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A Prospective Investigation of Biomechanical Risk Factors for Patellofemoral Pain Syndrome

The Joint Undertaking to Monitor and Prevent ACL Injury (JUMP-ACL) Cohort

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Background: Patellofemoral pain syndrome is one of the most common chronic knee injuries; however, little research has been done to determine the risk factors for this injury.

Hypothesis: Altered lower extremity kinematics and kinetics, decreased strength, and altered postural measurements will be risk factors.

Study Design: Cohort study (prognosis); Level of evidence, 2.

Methods: A total of 1597 participants were enrolled in this investigation and prospectively followed from the date of their enrollment (July 2005, July 2006, or July 2007) through January 2008, a maximum of 2.5 years of follow-up. Each participant underwent baseline data collection during their pre-freshman summer at the United States Naval Academy. Baseline data collection included 3-dimensional motion analysis during a jump-landing task, 6 lower extremity isometric strength tests, and postural alignment measurements (navicular drop and Q angle).

Results: Risk factors for the development of patellofemoral pain syndrome included decreased knee flexion angle, decreased vertical ground-reaction force, and increased hip internal rotation angle during the jump-landing task. Additionally, decreased quadriceps and hamstring strength, increased hip external rotator strength, and increased navicular drop were risk factors for the development of patellofemoral pain syndrome.

Conclusion: Multiple modifiable risk factors for patellofemoral pain syndrome pain have been identified in this investigation. To decrease the incidence of this chronic injury, the risk factors for patellofemoral pain syndrome need to be targeted in injury prevention programs.

Clinical Relevance: Prevention programs should focus on increasing strength of the lower extremity musculature along with instructing proper mechanics during dynamic movements to decrease the incidence of patellofemoral pain syndrome.

Keywords: incidence; anterior knee pain; risk factors

Patellofemoral pain syndrome (PFPS) is one of the most common lower extremity conditions reported in physically active populations, affecting 1 in 4 people.[4,5] Patellofemoral pain encompasses disorders in which pain and point tenderness are present in or around the patellofemoral joint. Despite its high prevalence, little is known regarding the risk factors that predispose people to developing PFPS.

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The development of PFPS can be devastating because of the common recurrence of symptoms and its influence on physical activity levels. In a retrospective case-control analysis of patients with PFPS who were examined 4 to 18 years after initial presentation, 91% of 22 patients still had knee pain (68% of these were female patients), and PFPS restricted physical activity in 36% of these 22 patients.[25] In addition, PFPS has been demonstrated to have an association with the development of patellofemoral osteoarthritis.[28] Utting et al[28] reported that 22% of 118 patients with patellofemoral osteoarthritis reported symptoms of anterior knee pain as an adolescent. Based on these findings, PFPS is considered a public health concern because of its detrimental effect on physical activity and its association with patellofemoral osteoarthritis. The development of prevention programs may be an effective strategy to decrease the occurrence of PFPS and, in turn, the occurrence of patellofemoral osteoarthritis.

There is a need to understand the risk factors for this disorder so that effective prevention strategies can be developed and implemented. Various risk factors have been proposed for PFPS, including lower extremity structural abnormalities, muscle weakness, and dynamic malalignment[8,16,17,26,29]; however, few studies have prospectively evaluated all of these risk factors.[17,24,29] The few prospective cohort investigations that have been performed indicate decreased quadriceps flexibility, shortened reflex time of the vastus medialis oblique muscle, reduction of vertical jump performance, increased medial patellar mobility, increased medial tibial intercondylar distance, and increased quadriceps strength as factors associated with the incidence of PFPS.[17,29] Although these risk factors provide some information for the development of prevention programs for PFPS, several of these factors are not modifiable. Therefore, there is a need for research that aims to identify modifiable risk factors for PFPS.

The modifiable risk factors that have been theorized to play a role in the development of PFPS include altered kinematics and kinetics during functional tasks and decreased strength of the hip and knee musculature.[21] Alterations in kinematics and kinetics may lead to increased loads being placed across the patellofemoral joint,[21] and may ultimately lead to PFPS.[13] It has also been proposed that weakness of the thigh and hip musculature can alter the alignment of the patella within the femoral trochlea, leading to abnormal patellar tracking.[10] Prospective investigations have yet to identify if these modifiable risk factors are associated with the development of PFPS.

