.*

STUDY DETAILS

AUTHOR CONTRIBUTIONS: All authors contributed to study concept and design. Dr Pasanen was responsible for conducting the data acquisition. Johanna Vesanto was responsible for the 2-D video analysis. Dr Räisänen, Tanja Kulmala, and Johanna Vesanto were responsible for data preparation. Drs Räisänen and Pasanen and Tanja Kulmala were responsible for the data analysis and interpretation. Dr Räisänen was responsible for writing the first draft of the manuscript. Tanja Kulmala, Drs Parkkari, Vasankari, Kannus, Krosshaug, Kujala, and Heinonen, Johanna Vesanto, and

Dr Pasanen were significant manuscript revisers. All authors approved the submitted version of the manuscript. Dr Räisänen is the guarantor.

DATA SHARING: There are no data available.

PATIENT AND PUBLIC INVOLVEMENT: There was no patient and public involvement in the study.

ACKNOWLEDGMENTS: *We would like to thank the athletes, coaches, and contact persons of each participating team for their excellent cooperation. We are grateful to research coordinator Irja Lahtinen, PT for conducting the baseline testing and exposure registration. We are also thankful to the study physicians Jussi Hietamo, MD and Teemu Ekola, MD for their efforts on the injury registration. We wish to thank statistician Kari Tokola, MSc for his invaluable contribution to the statistical analysis.*

REFERENCES

1. Aerts I, Cumps E, Verhagen E, Verschueren J, Meeusen R. A systematic review of different jump-landing variables in relation to injuries. *J Sports Med Phys Fitness*. 2013;53:509-519.
2. Bahr R. Why screening tests to predict injury do not work—and probably never will...: a critical review. *Br J Sports Med*. 2016;50:776-780. https://doi.org/10.1136/bjsports-2016-096256
3. Clarsen B, Berge HM. Screening is dead. Long live screening! *Br J Sports Med*. 2016;50:769. https://doi.org/10.1136/bjsports-2016-096475
4. Dallinga JM, Benjaminse A, Lemmink KA. Which screening tools can predict injury to the lower extremities in team sports? A systematic review. *Sports Med*. 2012;42:791-815. https://doi.org/10.2165/11632730-000000000-00000
5. DiCesare CA, Bates NA, Myer GD, Hewett TE. The validity of 2-dimensional measurement of trunk angle during dynamic tasks. *Int J Sports Phys Ther*. 2014;9:420-427.
6. Dingenen B, Malfait B, Nijs S, et al. Can two-dimensional video analysis during single-leg drop vertical jumps help identify non-contact knee injury risk? A one-year prospective study. *Clin Biomech (Bristol, Avon)*. 2015;30:781-787. https://doi.org/10.1016/j.clinbiomech.2015.06.013
7. Dingenen B, Malfait B, Vanrenterghem J, Verschueren SM, Staes FF. The reliability and validity of the measurement of lateral trunk motion in two-dimensional video analysis during unipodal functional screening tests in elite female athletes. *Phys Ther Sport*. 2014;15:117-123. https://doi.org/10.1016/j.ptsp.2013.05.001
8. Dingenen B, Staes FF, Santermans L, et al. Are two-dimensional measured frontal plane angles related to three-dimensional measured kinematic profiles during running? *Phys Ther Sport*. 2018;29:84-92. https://doi.org/10.1016/j.ptsp.2017.02.001
9. Donohue MR, Ellis SM, Heinbaugh EM, Stephenson ML, Zhu Q, Dai B. Differences and correlations in knee and hip mechanics during single-leg landing, single-leg squat, double-leg landing, and double-leg squat tasks. *Res Sports Med*. 2015;23:394-411. https://doi.org/10.1080/15438627.2015.1076413
10. Ekegren CL, Miller WC, Celebrini RG, Eng JJ, Macintyre DL. Reliability and validity of observational risk screening in evaluating dynamic knee valgus. *J Orthop Sports Phys Ther*. 2009;39:665-674. https://doi.org/10.2519/jospt.2009.3004
11. Emery CA, Meeuwisse WH. Injury rates, risk factors, and mechanisms of injury in minor hockey. *Am J Sports Med*. 2006;34:1960-1969. https://doi.org/10.1177/0363546506290061
12. Emery CA, Meeuwisse WH, Hartmann SE. Evaluation of risk factors for injury in adolescent soccer: implementation and validation of an injury surveillance system. *Am J Sports Med*. 2005;33:1882-1891. https://doi.org/10.1177/0363546505279576
13. Faude O, Rößler R, Junge A. Football injuries in children and adolescent players: are there clues for prevention? *Sports Med*. 2013;43:819-837. https://doi.org/10.1007/s40279-013-0061-x
14. Fong CM, Blackburn JT, Norcross MF, McGrath M, Padua DA. Ankle-dorsiflexion range of motion and landing biomechanics. *J Athl Train*. 2011;46:5-10. https://doi.org/10.4085/1062-6050-46.1.5
15. Fong DT, Hong Y, Chan LK, Yung PS, Chan KM. A systematic review on ankle injury and ankle sprain in sports. *Sports Med*. 2007;37:73-94. https://doi.org/10.2165/00007256-200737010-00006
16. Fox AS, Bonacci J, McLean SG, Saunders N. Efficacy of ACL injury risk screening methods in identifying high-risk landing patterns during a sport-specific task. *Scand J Med Sci Sports*. 2017;27:525-534. https://doi.org/10.1111/sms.12715
17. Fox AS, Bonacci J, McLean SG, Spittle M, Saunders N. A systematic evaluation of field-based screening methods for the assessment of anterior cruciate ligament (ACL) injury risk. *Sports Med*. 2016;46:715-735. https://doi.org/10.1007/s40279-015-0443-3
18. Fuller CW, Ekstrand J, Junge A, et al. Consensus statement on injury definitions and data collection procedures in studies of football (soccer) injuries. *Br J Sports Med*. 2006;40:193-201. https://doi.org/10.1136/bjsm.2005.025270
19. Gardiner JC, Weiss JA, Rosenberg TD. Strain in the human medial collateral ligament during valgus loading of the knee. *Clin Orthop Relat Res*. 2001:266-274. https://doi.org/10.1097/00003086-200110000-00031
20. Herrington L. The effects of 4 weeks of jump training on landing knee valgus and crossover hop performance in female basketball players. *J Strength Cond Res*. 2010;24:3427-3432. https://doi.org/10.1519/JSC.0b013e3181c1fcd8
21. Herrington L, Munro A. Drop jump landing knee valgus angle; normative data in a physically active population. *Phys Ther Sport*. 2010;11:56-59. https://doi.org/10.1016/j.ptsp.2009.11.004
22. 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*. 2005;33:492-501. https://doi.org/10.1177/0363546504269591
23. Krosshaug T, Steffen K, Kristianslund E, et al. The vertical drop jump is a poor screening test for ACL injuries in female elite soccer and handball players: a prospective cohort study of 710 athletes. *Am J Sports Med*. 2016;44:874-883. https://doi.org/10.1177/0363546515625048
24. Leppänen M, Pasanen K, Kujala UM, et al. Stiff landings are associated with increased ACL injury risk in young female basketball and floorball players. *Am J Sports Med*. 2017;45:386-393. https://doi.org/10.1177/0363546516665810
25. Leppänen M, Pasanen K, Kulmala JP, et al. Knee control and jump-landing technique in young basketball and floorball players. *Int J Sports Med*. 2016;37:334-338. https://doi.org/10.1055/s-0035-1565104
26. Markolf KL, Burchfield DM, Shapiro MM, Shepard MF, Finerman GA, Slauterbeck JL. Combined knee loading states that generate high anterior cruciate ligament forces. *J Orthop Res*. 1995;13:930-935. https://doi.org/10.1002/jor.1100130618
27. Mason-Mackay AR, Whatman C, Reid D. The effect of reduced ankle dorsiflexion on lower extremity mechanics during landing: a systematic review. *J Sci Med Sport*. 2017;20:451-458. https://doi.org/10.1016/j.jsams.2015.06.006
28. McLean SG, Walker K, Ford KR, Myer GD, Hewett TE, van den Bogert AJ. Evaluation of a two dimensional analysis method as a screening and evaluation tool for anterior cruciate ligament injury. *Br J Sports Med*. 2005;39:355-362. https://doi.org/10.1136/bjsm.2005.018598
29. Meeuwisse WH, Tyreman H, Hagel B, Emery C. A dynamic model of etiology in sport injury: the recursive nature of risk and causation. *Clin J Sport Med*. 2007;17:215-219. https://doi.org/10.1097/JSM.0b013e3180592a48
30. Miller A, Callister R. Reliable lower limb musculoskeletal profiling using easily operated, portable equipment. *Phys Ther Sport*. 2009;10:30-37. https://doi.org/10.1016/j.ptsp.2008.10.003
31. Mizner RL, Chmielewski TL, Toepke JJ, Tofte KB. Comparison of 2-dimensional measurement techniques for predicting knee angle and moment during a drop vertical jump. *Clin J Sport Med*. 2012;22:221-227. https://doi.org/10.1097/JSM.0b013e31823a46ce
32. Moller M, Attermann J, Myklebust G, Wedderkopp

N. Injury risk in Danish youth and senior elite handball using a new SMS text messages approach. *Br J Sports Med*. 2012;46:531-537. https://doi.org/10.1136/bjsports-2012-091022
33. Munro A, Herrington L, Carolan M. Reliability of 2-dimensional video assessment of frontal-plane dynamic knee valgus during common athletic screening tasks. *J Sport Rehabil*. 2012;21:7-11. https://doi.org/10.1123/jsr.21.1.7
34. Myer GD, Ford KR, Brent JL, Hewett TE. Differential neuromuscular training effects on ACL injury risk factors in "high-risk" versus "low-risk" athletes. *BMC Musculoskelet Disord*. 2007;8:39. https://doi.org/10.1186/1471-2474-8-39
35. Nagano Y, Ida H, Akai M, Fukubayashi T. Biomechanical characteristics of the knee joint in female athletes during tasks associated with anterior cruciate ligament injury. *Knee*. 2009;16:153-158. https://doi.org/10.1016/j.knee.2008.10.012
36. Nilstad A, Andersen TE, Bahr R, Holme I, Steffen K. Risk factors for lower extremity injuries in elite female soccer players. *Am J Sports Med*. 2014;42:940-948. https://doi.org/10.1177/0363546513518741
37. Nilstad A, Andersen TE, Kristianslund E, et al. Physiotherapists can identify female football players with high knee valgus angles during vertical drop jumps using real-time observational screening. *J Orthop Sports Phys Ther*. 2014;44:358-365. https://doi.org/10.2519/jospt.2014.4969
38. Numata H, Nakase J, Kitaoka K, et al. Two-dimensional motion analysis of dynamic knee valgus identifies female high school athletes at risk of non-contact anterior cruciate ligament injury. *Knee Surg Sports Traumatol Arthrosc*. 2018;26:442-447. https://doi.org/10.1007/s00167-017-4681-9
39. Pappas E, Hagins M, Sheikhzadeh A, Nordin M, Rose D. Biomechanical differences between unilateral and bilateral landings from a jump: gender differences. *Clin J Sport Med*. 2007;17:263-268. https://doi.org/10.1097/JSM.0b013e31811f415b
40. Parkkari J, Kannus P, Natri A, et al. Active living and injury risk. *Int J Sports Med*. 2004;25:209-216. https://doi.org/10.1055/s-2004-819935
41. Pasanen K, Rossi MT, Parkkari J, et al. Predictors of lower extremity injuries in team sports (PROFITS-study): a study protocol. *BMJ Open Sport Exerc Med*. 2015;1:e000076. https://doi.org/10.1136/bmjsem-2015-000076
42. Peduzzi P, Concato J, Feinstein AR, Holford TR. Importance of events per independent variable in proportional hazards regression analysis II. Accuracy and precision of regression estimates. *J Clin Epidemiol*. 1995;48:1503-1510. https://doi.org/10.1016/0895-4356(95)00048-8
43. Peterson L, Junge A, Chomiak J, Graf-Baumann T, Dvorak J. Incidence of football injuries and complaints in different age groups and skill-level groups. *Am J Sports Med*. 2000;28:S51-S57. https://doi.org/10.1177/28.suppl_5.s-51
44. Räisänen A, Pasanen K, Krosshaug T, Avela J, Perttunen J, Parkkari J. Single-leg squat as a tool to evaluate young athletes' frontal plane knee control. *Clin J Sport Med*. 2016;26:478-482. https://doi.org/10.1097/JSM.0000000000000288
45. Shimozaki K, Nakase J, Takata Y, Shima Y, Kitaoka K, Tsuchiya H. Greater body mass index and hip abduction muscle strength predict noncontact anterior cruciate ligament injury in female Japanese high school basketball players. *Knee Surg Sports Traumatol Arthrosc*. 2018;26:3004-3011. https://doi.org/10.1007/s00167-018-4888-4
46. Sigward SM, Ota S, Powers CM. Predictors of frontal plane knee excursion during a drop land in young female soccer players. *J Orthop Sports Phys Ther*. 2008;38:661-667. https://doi.org/10.2519/jospt.2008.2695
47. Spinks AB, McClure RJ. Quantifying the risk of sports injury: a systematic review of activity-specific rates for children under 16 years of age. *Br J Sports Med*. 2007;41:548-557; discussion 557. https://doi.org/10.1136/bjsm.2006.033605
48. Stensrud S, Myklebust G, Kristianslund E, Bahr R, Krosshaug T. Correlation between two-dimensional video analysis and subjective assessment in evaluating knee control among elite female team handball players. *Br J Sports Med*. 2011;45:589-595. https://doi.org/10.1136/bjsm.2010.078287
49. Therneau TM. coxme: Mixed Effects Cox Models. Available at: https://cran.r-project.org/package=coxme. Accessed April 4, 2020.
50. Thomas AC, Hubbard-Turner T, Wikstrom EA, Palmieri-Smith RM. Epidemiology of posttraumatic osteoarthritis. *J Athl Train*. 2017;52:491-496. https://doi.org/10.4085/1062-6050-51.5.08
51. Toohey LA, Drew MK, Cook JL, Finch CF, Gaida JE. Is subsequent lower limb injury associated with previous injury? A systematic review and meta-analysis. *Br J Sports Med*. 2017;51:1670-1678. https://doi.org/10.1136/bjsports-2017-097500
52. Valderrabano V, Hintermann B, Horisberger M, Fung TS. Ligamentous posttraumatic ankle osteoarthritis. *Am J Sports Med*. 2006;34:612-620. https://doi.org/10.1177/0363546505281813
53. Wilkerson GB, Giles JL, Seibel DK. Prediction of core and lower extremity strains and sprains in collegiate football players: a preliminary study. *J Athl Train*. 2012;47:264-272. https://doi.org/10.4085/1062-6050-47.3.17
54. Willson JD, Davis IS. Utility of the frontal plane projection angle in females with patellofemoral pain. *J Orthop Sports Phys Ther*. 2008;38:606-615. https://doi.org/10.2519/jospt.2008.2706
55. Witchalls J, Blanch P, Waddington G, Adams R. Intrinsic functional deficits associated with increased risk of ankle injuries: a systematic review with meta-analysis. *Br J Sports Med*. 2012;46:515-523. https://doi.org/10.1136/bjsports-2011-090137
56. Yeow CH, Lee PV, Goh JC. An investigation of lower extremity energy dissipation strategies during single-leg and double-leg landing based on sagittal and frontal plane biomechanics. *Hum Mov Sci*. 2011;30:624-635. https://doi.org/10.1016/j.humov.2010.11.010

MICHAEL P. REIMAN, PT, DPT, PhD, MEd, ATC[1] • JADA BOYD, BS[1] • NICOLETTE INGEL, BS[1]
ASHLEY REICHERT, BS[1] • MAX WESTHOVEN, BS[1] • SCOTT PETERS, PT, DPT, ATC[2]

There Is Limited and Inconsistent Reporting of Postoperative Rehabilitation for Femoroacetabular Impingement Syndrome: A Scoping Review of 169 Studies

OBJECTIVE: To evaluate the reporting of rehabilitation guidelines in studies of postoperative outcomes of patients with femoroacetabular impingement (FAI) syndrome and/or labral tear.

DESIGN: Scoping review.

LITERATURE SEARCH: A computer-assisted literature search was conducted of the MEDLINE, CINAHL, and Embase databases on June 17, 2018. Using key words related to FAI syndrome/labral tear and both open and arthroscopic surgical outcomes, we identified 169 studies that included 16 675 patients. Separate authors calculated and verified the prevalence of reported outcomes.

STUDY SELECTION CRITERIA: We included intervention and observational studies that were prospective or retrospective in design. Studies must have included patients with a primary diagnosis of FAI syndrome and/or labral tear.

DATA SYNTHESIS: We calculated the mean ± SD prevalence for continuous variables, where possible.

RESULTS: Hip arthroscopy was the primary surgical procedure (76% of studies). The mean ± SD age of participants was 34.8 ± 9.2 years and the mean ± SD follow-up time was 27 ± 15.3 months. Of the 169 included studies, 74 (44%) discussed phases of rehabilitation, 49 (29%) reported details on goals between phases, 1 in 3 described details on rehabilitation progression, and fewer than 1 in 10 reported sufficient detail to replicate the rehabilitation protocol. Weight-bearing and range-of-motion restrictions were poorly reported and variable in duration.

CONCLUSION: Surgical outcome studies do not provide sufficient detail or consistency for practicing clinicians to replicate a postoperative rehabilitation protocol for patients with FAI syndrome/labral tear.
J Orthop Sports Phys Ther 2020;50(5):252-258. doi:10.2519/jospt.2020.9189

KEY WORDS: *femoroacetabular impingement, hip, rehabilitation, surgery*

Several studies have reported the success of surgical intervention for patients with femoroacetabular impingement (FAI) syndrome.[3,12,15,17,21] The postoperative rehabilitation program is vital for successful outcome following surgery.[2] The details of postoperative rehabilitation programs are often unclear or inconsistent.[5,6,9,11,18,25,31]

The exponential growth in surgical intervention rates[26] and possible limitations of current postoperative programs[16] underscore why it is important to determine the necessary content of postoperative rehabilitation. To appropriately evaluate outcomes following hip arthroscopy, both the surgical intervention and the postoperative rehabilitation program should be considered. While the details of surgical intervention have been extensively described in multiple sources, the extent to which postoperative rehabilitation protocols are described and implemented in outcome studies is unclear.

A scoping review can identify gaps in the literature for the broad topic of FAI syndrome postoperative rehabilitation protocols and provide recommendations for future study. Scoping reviews map the existing evidence or literature[1] and are useful frameworks to collate and summarize information on a broad topic.[23] While systematic reviews formally assess bias and generate a conclusion related to a focused question, scoping reviews identify parameters and gaps in a body of literature without a formal analysis of the methods or bias in included studies. The present scoping review explored the reporting of postoperative rehabilitation guidelines for FAI syndrome, for the purpose of evaluating rehabilitation protocols in FAI syndrome and labral tear postoperative outcome studies.

[1]Department of Orthopaedic Surgery, Duke University School of Medicine, Durham, NC. [2]Toronto Blue Jays Baseball Club, Toronto, Canada. This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sector. The study protocol was registered with PROSPERO on June 8, 2018 (CRD42018090686). The authors certify that they have no affiliations with or financial involvement in any organization or entity with a direct financial interest in the subject matter or materials discussed in the article. Address correspondence to Dr Michael P. Reiman, Duke University School of Medicine, Department of Orthopaedic Surgery, Duke University Medical Center 2923, Durham, NC 27710. E-mail: reiman.michael@gmail.com

METHODS

We followed the 5-stage methodological framework[1] and the PRISMA Extension for Scoping Reviews (PRISMA-ScR).[35] The study protocol was registered with PROSPERO on June 8, 2018 (CRD42018090686).

Stage 1: Identifying the Research Question

Our research question was, "What is the prevalence and consistency in reporting of surgical rehabilitation guidelines utilized in current surgical intervention studies for FAI syndrome and/or labral tear?"

Stage 2: Identifying Relevant Studies

We conducted a librarian-assisted search of the MEDLINE, CINAHL, and Embase electronic databases for studies examining surgical outcomes for patients with FAI or FAI syndrome (with or without labral tear). The systematic search of electronic databases was performed on June 17, 2018 from database inception. Our search strategy was as follows: ("hip"[MeSH Terms] OR Hip[tiab] OR hips[tiab] OR "Hip Joint"[MeSH] OR "coxofemoral joint"[tiab]) AND ("Femoracetabular Impingement"[MeSH] OR "Femoracetabular Impingement"[tiab] OR "femoroacetabular impingement"[tiab] OR "Femoral acetabular impingement"[tiab] OR FAI[tiab] OR "femoral impingement"[tiab] OR impingement[tiab] OR "labral tear"[tiab] OR "labral tears"[tiab] OR (acetabular[tiab] AND tear[tiab]) OR (acetabular[tiab] AND tears[tiab]) AND ("Orthopedics"[MeSH] OR orthopedic[tiab] OR Surgery[tiab] OR "surgery"[Subheading]) NOT (Editorial[ptyp] OR Letter[ptyp] OR Case Reports[ptyp] OR Comment[ptyp]) NOT (animals[mh] NOT humans[mh]). We adapted the search strategy to each electronic database.

As search results frequently omit relevant articles,[7] systematic reviews and included articles were also screened to identify eligible studies that were not identified by the electronic search.

Screening, Eligibility, and Inclusion Our search strategy involved a 3-step approach.[23] Step 1 was the initial limited search. A pilot search was conducted in April 2018 in the MEDLINE electronic database using the terms "femoroacetabular impingement" AND "surgery." Step 2 was to identify key words and index terms. Title, abstract, and index terms were analyzed to describe the studies identified in step 1 to determine appropriate key words for inclusion in the final search strategy previously listed. Step 3 involved executing the final search strategy and further searching references and citations. Two independent reviewers completed title, abstract, and full-text screening, assessing for study inclusion. Discrepancies were resolved by discussion or by a third reviewer if required.

Stage 3: Study Selection

To be included in the scoping review, the studies had to satisfy the following criteria:

- Design: prospective or retrospective intervention or observational studies with a population greater than 10 patients, published in the English language, and published in a peer-reviewed journal. Systematic reviews, conference abstracts, case studies, narrative reviews, and non–peer-reviewed studies were excluded.
- Population: patients with a primary diagnosis of FAI syndrome/labral tear and treated with either arthroscopy or an open surgical procedure. Patients may have had concomitant pathology (eg, any intra- or extra-articular hip pathology reported by an included study). Studies reporting on hip surgery for a diagnosis other than FAI and/or labral tear (eg, only Legg-Calvé-Perthes disease, slipped capital femoral epiphysis, hip dysplasia) were excluded. Studies that included patients with a history of surgery to the index hip and patients undergoing peri-acetabular osteotomy were also excluded.
- Intervention: hip arthroscopy and/or an open surgical procedure for FAI syndrome/labral tear.
- Outcome: prevalence and consistency of reporting of rehabilitation protocols in postoperative outcome studies (**TABLE 1**).
- Time: all periods reporting postoperative rehabilitation were included.

TABLE 1 Rehabilitation Content Collected and Reported in the Review

General Demographic and Study Information	Surgical Procedure Data	Postsurgical Rehabilitation Domains
• Author and year of study publication • Country of study origin • Sample size • Demographics (age, sex) • Level of evidence for study	FAI syndrome procedures • Osteoplasty - Femoroplasty - Acetabuloplasty - Combined Concomitant procedures • Labral procedures - Resection - Repair - Reconstruction • Chondral procedures - Microfracture • Capsular procedures - Closure/imbrication - Capsulotomy without closure	• Orthosis/brace use • CPM use • Derotational boot use • Limitations for brace and CPM use • Range-of-motion limitations • Weight-bearing status and limitations • Phase progression parameters - Goals for each phase - Criteria for progression to the next phase • Return to activity/work/sport parameters

Abbreviations: CPM, continuous passive motion; FAI, femoroacetabular impingement.

Stage 4: Charting the Data

Prior to data collection, the review team met to discuss data collection and categorization. All members completed a pilot data extraction to calibrate. Additional meetings were required during data collection to verify data extraction and categorization. Two independent reviewers extracted all data. A third reviewer independently verified the data. If there was disagreement, a fourth reviewer resolved the disagreement.

Stage 5: Collating, Summarizing, and Reporting the Results

We calculated mean ± SD values for continuous variables where possible. Ranges were also provided where appropriate. All analyses were conducted in Excel 2016 (Microsoft Corporation, Redmond, WA) .

Demographic information (including prevalence of specific surgical procedures and postoperative time frames) and postoperative restrictions (eg, weight bearing and range of motion [ROM]) were collated and recorded in an Excel (Microsoft Corporation) spreadsheet. Mean ± SD values were calculated in Excel, and data are represented graphically. We also used the same procedure to present time frames for brace, continuous passive motion, and derotational brace use, as well as ROM and weight-bearing restrictions for each surgical procedure type (eg, osteoplasty, labral repair, and microfracture).

We summarized rehabilitation program details (eg, progression criteria, goals of the rehabilitation phase) using a stratification scheme that we developed. We categorized the extent to which the protocols of the rehabilitation program would allow the reader to reproduce the protocol in a format that could be used in a clinical setting to guide postoperative treatment (**TABLE 2**). Protocols categorized as "exceptional" could reasonably be reproduced the next day in the clinic setting.

TABLE 2 Detail of Rehabilitation Guideline Description in Studies

Reproducibility Quality	Reproducibility Guidelines[a]	Percentage of Studies
Exceptional	All guidelines reported; essentially, you could take it and use it in the clinic	8%
Moderate	5 of 7 guidelines reported	23%
Minimal	≤4 of 7 guidelines reported	69%

[a]*Guidelines: 1, Phases (eg, lists number of phases, goals for transition); 2, Exercises or primary principles for each phase listed; 3, weight-bearing limitations and time frame; 4, range-of-motion limitations and time frame; 5, brace use/no use and time frame; 6, continuous passive motion use/no use and time frame; 7, all are discussed relative to adjustment(s) based on surgical procedure performed.*

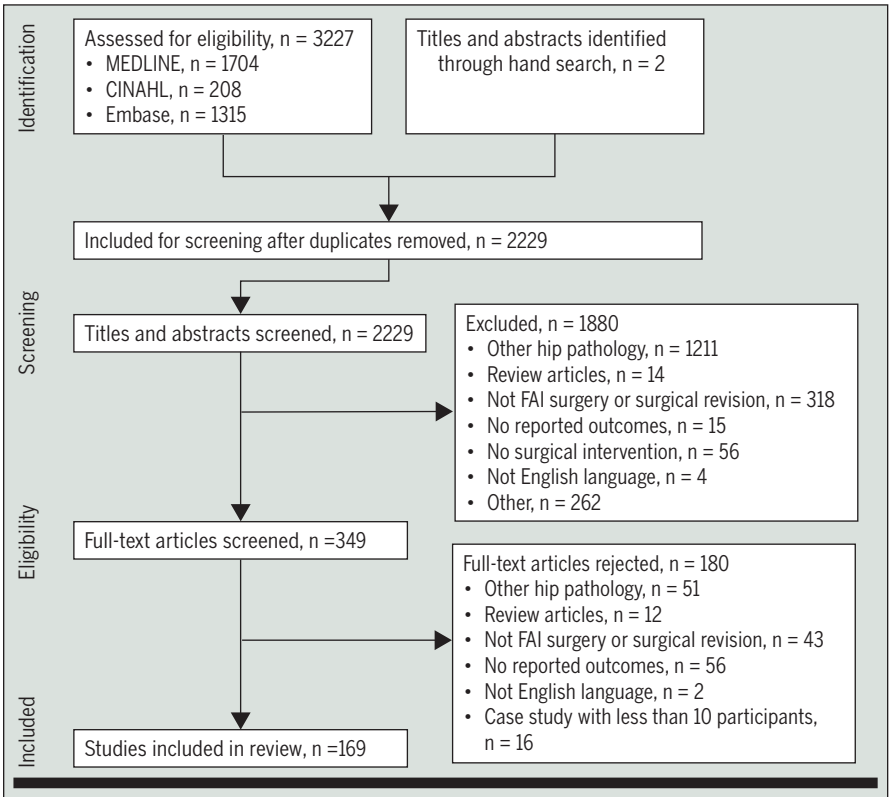

FIGURE 1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram for study inclusion. Abbreviation: FAI, femoroacetabular impingement.