Two additional risk factors that have been theorized to predispose people to PFPS are excessive pronation and increased Q angle. Excessive pronation through the measure of navicular drop has yet to be evaluated as a risk factor for the incidence of PFPS. Although Q angle has been investigated, researchers have not reported a clear association with an increased incidence of PFPS.[6,9,15,29]

The purpose of this investigation was to determine the biomechanical risk factors for PFPS. The specific factors examined were lower extremity kinematics and kinetics during a jump-landing task, Q angle, navicular drop, and the strength of the hip and knee musculature (hip abductors, hip extensors, hip external rotators, hip internal rotators, knee flexors, and knee extensors). We hypothesized that there would be an association between the development of PFPS and altered kinematics and kinetics, increased Q angle, increased navicular drop, and decreased lower extremity strength.

METHODS

Study Design and Participants

A total of 1597 midshipmen from the United States Naval Academy (USNA) were enrolled in this investigation. Inclusion criteria for enrollment into the cohort population included (1) being a freshman at USNA at the time of enrollment into the investigation and (2) no injury limiting participation in a jump-landing task and/or lower extremity strength tests. We chose this population because of the similar activity requirements placed on all midshipmen. Midshipmen are required to participate in a varsity or intramural sport every semester of their enrollment at USNA. Additionally, they must participate in military training that includes daily physical conditioning activities.

Enrolled study participants were spread among 3 classes of midshipmen (class of 2009 = 438 participants, 189 women and 249 men; class of 2010 = 525 participants, 223 women and 302 men; and class of 2011 = 562 participants, 194 women and 368 men). Each participant underwent a baseline biomechanical assessment during his or her first summer of enrollment at USNA. This baseline assessment is part of an ongoing study of risk factors for ACL injury (the Joint Undertaking to Monitor and Prevent ACL Injury [JUMP-ACL] study) in which baseline data are collected for participants at all 3 service academies (USNA, United States Air Force Academy, and United States Military Academy). This article uses data from the first 3 years of JUMP-ACL (2005-2007) and from one of the 3 sites (USNA).

Participants in this investigation were followed prospectively for the diagnosis of PFPS. The diagnosis of PFPS was determined based on a manual review of medical records by the first author. Participants in each class were followed prospectively from the date of their enrollment (July 2005, July 2006, or July 2007) in this investigation to January 2008. The criteria that had to be met to be included in the injury group are listed here.

Must demonstrate both during evaluation:

1. Retropatellar knee pain during at least 2 of the following activities: ascending/descending stairs, hopping/jogging, prolonged sitting, kneeling, and squatting.
2. Negative findings on examination of knee ligament, menisci, bursa, and synovial plica.

Must demonstrate one of the following during evaluation:

1. Pain on palpation of medial or lateral patellar facets.
2. Pain on palpation of the anterior portion of the medial or lateral femoral condyles.

Although duration of symptoms is commonly accounted for when defining PFPS, we did not account for this because of the lack of consistent documentation of duration of symptoms by military health professionals. However, if the mechanism of injury stated a traumatic blow to the knee/patella and the medical record note matched the inclusion criteria, we did not include the person in the injured cohort. Thus, we attempted to include only people who developed PFPS over a period of time (chronic) and not from an acute traumatic injury. People with a history of PFPS in the previous 6 months were excluded from the cohort because of the potential influence of the injury history on baseline measurements (see "Cohort Selection").

Baseline Assessment—Instrumentation

A Flock of Birds (Ascension Technologies, Inc, Burlington, Vermont) electromagnetic motion analysis system controlled by Motion Monitor software (Innovative Sports Training, Inc, Chicago, Illinois) was used to assess lower extremity kinematics at a sampling rate of 144 Hz. A nonconductive force plate (model 4060-NC, Bertec Corporation, Columbus, Ohio) was used to collect ground-reaction forces to allow for the calculation of lower extremity kinetics through inverse dynamic procedures. Force plate data were collected synchronously with the kinematic data at a sampling rate of 1440 Hz.