RESULTS

We included 169 studies (**FIGURE 1**) involving 16 675 adolescent and adult patients (47% female), with a mean ± SD age of 34.8 ± 9.2 years (**TABLE 3**). Interrater agreement among reviewers was moderate ($\kappa = 0.60$) for title and substantial ($\kappa = 0.71$) for abstract and full-text screening ($\kappa = 0.74$).[19]

Study Demographics

All included patients (**TABLE 3**) were either adolescents or adults.

Surgical Procedures

Prevalence of surgical procedures performed in the included studies is reported in **TABLE 3**. The most common procedure was arthroscopy (76.3% of studies).

Coexisting pathology (other than FAI syndrome) was reported in 95% (160/169) of studies. Labral and chondral pathology was addressed in 34% (57/169) of the studies; labral pathology only in 25% (43/169) of the studies; labral, chondral, and capsular pathology in 19% (32/169) of the studies; and labral

and capsular pathology in 13% (22/169) of the included studies.

Surgical Follow-up The mean time for postsurgery follow-up was 27.2 ± 15.3 months across the 94% of studies that reported postoperative follow-up. Prospective and retrospective studies reported data that included only patients who had completed follow-up.

Postoperative Reporting

Various levels of postoperative rehabilitation reporting were detailed across the 169 included studies (**TABLE 2**). Of the 169 included studies, 74 (44%) discussed phases of rehabilitation, 49 (29%) described details of goals between phases, and 53 (31%) described details of progression to the next rehabilitation phase. Of the 74 studies that discussed phases of rehabilitation, 21 (28%) described 4 or more phases of the rehabilitation program, and 8% of all studies reported the protocol in sufficient detail to replicate it in the clinical setting (**TABLE 2**).

Postoperative Restrictions Per Procedure In studies reporting postoperative restrictions, there was variability in weight-bearing (**FIGURE 2**) and ROM restrictions (**FIGURE 3**). Weight-bearing restrictions were reported in 129 (76%) studies for osteoplasty, with a mean ± SD duration of 2.96 ± 1.8 weeks. Weight-bearing restrictions were examined in 68 studies for microfracture, with a mean ± SD duration of 4.97 ± 2.35 weeks. Microfracture surgery required the longest duration of weight-bearing restrictions.

FIGURES 2 through **6** present mean duration (confidence interval) of postoperative restrictions (eg, weight bearing, brace use, ROM) for the included studies. The use of continuous passive motion had the greatest variability.

DISCUSSION

Our review provides an overview of the prevalence and consistency of reporting of rehabilitation protocols for FAI syndrome and labral tear. Similar to the findings of a postoperative rehabilitation systematic review in 2015,[9] a survey of international hip surgeons,[31] and a search of online postoperative protocols,[5] we found that surgical outcome studies were limited and inconsistent in their description of postoperative restrictions and rehabilitation protocols.

TABLE 3 Demographic Characteristics of Included Studies

Measure	Value (n = 169)
Population[a]	
Adults	123 (72.8)
Adolescents	7 (4.1)
Combination of adults and adolescents	37 (21.9)
Not reported	2 (1.2)
Age, y[b]	34.8 ± 9.2 (96)
Postsurgical follow-up time, mo[b]	27 ± 15.3 (94)
Surgical type[a]	
Open	23 (13.6)
Arthroscopy	129 (76.3)
Combined (open and arthroscopy) or mini-open	17 (10.1)

[a]*Values are n (percent).*
[b]*Values are mean ± SD (percent of studies that reported postoperative follow-up).*

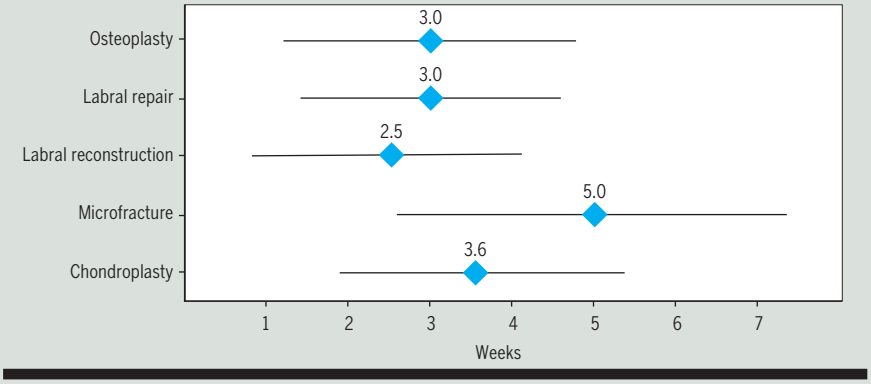

FIGURE 2. Time frame for utilization of weight-bearing restrictions in included studies.

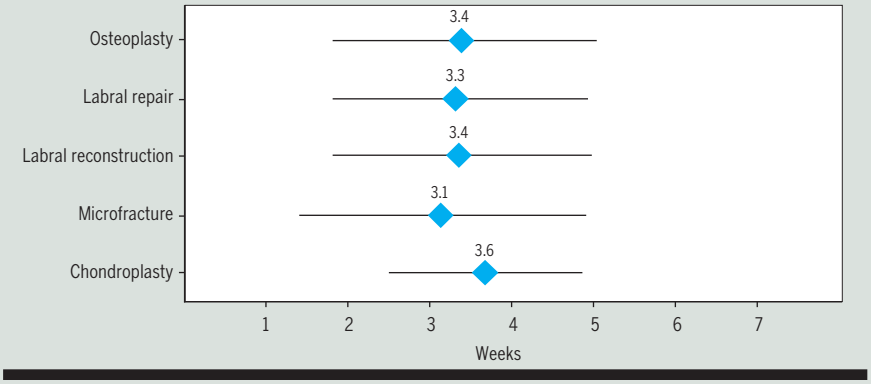

FIGURE 3. Time frame for utilization of range-of-motion restrictions in included studies.

Though surgical outcome studies appropriately focus on surgical outcomes, they provide extensive details on surgical procedures[26] but lack similar detail about postoperative rehabilitation. Without sufficient details, it is difficult to determine whether the rehabilitation program progression was based on functional criteria and healing times,[6,8,32,33,36] or whether it included the "type, dose and progression of exercise needed to generate a meaningful change in strength and function."[16]

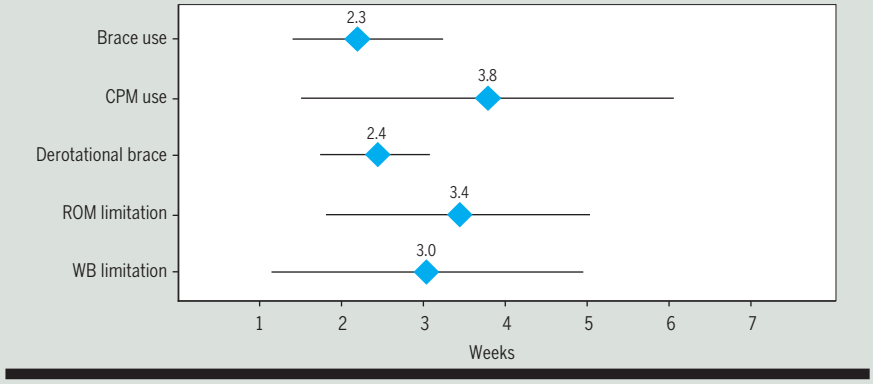

FIGURE 4. Specific restrictions, brace use, and CPM use for osteoplasty procedures. Abbreviations: CPM, continuous passive motion; ROM, range of motion; WB, weight bearing.

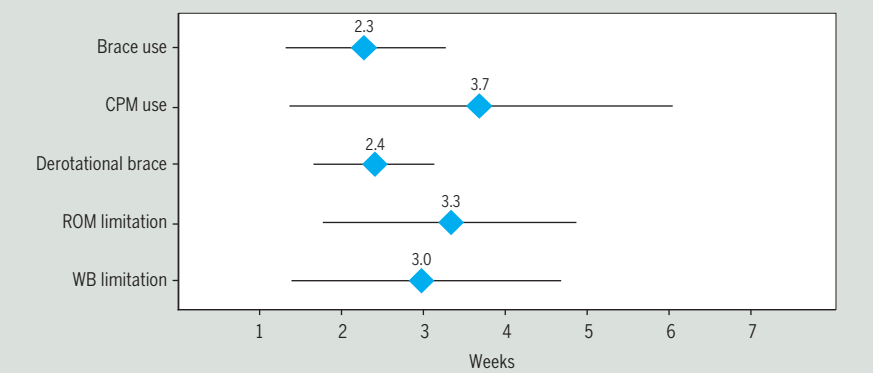

FIGURE 5. Specific restrictions, brace use, and CPM use for labral repair procedures. Abbreviations: CPM, continuous passive motion; ROM, range of motion; WB, weight bearing.

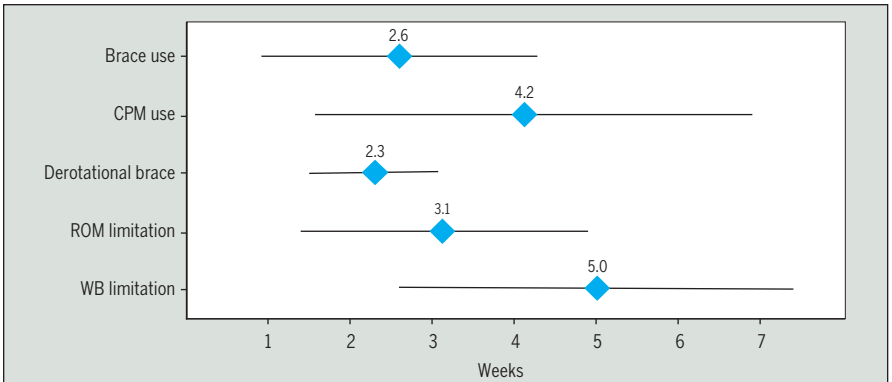

FIGURE 6. Specific restrictions, brace use, and CPM use for microfracture surgical procedures. Abbreviations: CPM, continuous passive motion; ROM, range of motion; WB, weight bearing.

Based on current literature, we cannot ascertain the extent to which postoperative rehabilitation influences surgical outcomes, due to limitations and inconsistencies in the reporting of postoperative rehabilitation programs. Postoperative rehabilitation is considered to be very important by both surgeons and physical therapists.[37] Yet, fewer than half of included studies discussed phases of the rehabilitation program. Goals and criteria for progression to the next rehabilitation phase were reported in 1 of 3 studies, and fewer than 1 in 10 studies provided sufficient details of the postoperative rehabilitation program to allow for replication in clinical or research practice.

Because the specific details of surgical treatments were often unclear (eg, femoroplasty versus acetabuloplasty, labral repair versus labral resection, and microfracture versus no cartilage procedures), it is difficult to know how tissue load[20] (eg, weight-bearing tolerance of cartilage and ROM strain on the labrum) and other rehabilitation principles should be appropriately applied to postoperative care in hip arthroscopy.[34] It is also necessary to determine whether restrictions (eg, weight bearing, ROM) are necessary for safe and successful outcomes across all hip surgical procedures.[14]

Patients who undergo hip surgery have poor outcomes when compared with healthy controls.[16,34] Changes in pain,[10,17] daily and sport function,[17,34] and satisfaction[17,22] all plateau within 2 years after surgery. The plateau coincides with surgical failure. While appropriate patient selection[24,28] and postoperative reporting[26-28] are justifiably critiqued, postoperative rehabilitation programs also warrant criticism. It is unclear whether current postoperative programs include the type, dose, and progression of exercise required for meaningful functional changes in the patient.[16] Our findings support the findings of other studies[5,9,26,31,34] that indicate a need for a better and more evidence-based approach to rehabilitation. Improved reporting and examination of postoperative rehabilitation protocols would help future

researchers to understand the influence of rehabilitation programs and their content on patient outcomes.

Recommendations

It is beyond the scope of this review to provide detailed and specific study design and reporting guidelines for future postoperative rehabilitation studies. The primary purpose of a scoping review is to identify parameters and gaps in a body of literature requiring further examination, potentially with systematic reviews.[1,23] We suggest that future trials reporting postoperative outcomes use published guidelines (eg, Standard Protocol Items: Recommendations for Interventional Trials,[4] CONsolidated Standards Of Reporting Trials [CONSORT],[29] Template for Intervention Description and Replication [TIDieR],[13] Consensus on Exercise Reporting Template [CERT][30]) for reporting trial protocols and trial results and for describing interventions.[26] Greater postoperative rehabilitation detail in these studies is also required to allow for clinical and research replication.

Limitations

It is unclear whether the inconsistency of protocol reporting reflects inadequate reporting or inadequate use of postoperative rehabilitation. Therefore, the prevalence of the findings may not completely reflect the rehabilitation that the patients received. Because only studies published in English were included, there is a risk of language bias. We did not assess study quality or risk of bias or heterogeneity, which is acceptable in a scoping review. Finally, our novel hierarchy for classifying rehabilitation program replicability (**TABLE 4**) has not been validated. We attempted to provide the reader with an idea of the level of consistency and extent of the rehabilitation protocols reported in included studies. It is possible that other classifications are more appropriate and feasible.

CONCLUSION

Surgical outcome studies do not provide sufficient details or consistency for practicing clinicians to replicate a postoperative rehabilitation protocol in patients with FAI syndrome/labral tear. Of 169 postoperative outcome studies, only 8% reported sufficient detail to replicate the rehabilitation protocol and only 44% reported the phases of rehabilitation.

KEY POINTS

FINDINGS: Fewer than 1 in 10 studies reported sufficient detail to replicate the rehabilitation protocol. Limitations for weight bearing and range of motion were poorly reported and variable in detail.

IMPLICATIONS: Practicing clinicians are not provided with enough detail or consistency in postoperative parameters to replicate rehabilitation protocols. These inconsistencies and lack of detail also preclude researchers from determining best postoperative protocol practice for outcomes.

CAUTION: Limitations in manuscript size could preclude reporting of rehabilitation protocol parameters in current surgical outcome studies. Our novel hierarchy for classifying rehabilitation program replicability has not been validated.

TABLE 4 Studies Employing Specific Surgical Procedures and Reporting Postoperative Rehabilitation Content[a]

	Studies, n	Brace Use	CPM Use	Derotational Brace Use	ROM Limitations	WB Limitations
Osteoplasty	158	23.4	30.4	10.1	37.6	87.3
Labral resection	117	22.2	29.9	9.4	37.6	87.2
Labral repair	128	25.0	28.9	11.7	42.2	89.1
Labral reconstruction	18	55.6	61.1	22.2	38.9	100.0
Microfracture	78	30.8	26.9	16.9	34.6	91.0
Chondroplasty	38	23.7	31.6	10.5	31.6	89.5
Capsule repair	53	32.1	32.1	20.8	50.9	84.9

Abbreviations: CPM, continuous passive motion; ROM, range of motion; WB, weight bearing.
[a]*Values are percent unless otherwise indicated.*

STUDY DETAILS

AUTHOR CONTRIBUTIONS: Dr Reiman designed the study. All authors contributed to data collection and to manuscript writing, editing, and approval.

DATA SHARING: Data (Excel spreadsheet) are available on request by contacting the corresponding author.

PATIENT AND PUBLIC INVOLVEMENT: No patients/athletes/public partners were involved in any aspect of this research.

ACKNOWLEDGMENTS: *The authors thank Leila Ledbetter, MLIS for assisting with the literature search for this study.*

REFERENCES

1. Arksey H, O'Malley L. Scoping studies: towards a methodological framework. *Int J Soc Res Methodol*. 2005;8:19-32. https://doi.org/10.1080/1364557032000119616
2. Bennell KL, O'Donnell JM, Takla A, et al. Efficacy of a physiotherapy rehabilitation program for individuals undergoing arthroscopic management of femoroacetabular impingement – the FAIR trial: a randomised controlled trial protocol. *BMC Musculoskelet Disord*. 2014;15:58. https://doi.org/10.1186/1471-2474-15-58
3. Casartelli NC, Leunig M, Maffiuletti NA, Bizzini M. Return to sport after hip surgery for femoroacetabular impingement: a systematic review. *Br J Sports Med*. 2015;49:819-824. https://doi.org/10.1136/bjsports-2014-094414
4. Chan AW, Tetzlaff JM, Gøtzsche PC, et al. SPIRIT 2013 explanation and elaboration: guidance for protocols of clinical trials. *BMJ*. 2013;346:e7586. https://doi.org/10.1136/bmj.e7586
5. Cvetanovich GL, Lizzio V, Meta F, et al. Variability and comprehensiveness of North American online available physical therapy protocols following hip arthroscopy for femoroacetabular impingement and labral repair. *Arthroscopy*.

2017;33:1998-2005. https://doi.org/10.1016/j.arthro.2017.06.045
6. Domb BG, Sgroi TA, VanDevender JC. Physical therapy protocol after hip arthroscopy: clinical guidelines supported by 2-year outcomes. *Sports Health*. 2016;8:347-354. https://doi.org/10.1177/1941738116647920
7. Doust JA, Pietrzak E, Sanders S, Glasziou PP. Identifying studies for systematic reviews of diagnostic tests was difficult due to the poor sensitivity and precision of methodologic filters and the lack of information in the abstract. *J Clin Epidemiol*. 2005;58:444-449. https://doi.org/10.1016/j.jclinepi.2004.09.011
8. Edelstein J, Ranawat A, Enseki KR, Yun RJ, Draovitch P. Post-operative guidelines following hip arthroscopy. *Curr Rev Musculoskelet Med*. 2012;5:15-23. https://doi.org/10.1007/s12178-011-9107-6
9. Grzybowski JS, Malloy P, Stegemann C, Bush-Joseph C, Harris JD, Nho SJ. Rehabilitation following hip arthroscopy – a systematic review. *Front Surg*. 2015;2:21. https://doi.org/10.3389/fsurg.2015.00021
10. Gupta A, Redmond JM, Stake CE, Dunne KF, Domb BG. Does primary hip arthroscopy result in improved clinical outcomes?: 2-year clinical follow-up on a mixed group of 738 consecutive primary hip arthroscopies performed at a high-volume referral center. *Am J Sports Med*. 2016;44:74-82. https://doi.org/10.1177/0363546514562563
11. Gupta A, Suarez-Ahedo C, Redmond JM, et al. Best practices during hip arthroscopy: aggregate recommendations of high-volume surgeons. *Arthroscopy*. 2015;31:1722-1727. https://doi.org/10.1016/j.arthro.2015.03.023
12. Hetaimish BM, Khan M, Crouch S, et al. Consistency of reported outcomes after arthroscopic management of femoroacetabular impingement. *Arthroscopy*. 2013;29:780-787. https://doi.org/10.1016/j.arthro.2012.11.011
13. Hoffmann TC, Glasziou PP, Boutron I, et al. Better reporting of interventions: Template for Intervention Description and Replication (TIDieR) checklist and guide. *BMJ*. 2014;348:g1687. https://doi.org/10.1136/bmj.g1687
14. Houck DA, Kraeutler MJ, Schuette HB, McCarty EC, Bravman JT. Early versus delayed motion after rotator cuff repair: a systematic review of overlapping meta-analyses. *Am J Sports Med*. 2017;45:2911-2915. https://doi.org/10.1177/0363546517692543
15. Impellizzeri FM, Mannion AF, Naal FD, Hersche O, Leunig M. The early outcome of surgical treatment for femoroacetabular impingement: success depends on how you measure it. *Osteoarthritis Cartilage*. 2012;20:638-645. https://doi.org/10.1016/j.joca.2012.03.019
16. Kemp JL, King MG, Barton C, et al. Is exercise therapy for femoroacetabular impingement in or out of FASHIoN? We need to talk about current best practice for the non-surgical management of FAI syndrome. *Br J Sports Med*. 2019;53:1204-1205. https://doi.org/10.1136/bjsports-2018-100173
17. Kierkegaard S, Langeskov-Christensen M, Lund B, et al. Pain, activities of daily living and sport function at different time points after hip arthroscopy in patients with femoroacetabular impingement: a systematic review with meta-analysis. *Br J Sports Med*. 2017;51:572-579. https://doi.org/10.1136/bjsports-2016-096618
18. Kuhns BD, Weber AE, Batko B, Nho SJ, Stegemann C. A four-phase physical therapy regimen for returning athletes to sport following hip arthroscopy for femoroacetabular impingement with routine capsular closure. *Int J Sports Phys Ther*. 2017;12:683-696.
19. Landis JR, Koch GG. An application of hierarchical kappa-type statistics in the assessment of majority agreement among multiple observers. *Biometrics*. 1977;33:363-374. https://doi.org/10.2307/2529786
20. Lee S, Shin J, Haro M, et al. Fifty most cited articles for femoroacetabular impingement and hip arthroscopy. *Front Surg*. 2015;2:41. https://doi.org/10.3389/fsurg.2015.00041
21. Lodhia P, Slobogean GP, Noonan VK, Gilbart MK. Patient-reported outcome instruments for femoroacetabular impingement and hip labral pathology: a systematic review of the clinimetric evidence. *Arthroscopy*. 2011;27:279-286. https://doi.org/10.1016/j.arthro.2010.08.002
22. Lovett Carte D, Kennedy N. What are athletes' perceptions of rehabilitation outcome 1 year after hip arthroscopy? *J Sport Rehabil*. 2014;23:339-350. https://doi.org/10.1123/JSR.2013-0078
23. Murray A, Daines L, Archibald D, Hawkes R, Grant L, Mutrie N. The relationship and effects of golf on physical and mental health: a scoping review protocol. *Br J Sports Med*. 2016;50:647-650. https://doi.org/10.1136/bjsports-2015-095914
24. Peters S, Laing A, Emerson C, et al. Surgical criteria for femoroacetabular impingement syndrome: a scoping review. *Br J Sports Med*. 2017;51:1605-1610. https://doi.org/10.1136/bjsports-2016-096936
25. Rath E, Sharfman ZT, Paret M, Amar E, Drexler M, Bonin N. Hip arthroscopy protocol: expert opinions on post-operative weight bearing and return to sports guidelines. *J Hip Preserv Surg*. 2017;4:60-66. https://doi.org/10.1093/jhps/hnw045
26. Reiman MP, Peters S, Sylvain J, Hagymasi S, Ayeni OR. Prevalence and consistency in surgical outcome reporting for femoroacetabular impingement syndrome: a scoping review. *Arthroscopy*. 2018;34:1319-1328.e9. https://doi.org/10.1016/j.arthro.2017.11.037
27. Reiman MP, Peters S, Sylvain J, Hagymasi S, Mather RC, Goode AP. Femoroacetabular impingement surgery allows 74% of athletes to return to the same competitive level of sports participation but their level of performance remains unreported: a systematic review with meta-analysis. *Br J Sports Med*. 2018;52:972-981. https://doi.org/10.1136/bjsports-2017-098696
28. Reiman MP, Thorborg K, Hölmich P. Femoroacetabular impingement surgery is on the rise—but what is the next step? *J Orthop Sports Phys Ther*. 2016;46:406-408. https://doi.org/10.2519/jospt.2016.0605
29. Schulz KF, Altman DG, Moher D, CONSORT Group. CONSORT 2010 statement: updated guidelines for reporting parallel group randomised trials. *PLoS Med*. 2010;7:e1000251. https://doi.org/10.1371/journal.pmed.1000251
30. Slade SC, Dionne CE, Underwood M, Buchbinder R. Consensus on Exercise Reporting Template (CERT): explanation and elaboration statement. *Br J Sports Med*. 2016;50:1428-1437. https://doi.org/10.1136/bjsports-2016-096651
31. Smith KM, Gerrie BJ, McCulloch PC, et al. Arthroscopic hip preservation surgery practice patterns: an international survey. *J Hip Preserv Surg*. 2017;4:18-29. https://doi.org/10.1093/jhps/hnw036
32. Spencer-Gardner L, Eischen JJ, Levy BA, Sierra RJ, Engasser WM, Krych AJ. A comprehensive five-phase rehabilitation programme after hip arthroscopy for femoroacetabular impingement. *Knee Surg Sports Traumatol Arthrosc*. 2014;22:848-859. https://doi.org/10.1007/s00167-013-2664-z
33. Stalzer S, Wahoff M, Scanlan M. Rehabilitation following hip arthroscopy. *Clin Sports Med*. 2006;25:337-357. https://doi.org/10.1016/j.csm.2005.12.008
34. Thorborg K, Kraemer O, Madsen AD, Hölmich P. Patient-reported outcomes within the first year after hip arthroscopy and rehabilitation for femoroacetabular impingement and/or labral injury: the difference between getting better and getting back to normal. *Am J Sports Med*. 2018;46:2607-2614. https://doi.org/10.1177/0363546518786971
35. Tricco AC, Lillie E, Zarin W, et al. PRISMA Extension for Scoping Reviews (PRISMA-ScR): checklist and explanation. *Ann Intern Med*. 2018;169:467-473. https://doi.org/10.7326/M18-0850
36. Wahoff M, Ryan M. Rehabilitation after hip femoroacetabular impingement arthroscopy. *Clin Sports Med*. 2011;30:463-482. https://doi.org/10.1016/j.csm.2011.01.001
37. Wörner T, Thorborg K, Moksnes H, Eek F. Similar views on rehabilitation following hip arthroscopy among physiotherapists and surgeons in Scandinavia: a specialized care survey. *Knee Surg Sports Traumatol Arthrosc*. 2018;26:2519-2526. https://doi.org/10.1007/s00167-017-4676-6

PAUL SALAMH, PT, DPT, PhD[1] • JEREMY LEWIS, PhD, FCSP[2-4]

It Is Time to Put Special Tests for Rotator Cuff–Related Shoulder Pain out to Pasture

Clinicians use orthopaedic physical examination tests to inform diagnosis and support decision making. Each region of the body has a unique set of orthopaedic physical examination tests ("special tests"). In this Viewpoint, we focus on tests used to assess rotator cuff–related shoulder pain (RCRSP) (an umbrella term that includes subacromial impingement syndrome, rotator cuff tendinopathy, bursa pathology, and atraumatic partial- and full-thickness rotator cuff tears).[11] Patients with RCRSP typically present with a painful and weak shoulder, most commonly in external rotation and/or abduction.

There are more than 70 shoulder special tests[5] in clinical use that have been developed to identify labral, rotator cuff, acromioclavicular, and biceps tendon pathology, instability, subacromial impingement, and scapular dyskinesis. It is unclear why the tests are afforded "special" status.[8] The aim of this Viewpoint is to outline the current use and validity of shoulder orthopaedic tests used in the diagnosis of RCRSP. We provide recommendations for how clinicians might consider using shoulder orthopaedic tests for RCRSP in practice.

Before reading any further, please take a few moments to reflect on your answers to the following questions. With respect to RCRSP:

1. When using clinical tests for RCRSP, are clinicians capable of identifying the structure(s) causing the symptoms?
2. Do imaging findings—such as a thickened bursa, acromial spurs, rotator cuff tendon degeneration and tears, long head of biceps tendinosis, type II superior labrum anterior and posterior (SLAP) tears, and acromioclavicular joint degeneration—explain the cause of symptoms?
3. When surgeons perform acromioplasties, biceps tenodesis, type II SLAP repairs, or rotator cuff tendon surgery for nontraumatic tears, can they be certain they are operating on the tissues causing the symptoms?

SYNOPSIS: "Special tests" for rotator cuff–related shoulder pain (RCRSP) have passed their sell-by date. In this Viewpoint, we outline fundamental flaws in the validity of these tests and their proposed ability to accurately identify a pathoanatomical source of pain. The potential harm of these special tests comes in conjunction with imaging findings that are utilized to inform a structural diagnosis or recommend invasive procedures. We offer recommendations for performing a clinical interview and physical examination for people with RCRSP that does not include shoulder orthopaedic tests. *J Orthop Sports Phys Ther 2020;50(5):222-225. doi:10.2519/jospt.2020.0606*

KEY WORDS: *diagnostic accuracy, orthopaedic tests, rotator cuff, shoulder pain, shoulder special tests*

Convergent Validity

A valid test is one that tests what it claims to test. The most common way to investigate the validity of shoulder orthopaedic tests is to compare the results of the orthopaedic test to a method (often called the gold standard or reference standard) accepted to be good at detecting the pathology associated with or causing the symptoms. Common reference standards for the shoulder are radiographs, magnetic resonance imaging, diagnostic ultrasound, and direct observation during arthroscopy. If a test is valid to implicate a specific shoulder structure, then the test should be positive when the reference test demonstrates the pathology, and negative when the reference test is reported as normal.