The Flock of Birds was used to measure the position and orientation of 3 electromagnetic tracking sensors placed on the sacrum, femur, and tibia. A standard range transmitter consisting of 3 orthogonal coils generated a magnetic field. The 3 electromagnetic sensors attached to participants collected the changes in the electromagnetic flux in the field generated by the transmitter. Previous research has reported that electromagnetic tracking systems provide accurate[1,18] and reliable[1] data for 3-dimensional movement of body segments and joints.

A handheld dynamometer (Chatillon MSC-500, AMETEK, Inc, Largo, Florida) was used to collect peak and mean isometric strength values for lower extremity musculature. A standard goniometer was used to measure Q angle. Each participant's height and weight were measured using a height gauge (Seca 206 Bodymeter, Seca Corp, Hanover, Maryland) and scale (Seca 780, Seca Corp), respectively.

Baseline Assessment Testing Procedures

Before the start of baseline data collection, all subjects provided informed consent in accordance with the National Naval Medical Center, Bethesda, Maryland, Institutional Review Board. Additionally, subjects completed a baseline questionnaire that contained questions regarding age, sex, history of participation in athletic activity, mental health, knee and lower limb injury history, and recent exercise and weight training history.

The jump-landing task consisted of participants jumping from a 30-cm (11.8-inch) high box set at a distance of 50% of their height, down to a force platform. Once subjects landed on the force platform, they jumped vertically for maximum height. After task instruction, the subject was given as many practice trials as needed to perform the task successfully. A successful jump was characterized by landing with the entire foot of the dominant lower extremity on the force plate, landing with the entire foot of the nondominant lower extremity off the force plate, and completing the task in a fluid motion.

After task instruction and practice, electromagnetic tracking sensors were attached to the dominant lower extremity. The dominant lower extremity was defined as the leg used to kick a ball for maximum distance. Electromagnetic sensors were placed on the subjects' skin over the superior sacrum, lateral aspect of the thigh, and anteromedial aspect of the proximal tibia. Each sensor was placed over an area of the least muscle mass to minimize potential sensor movement and was secured using double-sided tape, prewrap, and athletic tape. Six bony landmarks were digitized with the end point of a stylus on which a fourth receiver was mounted. The 6 bony landmarks were medial and lateral epicondyles of the femur, medial and lateral malleoli of the ankle, and left and right anterior superior iliac spine of the pelvis. Medial and lateral malleoli and femoral epicondyles were digitized to determine the ankle joint center and knee joint center, respectively. Left and right anterior superior iliac spine were digitized to determine the hip joint center of rotation using the Bell method.[2] Participants performed 3 successful trials of the jump-landing task.

Lower extremity isometric muscle strength tests were performed in the following order: knee extension (quadriceps), hip external rotation (hip external rotators), hip internal rotation (hip internal rotators), knee flexion (hamstrings), hip extension (gluteus maximus muscle), and hip abduction (gluteus medius muscle). A figure displaying participant and examiner positioning for each strength test is included in the Appendix (see online Appendix for this article at http://ajs.sagepub.com/supplemental/). During each test, participants were instructed to push as hard as they could, holding the contraction for 5 seconds. Peak isometric strength values for 2 separate trials were collected. All strength data were normalized to the mass of the subject and averaged over the 2 trials. Intrarater reliability (intraclass correlation coefficient $[ICC]_{2,k}$) calculated from pilot data for the strength tests ranged from 0.73 to 0.98.

The structural alignment measures assessed included Q angle and navicular drop. The Q angle was measured with participants in a standing position using a standard goniometer. The Q angle was recorded in degrees for 3 separate trials. The average of the 3 trials was used for data analysis. Intrarater reliability from pilot data showed good reliability for Q angle measurement ($ICC_{2,k} = 0.83$). Navicular drop was measured as the difference between the navicular tuberosity height in a nonweightbearing subtalar joint neutral position and a weightbearing position. The average of the 3 navicular drop measurements was used for data analysis. Intrarater reliability from pilot data showed good reliability for navicular drop measurement ($ICC_{2,k} = 0.79$).