Reference Standards: All That Glitters Is Not Gold

Validating shoulder orthopaedic tests to identify structures as causing symptoms is difficult, because imaging regularly detects abnormalities of the rotator cuff and bursa, acromial shape, the glenoid labrum, and other shoulder structures in people without shoulder symptoms. In 123 people with unilateral shoulder pain who had bilateral magnetic resonance imaging, there were as many abnormalities in the symptomatic shoulder as there were in the pain-free shoulder. Only

[1]Krannert School of Physical Therapy, University of Indianapolis, Indianapolis, IN. [2]School of Health and Social Work, University of Hertfordshire, Hatfield, United Kingdom. [3]Central London Community Healthcare National Health Services Trust, London, United Kingdom. [4]Department of Physical Therapy and Rehabilitation Science, Qatar University, Doha, Qatar. The authors received no funding for any portion of this article. Dr Lewis teaches and lectures internationally on the assessment and management of musculoskeletal conditions involving the shoulder. The other author certifies that he has no affiliations with or financial involvement in any organization or entity with a direct financial interest in the subject matter or materials discussed in the article. Address correspondence to Dr Paul A. Salamh, Krannert School of Physical Therapy, University of Indianapolis, 1400 East Hanna Avenue, Indianapolis, IN 46227. E-mail: salamhp@uindy.edu

full-thickness supraspinatus tears and glenohumeral osteoarthritis had a 10% higher incidence in symptomatic shoulders.[1] Magnetic resonance imaging and ultrasound are probably poor gold standard reference comparisons for shoulder tests. Therefore, at best, it is impossible to determine the validity of shoulder orthopaedic tests for RCRSP.

Isolating Specific Shoulder Structures: We Are Kidding Ourselves

Special tests designed to identify RCRSP[11] rely heavily on the assumption that a specific structure can be isolated, and that the pain reproduced with a positive finding originates from the structure being tested. For example, it is assumed that the empty-can test will isolate the supraspinatus muscle and tendon, and that the patient's shoulder pain, if reproduced by the test, must implicate the supraspinatus.

Anatomical dissection and histological investigations[4] highlight the interwoven nature of the rotator cuff tendons and their intimate relationship with capsule, ligament, and bursa tissue. How could any clinician expect to isolate an individual rotator cuff muscle and tendon from a group of related and interwoven structures using a shoulder test? To further support this argument, it is clear that the empty- and full-can tests cannot isolate the supraspinatus: during the empty-can test, 9 shoulder muscles were active; during the full-can test, 8 other muscles were active.[2] These issues pose a strong challenge to clinical reasoning to determine the exact source of symptoms based on the patient's report of pain during a special test.

If Not the Supraspinatus Tendon, Where Is the Pain Coming From?

Associating the experience of pain during shoulder examination with a specific structure lacks credibility. During the inflammatory process, interleukin-1β is released and may contribute to hyperalgesia.[7] The empty-can test compresses and stretches highly innervated bursa tissue that, in people diagnosed with RCRSP, has high concentrations of substance P and proinflammatory cytokines.[7] We appreciate that the experience of pain, an output of the brain, is much more complex and may be experienced without nociception,[6] further challenging the validity of shoulder orthopaedic tests. The empty-can test, and many others, might simply be irritating already sensitive tissue.

If Special Tests Are Not All That Special, Why Do Clinicians Still Use Them?

The current evidence challenges the clinical utility of shoulder orthopaedic tests for RCRSP and questions their widespread clinical use. There is clearly an elephant in the assessment room. We propose 3 reasons for this.

Simplicity Contemporary musculoskeletal practice is seemingly obsessed with finding a structural explanation for symptoms. There is great allure in taking a complex and multifaceted examination process and distilling it into a simple yes/no question that may be answered by a special test result.[10] A systematic review and meta-analysis of the literature examining shoulder tests could not recommend a single test to clinicians.[9] Out of 11 best-practice recommendations for care in musculoskeletal pain,[12] none included orthopaedic physical examination (special) tests.

Teaching Old Clinicians New Tricks Due to time constraints and access to research, clinicians may practice as they were trained to and may be unaware of contemporary clinical challenges, taking comfort in an "it's what we have always done" approach. Health-related research may take decades to be incorporated into practice, and by the time it has been adopted, precious little benefit may reach the intended recipient.[3]

Teaching New Clinicians Old Tricks Students are commonly taught special tests during undergraduate or postgraduate training. If attaining a level of competency is an academic expectation, students have no choice but to learn, apply, and rationalize as they are taught. Students and junior clinicians will observe practicing clinicians use and clinically reason the findings of shoulder special tests in clinical practice. For myriad reasons, it is likely that new clinicians will wish to emulate this clinical practice.

Evolving the Approach to Diagnosing Shoulder Problems

We argue that academic institutions and practicing clinicians should stop teaching and using shoulder special tests related to RCRSP. The tests have passed their sell-by date. We are grateful to the clinicians and researchers who, aiming to help their colleagues and patients, have attempted to develop clinical tests to identify the structure(s) associated with RCRSP. Given the current evidence, and until we have a reference system that can accurately detect the tissues associated with the experience of pain, clinicians and educators need to put special tests out to pasture. The tests should no longer be used to inform patients of the source of their symptoms in surgical and nonsurgical practice. Continuing to rely on special test results and imaging to inform recommendations for invasive procedures, such as injections or surgery in nontraumatic presentations, is arguably not acceptable practice.

Special tests for RCRSP do not help clinicians identify the shoulder structure causing the symptoms, and may discourage looking beyond a macropathoanatomical explanation for symptoms. It is feasible to conduct a clinical interview and physical examination without including shoulder orthopaedic (special) tests to hypothesize that RCRSP is the likely reason for symptoms (**TABLE**). If shoulder orthopaedic tests related to RCRSP are used, then interpretation should only relate to reproduction of symptoms, with no definitive emphasis on the specific structures associated with the symptoms.

Given the current evidence surrounding RCRSP, what is our answer to the

TABLE Examination Elements for Rotator Cuff–Related Shoulder Pain

Examination Component	Specific Element
Conduct comprehensive interview with the patient	• Identify changes in loading history that may support the clinical hypothesis of RCRSP • Identify the impact of the symptoms on the individual, his or her beliefs and expectations, and the valued activities the patient wishes to return to • Identify relevant psychosocial factors, lifestyle factors, current activity levels, medications (prescribed, over the counter), and supplements
Screen for serious pathology/red flags	• Consider comorbidities, risk factors (specifically age, diabetes, and overhead activities), and red flags
Use functional disability questionnaires	• General functional disability questionnaires • Shoulder-specific questionnaires • Psychosocial questionnaires
Assess impairments	• Conduct neurological screening, if appropriate • Exclude referred pain as much as possible • Conduct bilateral assessment • Assess range of motion (active and passive) • Assess strength, repetitions to pain and/or fatigue • Assess response to changes in load on the muscle-tendon units • Assess lower-limb and trunk range of movement and function • Appreciate that nociception is not necessary for the experience of pain
Provide patient with education and advice regarding the condition and management options	• Engage in shared decision making that incorporates harms, benefits, and the requirements of management options for the main management alternatives (no intervention, rehabilitation, injections, and surgery) • Aim to encourage low-risk, high-value, evidence-informed care both for the individual and the sustainability of health care provision
If the management decision is nonsurgical, then provide care based on findings of the examination addressing physical activity and function	• Prescribe a graduated rehabilitation progression for at least 3 months, with activity modification as indicated, with the aim to exceed the patient's functional expectations • Include all functional activities in rehabilitation: open-chain and closed-chain, precision, and "chaotic" activities • Address lifestyle issues: smoking, nutrition, sleep, stress • Appreciate that there is no cure and that attention to lifestyle, together with a range of whole-body exercises and activities, should be maintained and, if possible, incrementally increased, with no end date • If not achieving desired outcomes, or if the condition worsens, consider other management options—but only after harms and potential benefits have been discussed and understood

Abbreviation: RCRSP, rotator cuff–related shoulder pain.

3 questions posed earlier in this Viewpoint? A resounding "no" on all 3 counts.

Key Points

- Shoulder "special tests" cannot identify the structure causing RCRSP symptoms.
- The so-called special tests should only be considered as pain-provocation tests. If the individual has reproduced his or her symptoms during a physiological movement, activity, or functional task, then symptoms produced during the special tests do not add additional information.
- Using special tests to inform individuals of the specific source of their symptoms, and then recommending surgical or nonsurgical intervention for that structure, is arguably not best, or even acceptable, practice.
- A comprehensive clinical interview and physical examination can be used to inform a working hypothesis to implicate RCRSP without the need for special tests. ◉

STUDY DETAILS

AUTHOR CONTRIBUTIONS: Dr Salamh conceived the original idea for this Viewpoint, and both authors contributed to the manuscript.

DATA SHARING: There are no data in this manuscript.

PATIENT AND PUBLIC INVOLVEMENT: There was no patient or public involvement in the development of this Viewpoint.

ACKNOWLEDGMENTS: *The authors would like to thank Dr Clare Ardern for her expertise and guidance in the final stages of this manuscript.*

REFERENCES

1. Barreto RPG, Braman JP, Ludewig PM, Ribeiro LP, Camargo PR. Bilateral magnetic resonance imaging findings in individuals with unilateral shoulder pain. *J Shoulder Elbow Surg*. 2019;28:1699-1706. https://doi.org/10.1016/j.jse.2019.04.001
2. Boettcher CE, Ginn KA, Cathers I. The 'empty can' and 'full can' tests do not selectively activate supraspinatus. *J Sci Med Sport*. 2009;12:435-439. https://doi.org/10.1016/j.jsams.2008.09.005. Epub 2008 Dec 2.
3. Brownson RC, Kreuter MW, Arrington BA, True WR. Translating scientific discoveries into public health action: how can schools of public health move us forward? *Public Health Rep*. 2006;121:97-103. https://doi.org/10.1177/003335490612100118
4. Clark JM, Harryman DT, 2nd. Tendons, ligaments, and capsule of the rotator cuff. Gross and microscopic anatomy. *J Bone Joint Surg Am*. 1992;74:713-725.
5. Cook CE, Hegedus EJ. *Orthopedic Physical*

Examination Tests: An Evidence-Based Approach. 2nd ed. Upper Saddle River, NJ: Pearson/Prentice Hall; 2012.
6. Dean BJ, Gwilym SE, Carr AJ. Why does my shoulder hurt? A review of the neuroanatomical and biochemical basis of shoulder pain. *Br J Sports Med*. 2013;47:1095-1104. https://doi.org/10.1136/bjsports-2012-091492
7. Gotoh M, Hamada K, Yamakawa H, et al. Interleukin-1-induced subacromial synovitis and shoulder pain in rotator cuff diseases. *Rheumatology (Oxford)*. 2001;40:995-1001. https://doi.org/10.1093/rheumatology/40.9.995
8. Hegedus EJ, Cook C, Lewis J, Wright A, Park JY. Combining orthopedic special tests to improve diagnosis of shoulder pathology. *Phys Ther Sport*. 2015;16:87-92. https://doi.org/10.1016/j.ptsp.2014.08.001
9. Hegedus EJ, Goode AP, Cook CE, et al. Which physical examination tests provide clinicians with the most value when examining the shoulder? Update of a systematic review with meta-analysis of individual tests. *Br J Sports Med*. 2012;46:964-978. https://doi.org/10.1136/bjsports-2012-091066
10. Hegedus EJ, Wright AA, Cook C. Orthopaedic special tests and diagnostic accuracy studies: house wine served in very cheap containers. *Br J Sports Med*. 2017;51:1578-1579. https://doi.org/10.1136/bjsports-2017-097633
11. Lewis J. Rotator cuff related shoulder pain: assessment, management and uncertainties. *Man Ther*. 2016;23:57-68. https://doi.org/10.1016/j.math.2016.03.009
12. Lin I, Wiles L, Waller R, et al. What does best practice care for musculoskeletal pain look like? Eleven consistent recommendations from high-quality clinical practice guidelines: systematic review. *Br J Sports Med*. 2020;54:79-86. https://doi.org/10.1136/bjsports-2018-099878

ANGELA HUTCHINSON SMITH, PT, DPT[1] • **JACOB J. CAPIN,** PT, PhD[1,2] • **RYAN ZARZYCKI,** PT, PhD[3] • **LYNN SNYDER-MACKLER,** PT, ScD[1,2]

Athletes With Bone-Patellar Tendon-Bone Autograft for Anterior Cruciate Ligament Reconstruction Were Slower to Meet Rehabilitation Milestones and Return-to-Sport Criteria Than Athletes With Hamstring Tendon Autograft or Soft Tissue Allograft : Secondary Analysis From the ACL-SPORTS Trial

OBJECTIVE: Graft choices for athletes undergoing anterior cruciate ligament reconstruction (ACLR) include bone-patellar tendon-bone (BPTB) and hamstring tendon (HT) autografts and soft tissue allografts. The objective was to assess time to meet clinical milestones by graft type in athletes who completed a return-to-sport (RTS) program after ACLR.

DESIGN: Retrospective cohort study.

METHODS: Seventy-nine athletes enrolled after ACLR (allograft, n = 18; BPTB, n = 24; HT, n = 37). Time from surgery to meet (1) enrollment criteria (12 or more weeks post surgery, 80% or greater isometric quadriceps strength index, minimal effusion, and full knee range of motion), and (2) RTS criteria (90% or greater quadriceps strength index, hop testing limb symmetry, and patient-reported outcomes) was calculated. Quadriceps strength, hop performance, and patient-reported outcomes were measured before and after training, and at 1 year post surgery. Descriptive statistics, chi-square tests, and 1-way analyses of variance (α = .05) were used to analyze differences among graft types.

RESULTS: On average, the BPTB group (28.5 ± 7.6 weeks) took longer to meet enrollment milestones than the HT (22.5 ± 7.6 weeks, P = .007) and allograft (18.9 ± 5.8 weeks, P<.001) groups. The BPTB group (44.7 ± 15.8 weeks) took longer from surgery to meet RTS criteria than the HT (32.5 ± 9.9 weeks, P = .001) and allograft (29.3 ± 9.0 weeks, P<.001) groups. After training, the quadriceps strength index was lower in the BPTB group (86.1% ± 11.4%) than it was in the HT (96.1% ± 12.9%, P = .004) and allograft (96.9% ± 5.9%, P = .009) groups.

CONCLUSION: Athletes with a BPTB autograft may take longer than athletes with an HT autograft or a soft tissue allograft to complete postoperative rehabilitation, recover quadriceps strength, and meet RTS criteria. *J Orthop Sports Phys Ther 2020;50(5):259-266. Epub 27 Nov 2019. doi:10.2519/jospt.2020.9111*

KEY WORDS: *ACL reconstruction, knee, outcome measures, rehabilitation, return to sport*

Although anterior cruciate ligament reconstruction (ACLR) is one of the most common sports medicine orthopaedic procedures, graft selection for the surgery is still a highly debated topic, particularly for athletes returning to sport. Many factors can contribute to graft choice, including age, sex, athlete/surgeon preference, return-to-activity goals, patient outcomes, and risk of graft failure. The most common autograft choices are bone-patellar tendon-bone

[1]Department of Physical Therapy, University of Delaware, Newark, DE. [2]Biomechanics and Movement Science Program, University of Delaware, Newark, DE. [3]Department of Physical Therapy, Arcadia University, Glenside, PA. The Institutional Review Board of the University of Delaware approved this study protocol. This work was supported by National Institutes of Health grants R01-AR048212, R37-HD037985, P30-GM103333, U54-GM104941, F30-HD096830, and T32-HD00749. Dr Capin received funding from the University of Delaware (University Doctoral Fellowship Award and University of Delaware Dissertation Fellowship Award). His work was supported in part by Promotion of Doctoral Studies Level I and Level II Scholarships from the Foundation for Physical Therapy Research. The parent study of this secondary analysis was registered with www.clinicaltrials.gov (NCT01773317). The authors certify that they have no affiliations with or financial involvement in any organization or entity with a direct financial interest in the subject matter or materials discussed in the article. Address correspondence to Dr Angela H. Smith, 540 South College Avenue, Suite 160, Newark, DE 19713. E-mail: ahutch@udel.edu

(BPTB) and quadrupled hamstring tendon (HT).[15,26,49]

The BPTB autograft has been the gold standard for reconstruction[25] due to graft stability associated with bone-to-bone fixation.[7] However, BPTB grafts are linked to anterior knee pain, particularly with kneeling,[19,42] and clinical, radiographic, and histologic abnormalities at the donor site.[25] Quadrupled hamstring tendon autografts have grown in favor due to larger graft diameter and sparing of the knee extensor mechanism.[10,17] However, HT autografts are associated with complications including tunnel widening, problematic fixation, increased laxity, and poor postoperative functioning of the harvested hamstring.[6,17]

The use of allografts has risen over the past 20 years due to the lack of donor site morbidity and reduced operative time.[5,44] However, allografts have fallen out of favor in the past decade because of a higher risk of graft failure compared to autografts among young, active individuals.[23,24,44] Other risks associated with allograft use include delayed bone integration and infection.[10]

Medium- and long-term outcomes in strength, range of motion (ROM), knee stability, subjective reports, and patient performance are similar between HT and BPTB autografts.[9,17,19,27] Similar results have also been reported in pain, laxity, ROM, patient-reported outcomes, and return to preinjury activity when comparing autografts to allografts.[36] The impact of graft choice on outcomes, including timelines to meet clinical milestones (eg, return-to-sport [RTS] criteria) or response to specific rehabilitation protocols, is unclear. Clinicians need this information as they strive to best educate patients regarding postoperative outcomes and timelines, maximize results during rehabilitation, and help athletes prepare for the demands of return to sport.

Given the dramatic influence that early return to sport has on second injury risk,[8,16,28] comparing rehabilitation timelines and clinical outcomes at different postoperative stages is important. Therefore, the primary purpose of this analysis was to investigate the time taken to meet postoperative clinical milestones (enrollment and RTS criteria) according to graft type in athletes who enrolled in an RTS program as part of the Anterior Cruciate Ligament-Specialized Post-Operative Return To Sports (ACL-SPORTS) clinical trial. Our secondary objective was to compare clinical (functional and patient-reported) outcomes among these athletes by graft type.

METHODS

Participants

Seventy-nine athletes (40 men, 39 women) between 13 and 55 years of age, who underwent primary ACLR, were included in this secondary analysis of a prospective randomized controlled trial (parent study registered at www.clinicaltrials.gov; NCT01773317). Prior to inclusion, all participants gave written informed consent (or assent, when younger than 18 years, with parent/guardian written informed consent). Participants were recruited from the University of Delaware Physical Therapy Clinic, and from the community via physician and physical therapist referral, newspaper advertisement, and word of mouth. All participants were level 1 (n = 72) or level 2 (n = 7) athletes[11] (minimum of 50 hours per year) prior to surgery and intended to return to their prior level of sporting activity following ACLR.

Thirty different orthopaedic surgeons performed surgery using the most common graft types, including HT autograft, BPTB autograft, or soft tissue allograft. Potential participants were excluded if they (1) did not meet enrollment criteria by 9 months, (2) had a history of ACLR, (3) had a history of a significant lower extremity injury or surgery, or (4) had a grade III concomitant ligamentous injury or large osteochondral defect (greater than 1 cm^2). Early postoperative rehabilitation took place at multiple clinics and was not controlled for in order to form a more generalizable population. Strict enrollment criteria were used to ensure a homogeneous population at the time of training.

Enrollment Criteria

Participants were enrolled in the ACL-SPORTS clinical trial, between 3 and 9 months (mean ± SD, 23.5 ± 8.0 weeks) after surgery, when they met all enrollment criteria. Prior to enrollment, participants had to achieve the following clinical milestones: (1) full knee ROM, (2) minimal to no knee effusion, and (3) a quadriceps strength index (QI) of 80% or greater. Participants also had to complete a walk/jog progression prior to enrollment to assess the ability of the athlete's knee to tolerate increased loading without increased knee soreness or effusion. These stringent enrollment criteria ensured that each participant was safe and prepared to begin the higher-level activity required in the training program.

Interventions

All participants completed 10 sessions of a comprehensive RTS program over a 5- to 7-week period (1-2 sessions per week), either with or without perturbation training.[13] Our program was developed based on the primary anterior cruciate ligament (ACL) injury prevention literature[2,46] and included progressive quadriceps strengthening, neuromuscular training activities, plyometrics, and agility exercises. Participants completed the RTS program under one-on-one supervision from a licensed physical therapist in the University of Delaware's Physical Therapy Clinic.

Participants progressed through the 10-session ACL-SPORTS protocol.[47] Physical therapists used soreness rules[12] and monitored effusion[43] to guide clinical decision making for appropriate progression. Appropriate landing form and lower extremity biomechanics were emphasized throughout the program, with feedback from the treating physical therapist. Training variables and progression at each session were adapted based on participant performance. The final stage of the program focused on incorporating distractions and sport-specific skills

within the activities of the treatment protocol (eg, stick handling with direction changes for a lacrosse player).

Half of the cohort also received 10 sessions of perturbation training. There were no differences following training in quadriceps strength, hop tests, and self-reported function between the participants in our cohort who received perturbation training and those who did not.[3,4] Thus, the present study did not include the perturbation training variable (ie, perturbation versus no perturbation) in the analyses.

If participants did not meet the University of Delaware's RTS criteria at the posttraining time point, they were educated on a continued home program to address remaining impairments and seen for additional sessions if deemed necessary by the testing physical therapist. Participants returned for follow-up testing until all RTS criteria were met: 90% or greater on the QI, the limb symmetry index (LSI) for all 4 hop tests, the Knee Outcome Survey-Activities of Daily Living Scale (KOS-ADLS), and the global rating scale (GRS). Participants returned for testing again at 1 year after surgery.

Functional Testing and Patient-Reported Outcomes

At the time of enrollment (pretraining) and after finishing the RTS program (posttraining), all participants completed a clinical test battery that included isometric quadriceps strength, single-leg hop testing, the KOS-ADLS, and the GRS. Additional patient-reported outcome measures collected included the International Knee Documentation Committee 2000 Subjective Knee Evaluation Form (IKDC) and the Knee injury and Osteoarthritis Outcome Score (KOOS).

Quadriceps strength was assessed via maximal voluntary isometric contraction using an electromechanical dynamometer (KinCom; DJO Global, Lewisville, TX or System 4; Biodex, Shirley, NY). Maximal voluntary isometric contractions were collected with participants seated, the hips and knees flexed to 90°, and the axis of rotation of the knee attachment aligned with the axis of rotation of the knee.[41] The participant's QI was calculated by dividing the maximal voluntary isometric contraction of the involved side by the maximal voluntary isometric contraction of the uninvolved side and multiplying by 100.

Hop testing, a reliable and valid performance-based outcome measure following ACLR,[33,37] was completed using a series of single-limb hop tests, as described by Noyes et al.[32] This sequence of tests was performed on a line 6 m long and 15 cm wide.[29] We measured the single hop for distance, the crossover hop for distance, the triple hop for distance, and the 6-meter timed hop. Each hop was completed on the uninvolved limb first, with 2 practice trials followed by 2 measured trials. This sequence was repeated on the involved limb. The mean distance of the 2 measured trials was calculated for each leg for the single hop, crossover hop, and triple hop. We calculated the LSI by computing the ratio of the mean distance on the involved limb to the mean distance on the uninvolved limb, multiplied by 100. For the timed hop, the LSI was calculated as a ratio of the uninvolved-limb mean time to the involved-limb mean time, multiplied by 100.

Participants completed several patient-reported outcome measures to assess knee symptoms and function. The KOS-ADLS is a valid, reliable, and responsive measurement tool to assess the functional limitations in a varied population with knee injuries and impairments.[22] The GRS is a single question that asks the patient to rate the function of his or her knee on a scale from 0 to 100, with 100 representing function before injury.[21] The IKDC is a measure of knee-specific symptoms, function, and sports activities, and is valid and reliable for a variety of knee conditions, including ACL injury.[20] The KOOS is a reliable measure often used in the ACL population[1,14,30,48] and consists of 5 subscales assessing patient symptoms, complaints of pain, function in daily life, function during sports and recreational activities, and knee-related quality of life.[38]

Statistical Analysis

Statistical analyses were performed using SPSS Version 25 (IBM Corporation, Armonk, NY). Primary variables of interest were the time from surgery to meet enrollment criteria and the time from surgery to meet RTS criteria. Functional and patient-reported clinical outcomes of secondary interest were the QI, LSI on each hop test, KOS-ADLS, GRS, IKDC, and KOOS scores at pretraining, posttraining, and 1 year after ACLR. Demographic characteristics and surgical details were compared across groups using 1-way analyses of variance and chi-square tests of proportions for continuous and categorical variables, respectively. We used 2 one-way analyses of variance, with and without the covariates of age and sex, to compare across groups our 2 primary outcomes of interest: (1) time to meet enrollment criteria and (2) time to meet RTS criteria. We used 1-way analyses of variance to compare clinical and functional outcomes across groups (secondary analyses). Post hoc *t* tests with Bonferroni corrections were used to test differences between groups if the *P* value for the model was statistically significant. A priori statistical significance was set at $\alpha = .05$ for all analyses. No a priori power calculation was performed because this was a secondary analysis of a pre-existing data set; all available data were used in the present study, and the primary analyses of the present study were adequately powered.

RESULTS

Seventy-nine participants completed the RTS program (allograft, n = 18; BPTB, n = 24; HT, n = 37) (**TABLE 1**). The allograft group was older than the BPTB and HT groups (post hoc, $P<.001$), but the HT and BPTB groups did not differ in age ($P = 1.000$). There was an interaction in distribution of sex and graft type, with more men in the allograft group and more women in the

BPTB group. There were no between-group differences for body mass index, training group, medial or lateral meniscus treatment, or preinjury level of sport.

Time to Meet Postoperative Clinical Milestones

There was a significant effect of graft type on the time from surgery to meet enrollment criteria in the unadjusted model (P<.001); graft type remained the only significant predictor (P = .005) in the full model, which included the covariates of age (P = .789) and sex (P = .237). There was a significant effect of graft type on the time from surgery to meet RTS criteria in the unadjusted model (P<.001); graft type was the only significant predictor (P = .001) in the full model, which included the covariates of age (P = .804) and sex (P = .973).

The BPTB group took longer to meet postoperative clinical milestones for enrollment and return to sport (**FIGURE 1**). The BPTB group took 6 weeks longer than the HT group (P = .007) and 9.5 weeks longer than the allograft group (P<.001) to meet the clinical milestones for enrollment. There was no difference (P = .283) in time to enrollment between the HT and allograft groups. Seventy-five participants met all RTS criteria at some point after finishing the RTS program. Of the 4 who did not meet the criteria, 3 had BPTB grafts and 1 had an HT graft. For time from surgery to meet RTS criteria, the BPTB group took 12 weeks longer than the HT group (P = .001) and 15.5 weeks longer than the allograft group (P<.001), but there was no difference (P = 1.000) between the HT and allograft groups.

Clinical Outcomes: Functional Testing and Patient-Reported Outcome Measures

There were group differences in clinical outcome measures at enrollment (**APPENDIX A**, available at www.jospt.org) and posttraining (**APPENDIX B**, available at www.jospt.org), but not at 1 year after ACLR (**APPENDIX C**, available at www.jospt.org).

At enrollment, there were differences between groups for all hop tests and the KOS-ADLS. There were no differences between groups for the GRS, IKDC, or any of the KOOS subscales.

After completing the RTS program, 79 participants completed strength testing and patient-reported outcome measures. Sixty-four participants completed posttraining hop testing; testing was deferred for 15 participants due to knee effusion, a QI less than 80%, and/or pain (**TABLE 2**). The QI was lower in the BPTB group than in the HT (P = .004) and allograft (P = .009) groups, but there was no difference (P = 1.000) between the HT and allograft groups (**FIGURE 2**). The BPTB group had a lower KOS-ADLS score than the HT group (P = .007); there were no differences between the allograft and BPTB (P = .479) or the allograft and HT (P = .548) groups.

Sixty-six participants completed all testing (strength, hop testing, and patient-reported outcomes) at 1 year post ACLR. Among participants with incomplete data, 10 completed all testing with the exception of hop testing, which was deferred due to pain, a decreased QI, increased effusion, or second injury (**TABLE 2**). One participant only completed patient-reported outcome measures because she lived out of the area. Two participants were lost to follow-up and did not complete any testing at 1 year. There

TABLE 1 Athlete Demographics and Graft Type Groups[a]

	Allograft (n = 18)	BPTB Autograft (n = 24)	HT Autograft (n = 37)	*P* Value
Age at surgery, y	30.5 ± 10.5	18.3 ± 3.2	18.5 ± 3.3	<.001
Body mass index, kg/m^2	27.1 ± 3.3	25.9 ± 3.4	25.6 ± 3.2	.298
Sex, n				.044
Female	5	16	18	
Male	13	8	19	
Training group, n				.734
SAPP	10	13	17	
SAPP plus perturbation training	8	11	20	
Medial meniscus treatment[b]				.479
None	10	13	22	
Partial meniscectomy	5	1	8	
Repair	2	3	7	
Lateral meniscus treatment[b]				.915
None	10	8	19	
Partial meniscectomy	6	7	13	
Repair	1	2	5	
Preinjury level of sport				.929
Level 1	16	22	34	
Level 2	2	2	3	

Abbreviations: BPTB, bone-patellar tendon-bone; HT, hamstring tendon; SAPP, strength, agility, plyometric, and secondary prevention.
[a]*Values are mean ± SD unless otherwise indicated.*
[b]*Meniscus treatment data were not available for 8 athletes.*

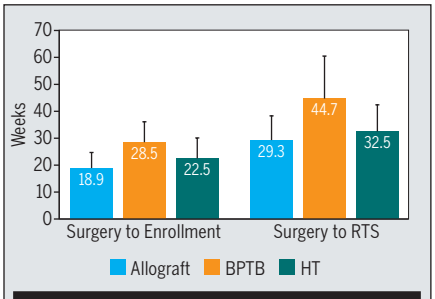

FIGURE 1. Time to meet enrollment and RTS criteria. Abbreviations: BPTB, bone-patellar tendon-bone autograft; HT, hamstring tendon autograft; RTS, return to sport.

were no between-group differences for any clinical variable at 1 year.

DISCUSSION

The objective of this secondary analysis was to compare timelines to meet important postoperative clinical milestones between athletes with different ACLR graft types who enrolled in an RTS program. Athletes with BPTB grafts took longer to meet enrollment and RTS criteria than those who received an HT autograft or a soft tissue allograft. Accounting for age and sex, graft type was the discriminating factor, suggesting that graft type has an impact on rehabilitation and return-to-play timelines after ACLR.

Our enrollment criteria encompassed important late-stage clinical markers that identify when a patient is ready to move on to higher-level activity such as running, agility, and plyometrics. The BPTB group took 1.5 months longer from ACLR than the HT group and 2.5 months longer than the allograft group to achieve these clinical milestones, indicating that those with BPTB grafts may take longer to recover full knee ROM, reduce effusion, and recover quadriceps strength after ACLR. The BPTB group did not meet RTS criteria until over 10 months after surgery; the allograft and HT groups met these criteria at 6.5 and 7.5 months post surgery, respectively. The time difference could not simply be attributed to the BPTB group having started the training later than the other groups, but was also due to the additional time it took after completing the RTS program to meet these RTS criteria.

Our secondary aim was to assess differences between graft types with regard to functional and patient-reported outcomes at different stages of rehabilitation (enrollment, posttraining, and 1 year post surgery). The BPTB group had a lower QI after completing the RTS program, suggesting that athletes with a BPTB graft may require additional time or interventions to restore quadriceps strength after ACLR. Clinicians should consider continuing unilateral quadriceps strengthening in the RTS phase of rehabilitation, focusing on providing appropriate (heavy resistance) loading to facilitate strength gains in athletes with a BPTB graft. By 1 year, outcomes did not differ between groups, indicating that those in the BPTB group "caught up" to their peers in the period between posttraining and 1 year.

Our results have important clinical implications for graft selection, as postoperative outcomes and timelines for rehabilitation may inform an athlete's graft selection for ACLR. If an athlete is considering an accelerated return to sport following ACLR, opting for an allograft or HT autograft may facilitate faster rehabilitation and return to play. However, in light of growing evidence, RTS timelines and risk of second injury need to be considered. At least 1 in 4 young athletes experience a second ACL injury following RTS,[34,35,45] and these injuries usually occur early after return, with minimal athletic exposure.[35] For every 1-month delay in return to sport up to 9 months, the rate of knee reinjury can be halved.[16] In light of the time frames for each graft type meeting RTS criteria in this study, athletes in the allograft and HT groups may be at a higher risk of sustaining another knee injury when they return to sport, as they meet RTS criteria earlier than those in the BPTB group.

Graft rupture rates may not be equivalent between graft types, particularly among young athletes. The evidence is clear that the use of an autograft is preferred over an allograft for primary ACLR in young, active individuals, due to the increased risk of revision with allografts.[5,23,31,44] The trend toward the use of allografts in older patients was reflected in our study by the age dif-

TABLE 2 Reasons for Not Completing Hop Testing at Posttraining and at 1-Year Follow-up

Timepoint	Allograft	BPTB Autograft	HT Autograft
Posttraining	NA	• Pain, n = 1 • Quadriceps strength/activation, n = 4 • Combination of pain, quadriceps strength, and/or effusion, n = 3	• Effusion, n = 3 • Quadriceps strength/activation, n = 4
1-y follow-up	• Second injury, n = 1	• Effusion, n = 1 • Quadriceps strength/activation, n = 1 • Pain, n = 1	• Effusion, n = 1 • Quadriceps strength/activation, n = 2 • Second injury, n = 3

Abbreviations: BPTB, bone-patellar tendon-bone; HT, hamstring tendon; NA, not applicable.

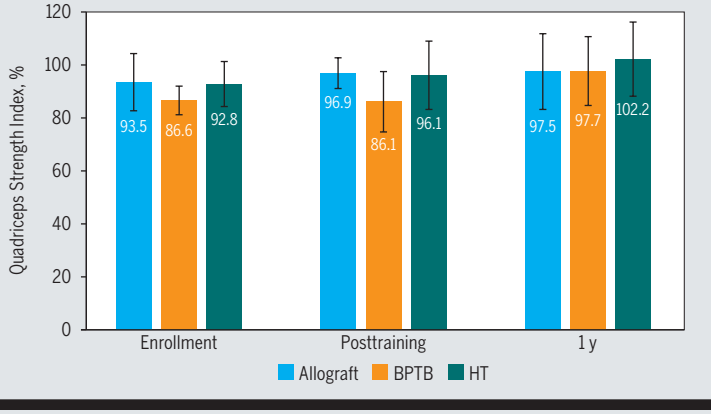

FIGURE 2. Quadriceps index at enrollment, posttraining, and 1-year follow-up. Abbreviations: BPTB, bone-patellar tendon-bone autograft; HT, hamstring tendon autograft.

ference in the allograft group versus the HT and BPTB groups. However, our allograft group was highly active. With regard to differences in autograft choice, similar mid- to long-term clinical, patient-reported, and performance outcomes have been reported between HT and BPTB autografts.[18,26,49] However, when comparing HT and BPTB grafts, failure rates are slightly higher in HT autografts, and there is a lower risk of revision with BPTB autografts.[15,39,40] In the case of our findings, the delay in meeting RTS criteria gives the BPTB graft a longer time to incorporate and may contribute to the lower risk of graft rupture, as these athletes return to play later, at a point when the risk of second injury has declined. Future research should explore relationships between second ACL injury and graft type and timing of return to sport.

There are limitations to this study. Postoperative rehabilitation prior to enrollment was not standardized and many surgeons were involved, but this also improves the generalizability. All athletes had to meet common enrollment criteria prior to participating in the RTS program, ensuring a standardized starting point. Although many physical therapists from the University of Delaware treated the participants in the RTS program, all physical therapists used the ACL-SPORTS protocol[47] to progress the athletes through the program. Again, this increases generalizability, as any clinician could use the protocol to complete the RTS program. There was an unequal distribution between groups in sex and age, with more men in the allograft group and more women in the BPTB group; the allograft group was older than the HT and BPTB groups. However, graft type alone was the discriminating factor when adjusting for sex and age. Although all participants completed the comprehensive RTS program, half also received additional perturbation training. Participants who received perturbation training were equally distributed among the graft types. Previously published data from our clinical trial indicate that there are no differences in clinical or functional outcomes in those completing the RTS program with or without perturbation training at 1 or 2 years after ACLR.[3,4]

CONCLUSION

Athletes who received a BPTB autograft took between 1.5 and 2.5 months longer to meet key rehabilitation milestones than athletes who received an allograft or an HT autograft, and up to 4 months longer to meet RTS criteria. The BPTB group also had quadriceps weakness (QI = 86%) after RTS training, whereas the allograft (QI = 97%) and HT (QI = 96%) groups did not. In our cohort, athletes with a BPTB graft needed additional time to complete postoperative rehabilitation, recover quadriceps strength, and meet RTS criteria, delaying their return to the field. ◉

KEY POINTS

FINDINGS: Athletes who received a bone-patellar tendon-bone autograft took longer than those who received a soft tissue allograft or a hamstring tendon autograft to reach important postoperative clinical milestones, including recovering quadriceps strength and meeting return-to-sport criteria.

IMPLICATIONS: The increased time to achieve postoperative clinical and return-to-sport milestones means athletes with bone-patellar tendon-bone grafts returned to sport later after anterior cruciate ligament reconstruction than athletes with other graft types; this delay may help protect these athletes from second anterior cruciate ligament injury.

CAUTION: Anterior cruciate ligament reconstruction was completed by many (30) orthopaedic surgeons, and early rehabilitation was not controlled prior to enrollment. All participants were athletes planning to return to level 1 to 2 sporting activity, which may limit the generalizability of these findings to all athletic populations.

REFERENCES

1. Ahldén M, Samuelsson K, Sernert N, Forssblad M, Karlsson J, Kartus J. The Swedish National Anterior Cruciate Ligament Register: a report on baseline variables and outcomes of surgery for almost 18,000 patients. *Am J Sports Med*. 2012;40:2230-2235. https://doi.org/10.1177/0363546512457348
2. Arundale AJH, Bizzini M, Giordano A, et al. Exercise-based knee and anterior cruciate ligament injury prevention. *J Orthop Sports Phys Ther*. 2018;48:A1-A42. https://doi.org/10.2519/jospt.2018.0303
3. Arundale AJH, Capin JJ, Zarzycki R, Smith A, Snyder-Mackler L. Functional and patient-reported outcomes improve over the course of rehabilitation: a secondary analysis of the ACL-SPORTS trial. *Sports Health*. 2018;10:441-452. https://doi.org/10.1177/1941738118779023
4. Arundale AJH, Cummer K, Capin JJ, Zarzycki R, Snyder-Mackler L. Report of the clinical and functional primary outcomes in men of the ACL-SPORTS trial: similar outcomes in men receiving secondary prevention with and without perturbation training 1 and 2 years after ACL reconstruction. *Clin Orthop Relat Res*. 2017;475:2523-2534. https://doi.org/10.1007/s11999-017-5280-2
5. Bottoni CR, Smith EL, Shaha J, et al. Autograft versus allograft anterior cruciate ligament reconstruction: a prospective, randomized clinical study with a minimum 10-year follow-up. *Am J Sports Med*. 2015;43:2501-2509. https://doi.org/10.1177/0363546515596406
6. Bourke HE, Gordon DJ, Salmon LJ, Waller A, Linklater J, Pinczewski LA. The outcome at 15 years of endoscopic anterior cruciate ligament reconstruction using hamstring tendon autograft for 'isolated' anterior cruciate ligament rupture. *J Bone Joint Surg Br*. 2012;94:630-637. https://doi.org/10.1302/0301-620X.94B5.28675
7. Brown CH, Jr., Hecker AT, Hipp JA, Myers ER, Hayes WC. The biomechanics of interference screw fixation of patellar tendon anterior cruciate ligament grafts. *Am J Sports Med*. 1993;21:880-886. https://doi.org/10.1177/036354659302100622
8. Capin JJ, Khandha A, Zarzycki R, Manal K, Buchanan TS, Snyder-Mackler L. Gait mechanics and second ACL rupture: implications for delaying return-to-sport. *J Orthop Res*. 2017;35:1894-1901. https://doi.org/10.1002/jor.23476
9. Carter TR, Edinger S. Isokinetic evaluation of anterior cruciate ligament reconstruction: hamstring versus patellar tendon. *Arthroscopy*. 1999;15:169-172. https://doi.org/10.1053/ar.1999.v15.0150161
10. Cerulli G, Placella G, Sebastiani E, Tei MM, Speziali A, Manfreda F. ACL reconstruction: choosing the graft. *Joints*. 2013;1:18-24.
11. Daniel DM, Stone ML, Dobson BE, Fithian DC, Rossman DJ, Kaufman KR. Fate of the ACL-injured patient: a prospective outcome study.

Am J Sports Med. 1994;22:632-644. https://doi.org/10.1177/036354659402200511
12. Fees M, Decker T, Snyder-Mackler L, Axe MJ. Upper extremity weight-training modifications for the injured athlete. *Am J Sports Med*. 1998;26:732-742. https://doi.org/10.1177/03635465980260052301
13. Fitzgerald GK, Axe MJ, Snyder-Mackler L. Proposed practice guidelines for nonoperative anterior cruciate ligament rehabilitation of physically active individuals. *J Orthop Sports Phys Ther*. 2000;30:194-203. https://doi.org/10.2519/jospt.2000.30.4.194
14. Frobell RB, Roos HP, Roos EM, Roemer FW, Ranstam J, Lohmander LS. Treatment for acute anterior cruciate ligament tear: five year outcome of randomised trial. *BMJ*. 2013;346:f232. https://doi.org/10.1136/bmj.f232
15. Gifstad T, Foss OA, Engebretsen L, et al. Lower risk of revision with patellar tendon autografts compared with hamstring autografts: a registry study based on 45,998 primary ACL reconstructions in Scandinavia. *Am J Sports Med*. 2014;42:2319-2328. https://doi.org/10.1177/0363546514548164
16. Grindem H, Snyder-Mackler L, Moksnes H, Engebretsen L, Risberg MA. Simple decision rules can reduce reinjury risk by 84% after ACL reconstruction: the Delaware-Oslo ACL cohort study. *Br J Sports Med*. 2016;50:804-808. https://doi.org/10.1136/bjsports-2016-096031
17. Herrington L, Wrapson C, Matthews M, Matthews H. Anterior cruciate ligament reconstruction, hamstring versus bone–patella tendon–bone grafts: a systematic literature review of outcome from surgery. *Knee*. 2005;12:41-50. https://doi.org/10.1016/j.knee.2004.02.003
18. Holm I, Øiestad BE, Risberg MA, Aune AK. No difference in knee function or prevalence of osteoarthritis after reconstruction of the anterior cruciate ligament with 4-strand hamstring autograft versus patellar tendon–bone autograft: a randomized study with 10-year follow-up. *Am J Sports Med*. 2010;38:448-454. https://doi.org/10.1177/0363546509350301
19. Hui C, Salmon LJ, Kok A, Maeno S, Linklater J, Pinczewski LA. Fifteen-year outcome of endoscopic anterior cruciate ligament reconstruction with patellar tendon autograft for "isolated" anterior cruciate ligament tear. *Am J Sports Med*. 2011;39:89-98. https://doi.org/10.1177/0363546510379975
20. Irrgang JJ, Anderson AF, Boland AL, et al. Development and validation of the International Knee Documentation Committee Subjective Knee Form. *Am J Sports Med*. 2001;29:600-613. https://doi.org/10.1177/03635465010290051301
21. Irrgang JJ, Ho H, Harner CD, Fu FH. Use of the International Knee Documentation Committee guidelines to assess outcome following anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 1998;6:107-114. https://doi.org/10.1007/s001670050082
22. Irrgang JJ, Snyder-Mackler L, Wainner RS, Fu FH, Harner CD. Development of a patient-reported measure of function of the knee. *J Bone Joint Surg Am*. 1998;80:1132-1145. https://doi.org/10.2106/00004623-199808000-00006
23. Kaeding CC, Pedroza AD, Reinke EK, et al. Change in anterior cruciate ligament graft choice and outcomes over time. *Arthroscopy*. 2017;33:2007-2014. https://doi.org/10.1016/j.arthro.2017.06.019
24. Kaeding CC, Pedroza AD, Reinke EK, Huston LJ, MOON Consortium, Spindler KP. Risk factors and predictors of subsequent ACL injury in either knee after ACL reconstruction: prospective analysis of 2488 primary ACL reconstructions from the MOON cohort. *Am J Sports Med*. 2015;43:1583-1590. https://doi.org/10.1177/0363546515578836
25. Kartus J, Movin T, Karlsson J. Donor-site morbidity and anterior knee problems after anterior cruciate ligament reconstruction using autografts. *Arthroscopy*. 2001;17:971-980. https://doi.org/10.1053/jars.2001.28979
26. Kautzner J, Kos P, Hanus M, Trc T, Havlas V. A comparison of ACL reconstruction using patellar tendon versus hamstring autograft in female patients: a prospective randomised study. *Int Orthop*. 2015;39:125-130. https://doi.org/10.1007/s00264-014-2495-7
27. Keays SL, Bullock-Saxton JE, Keays AC, Newcombe PA, Bullock MI. A 6-year follow-up of the effect of graft site on strength, stability, range of motion, function, and joint degeneration after anterior cruciate ligament reconstruction: patellar tendon versus semitendinosus and gracilis tendon graft. *Am J Sports Med*. 2007;35:729-739. https://doi.org/10.1177/0363546506298277
28. Laboute E, Savalli L, Puig P, et al. Analysis of return to competition and repeat rupture for 298 anterior cruciate ligament reconstructions with patellar or hamstring tendon autograft in sportspeople. *Ann Phys Rehabil Med*. 2010;53:598-614. https://doi.org/10.1016/j.rehab.2010.10.002
29. Logerstedt D, Grindem H, Lynch A, et al. Single-legged hop tests as predictors of self-reported knee function after anterior cruciate ligament reconstruction: the Delaware-Oslo ACL cohort study. *Am J Sports Med*. 2012;40:2348-2356. https://doi.org/10.1177/0363546512457551
30. Magnussen RA, Granan LP, Dunn WR, et al. Cross-cultural comparison of patients undergoing ACL reconstruction in the United States and Norway. *Knee Surg Sports Traumatol Arthrosc*. 2010;18:98-105. https://doi.org/10.1007/s00167-009-0919-5
31. Maletis GB, Inacio MC, Desmond JL, Funahashi TT. Reconstruction of the anterior cruciate ligament: association of graft choice with increased risk of early revision. *Bone Joint J*. 2013;95-B:623-628. https://doi.org/10.1302/0301-620X.95B5.30872
32. Noyes FR, Barber SD, Mangine RE. Abnormal lower limb symmetry determined by function hop tests after anterior cruciate ligament rupture. *Am J Sports Med*. 1991;19:513-518. https://doi.org/10.1177/036354659101900518
33. Paterno MV, Greenberger HB. The test-retest reliability of a one legged hop for distance in young adults with and without ACL reconstruction. *Isokinet Exerc Sci*. 1996;6:1-6. https://doi.org/10.3233/IES-1996-6101
34. Paterno MV, Rauh MJ, Schmitt LC, Ford KR, Hewett TE. Incidence of contralateral and ipsilateral anterior cruciate ligament (ACL) injury after primary ACL reconstruction and return to sport. *Clin J Sport Med*. 2012;22:116-121. https://doi.org/10.1097/JSM.0b013e318246ef9e
35. Paterno MV, Rauh MJ, Schmitt LC, Ford KR, Hewett TE. Incidence of second ACL injuries 2 years after primary ACL reconstruction and return to sport. *Am J Sports Med*. 2014;42:1567-1573. https://doi.org/10.1177/0363546514530088
36. Pujji O, Keswani N, Collier N, Black M, Doos L. Evaluating the functional results and complications of autograft vs allograft use for reconstruction of the anterior cruciate ligament: a systematic review. *Orthop Rev*. 2017;9:32-37. https://doi.org/10.4081/or.2017.6833
37. Reid A, Birmingham TB, Stratford PW, Alcock GK, Giffin JR. Hop testing provides a reliable and valid outcome measure during rehabilitation after anterior cruciate ligament reconstruction. *Phys Ther*. 2007;87:337-349. https://doi.org/10.2522/ptj.20060143
38. Roos EM, Roos HP, Lohmander LS, Ekdahl C, Beynnon BD. Knee Injury and Osteoarthritis Outcome Score (KOOS)—development of a self-administered outcome measure. *J Orthop Sports Phys Ther*. 1998;28:88-96. https://doi.org/10.2519/jospt.1998.28.2.88
39. Samuelsen BT, Webster KE, Johnson NR, Hewett TE, Krych AJ. Hamstring autograft versus patellar tendon autograft for ACL reconstruction: is there a difference in graft failure rate? A meta-analysis of 47,613 patients. *Clin Orthop Relat Res*. 2017;475:2459-2468. https://doi.org/10.1007/s11999-017-5278-9
40. Shakked R, Weinberg M, Capo J, Jazrawi L, Strauss E. Autograft choice in young female patients: patella tendon versus hamstring. *J Knee Surg*. 2017;30:258-263. https://doi.org/10.1055/s-0036-1584561
41. Snyder-Mackler L, Delitto A, Bailey SL, Stralka SW. Strength of the quadriceps femoris muscle and functional recovery after reconstruction of the anterior cruciate ligament. A prospective, randomized clinical trial of electrical stimulation. *J Bone Joint Surg Am*. 1995;77:1166-1173. https://doi.org/10.2106/00004623-199508000-00004
42. Spindler KP, Kuhn JE, Freedman KB, Matthews CE, Dittus RS, Harrell FE, Jr. Anterior cruciate ligament reconstruction autograft choice: bone-tendon-bone versus hamstring: does it really matter? A systematic review. *Am J Sports Med*. 2004;32:1986-1995. https://doi.org/10.1177/0363546504271211
43. Sturgill LP, Snyder-Mackler L, Manal TJ, Axe MJ. Interrater reliability of a clinical scale to assess knee joint effusion. *J Orthop Sports Phys Ther*. 2009;39:845-849. https://doi.org/10.2519/

jospt.2009.3143
44. Wasserstein D, Sheth U, Cabrera A, Spindler KP. A systematic review of failed anterior cruciate ligament reconstruction with autograft compared with allograft in young patients. *Sports Health*. 2015;7:207-216. https://doi.org/10.1177/1941738115579030
45. Webster KE, Feller JA, Leigh WB, Richmond AK. Younger patients are at increased risk for graft rupture and contralateral injury after anterior cruciate ligament reconstruction. *Am J Sports Med*. 2014;42:641-647. https://doi.org/10.1177/0363546513517540
46. Webster KE, Hewett TE. Meta-analysis of meta-analyses of anterior cruciate ligament injury reduction training programs. *J Orthop Res*. 2018;36:2696-2708. https://doi.org/10.1002/jor.24043
47. White K, Di Stasi SL, Smith AH, Snyder-Mackler L. Anterior Cruciate Ligament-Specialized Post-Operative Return To Sports (ACL-SPORTS) training: a randomized control trial. *BMC Musculoskelet Disord*. 2013;14:108. https://doi.org/10.1186/1471-2474-14-108
48. Wright R, Spindler K, Huston L, et al. Revision ACL reconstruction outcomes: MOON cohort. *J Knee Surg*. 2011;24:289-294. https://doi.org/10.1055/s-0031-1292650
49. Xie X, Liu X, Chen Z, Yu Y, Peng S, Li Q. A meta-analysis of bone–patellar tendon–bone autograft versus four-strand hamstring tendon autograft for anterior cruciate ligament reconstruction. *Knee*. 2015;22:100-110. https://doi.org/10.1016/j.knee.2014.11.014

APPENDIX A

ENROLLMENT (PRETRAINING) CLINICAL OUTCOMES[a]

	Allograft	BPTB Autograft	HT Autograft	Model *P* Value
Limb symmetry index				
Single hop for distance	75.8 ± 18.6	73.6 ± 14.5	84.5 ± 11.5	.010
Crossover hop for distance	82.8 ± 14.3	81.0 ± 16.4	90.5 ± 13.6	.034
Triple hop for distance	83.7 ± 13.8	82.4 ± 11.4	90.4 ± 10.4	.020
Timed hop	89.7 ± 10.7	88.5 ± 8.7	94.7 ± 7.8	.018
KOS-ADLS	92.1 ± 4.8	90.4 ± 7.2	94.9 ± 5.6	.017
GRS	77.8 ± 7.5	78.4 ± 7.1	80.4 ± 10.8	.529
IKDC	76.9 ± 7.4	77.4 ± 10.7	81.0 ± 6.6	.124
KOOS				
Pain	89.4 ± 6.6	90.7 ± 7.3	93.0 ± 6.8	.156
Symptoms	84.9 ± 9.1	86.5 ± 8.8	83.0 ± 10.3	.388
Activities of daily living	96.7 ± 3.3	97.1 ± 3.7	98.3 ± 3.3	.217
Sport and recreation	77.8 ± 13.7	74.8 ± 16.4	83.0 ± 12.9	.086
Quality of life	55.6 ± 10.0	54.7 ± 16.4	62.3 ± 17.6	.130

Abbreviations: BPTB, bone-patellar tendon-bone; GRS, global rating scale; HT, hamstring tendon; IKDC, International Knee Documentation Committee 2000 Subjective Knee Evaluation Form; KOOS, Knee injury and Osteoarthritis Outcome Score; KOS-ADLS, Knee Outcome Survey-Activities of Daily Living Scale.
[a]*Values are mean ± SD percent unless otherwise indicated.*

APPENDIX B

POSTTRAINING CLINICAL OUTCOMES[a]

	Allograft	BPTB Autograft	HT Autograft	Model *P* Value
Limb symmetry index				
Single hop for distance	89.5 ± 13.3	92.0 ± 11.0	96.6 ± 9.8	.100
Crossover hop for distance	96.4 ± 6.6	95.5 ± 8.0	97.7 ± 7.6	.601
Triple hop for distance	95.1 ± 5.1	94.0 ± 7.1	98.4 ± 6.2	.047
Timed hop	97.5 ± 5.4	98.9 ± 8.3	101.2 ± 7.2	.206
KOS-ADLS	94.8 ± 3.8	92.6 ± 6.9	96.9 ± 4.4	.009
GRS	87.3 ± 8.9	87.3 ± 5.5	86.4 ± 9.6	.892
IKDC	84.4 ± 8.5	84.3 ± 10.3	88.9 ± 7.6	.072
KOOS				
Pain	92.3 ± 5.8	93.2 ± 5.8	95.3 ± 6.3	.161
Symptoms	85.1 ± 8.2	86.0 ± 12.5	84.6 ± 13.0	.898
Activities of daily living	98.9 ± 1.7	98.8 ± 2.1	98.3 ± 3.2	.610
Sport and recreation	87.5 ± 10.6	87.5 ± 13.5	90.3 ± 12.0	.604
Quality of life	67.7 ± 12.9	60.9 ± 21.8	71.1 ± 18.4	.117

Abbreviations: BPTB, bone-patellar tendon-bone; GRS, global rating scale; HT, hamstring tendon; IKDC, International Knee Documentation Committee 2000 Subjective Knee Evaluation Form; KOOS, Knee injury and Osteoarthritis Outcome Score; KOS-ADLS, Knee Outcome Survey-Activities of Daily Living Scale.
[a]*Values are mean ± SD percent unless otherwise indicated.*

APPENDIX C

1-YEAR CLINICAL OUTCOMES[a]

	Allograft	BPTB Autograft	HT Autograft	Model *P* Value
Limb symmetry index				
Single hop for distance	94.8 ± 9.7	97.6 ± 7.0	99.5 ± 7.3	.153
Crossover hop for distance	99.7 ± 6.6	98.1 ± 6.2	100.1 ± 9.0	.656
Triple hop for distance	98.9 ± 7.5	97.4 ± 5.5	99.4 ± 6.3	.548
Timed hop	102.6 ± 5.6	102.3 ± 5.3	102.0 ± 7.0	.960
KOS-ADLS	95.6 ± 5.9	95.5 ± 5.5	98.0 ± 3.0	.075
GRS	93.1 ± 8.8	91.9 ± 13.6	95.4 ± 6.7	.370
IKDC	91.6 ± 9.9	90.4 ± 10.2	94.6 ± 7.4	.181
KOOS				
Pain	95.1 ± 5.0	95.5 ± 4.7	97.0 ± 4.2	.270
Symptoms	86.5 ± 12.3	90.1 ± 11.3	90.4 ± 9.7	.441
Activities of daily living	98.4 ± 4.0	99.0 ± 1.9	99.6 ± 1.0	.185
Sport and recreation	93.1 ± 9.6	91.3 ± 10.7	94.7 ± 8.9	.412
Quality of life	82.6 ± 16.4	76.4 ± 13.5	82.0 ± 17.3	.347

Abbreviations: BPTB, bone-patellar tendon-bone; GRS, global rating scale; HT, hamstring tendon; IKDC, International Knee Documentation Committee 2000 Subjective Knee Evaluation Form; KOOS, Knee injury and Osteoarthritis Outcome Score; KOS-ADLS, Knee Outcome Survey-Activities of Daily Living Scale.
[a]*Values are mean ± SD percent unless otherwise indicated.*