TABLE 1
Means, Standard Deviations (SDs), *F* values, and *P* Values Comparing Injured and Noninjured Cohorts[a]

Domain	Dependent Variable	Injured (Mean ± SD)	Noninjured (Mean ± SD)	*F* Value	*P* Value
Kinematic variables	Hip flexion angle (°)	−67.0 ± 19.8	−71.8 ± 20.1	2.18	.14
	Hip adduction angle (°)	1.9 ± 7.2	2.8 ± 6.7	0.76	.38
	Hip internal rotation angle (°)	7.6 ± 8.9	7.2 ± 8.4	0.09	.76
	Knee flexion angle (°)	76.5 ± 11.7	80.8 ± 14.3	3.82	.06
	Knee valgus angle (°)	−13.6 ± 7.8	−14.1 ± 7.9	0.14	.71
	Knee internal rotation angle (°)	12.2 ± 8.0	14.7 ± 8.4	3.39	.07
Kinetic variables	Vertical ground-reaction force (%BW)	2.6 ± 0.5	2.9 ± 0.9	4.40	.04
	Hip abduction moment (%BW·ht)	−0.13 ± 0.08	−0.14 ± 0.07	0.99	.32
	Hip external rotation moment (%BW·ht)	−0.06 ± 0.03	−0.08 ± 0.05	4.64	.03
	Knee extension moment (%BW·ht)	−0.21 ± 0.05	−0.23 ± 0.05	4.70	.03
	Knee varus moment (%BW·ht)	0.05 ± 0.03	0.05 ± 0.03	0.01	.98
Muscle strength variables	Knee flexion strength (%BW)	0.23 ± 0.06	0.25 ± 0.05	7.67	.01
	Knee extension strength (%BW)	0.46 ± 0.09	0.52 ± 0.12	13.22	.01
	Hip extension strength (%BW)	0.30 ± 0.07	0.32 ± 0.09	2.09	.15
	Hip internal rotation strength (%BW)	0.21 ± 0.04	0.22 ± 0.04	1.31	.25
	Hip external rotation strength (%BW)	0.21 ± 0.04	0.22 ± 0.05	0.99	.32
	Hip abduction strength (%BW)	0.35 ± 0.09	0.38 ± 0.09	3.83	.05
Alignment variables	Q angle (°)	10.1 ± 4.2	9.8 ± 4.3	0.22	.64
	Navicular drop (mm)	8.1 ± 3.2	7.2 ± 2.7	4.24	.04

[a]%BW, percent body weight; ht, height.

Biomechanical Data Reduction

All kinematic data were filtered using a fourth order low-pass Butterworth filter at 14.5 Hz. A global reference system was defined using the right-hand rule, in which the x-axis was positive in the anterior direction, the y-axis was positive to the left of each participant, and the z-axis was positive in the superior direction. Lower extremity joint rotations were calculated using the Euler rotation method in the following order: Y, X, Z. The y-axis corresponded to the flexion-extension axis, the x-axis corresponded to the abduction-adduction axis, and the z-axis corresponded to the internal-external rotation axis.

The kinematic and kinetic data were reduced using custom MATLAB software (The MathWorks, Natick, Massachusetts). Three-dimensional peak knee and hip joint angles, peak vertical ground-reaction force, and internal joint moments for hip abduction, hip external rotation, knee extension, and knee varus were determined during the stance phase. The stance phase was defined as the period between initial ground contact with the force plate until takeoff for the rebound jump. Initial ground contact was the time point at which vertical ground-reaction force exceeded 10 N as the subject landed on the force plate from the 30-cm high platform. Takeoff was identified as the time when vertical ground-reaction force dropped below 10 N after initial contact. The average of the peak values across the 3 trials was calculated for each of the kinematic and kinetic variables. The peak vertical ground-reaction force was normalized to body weight (N) for each participant (percent body weight). Peak internal joint moments were normalized to the product of body weight (N) and body height (m) (body weight × body height). Table 1 provides a list of all kinematic, kinetic, strength, and postural variables assessed in this investigation.

Follow-up Procedures

Physicians at USNA diagnosed cases of PFPS and the diagnosis code was entered into an electronic medical record database, the Armed Forces Health Longitudinal Technology Application (AHLTA). The Defense Medical Surveillance System (DMSS) was used to search for diagnosis codes in AHLTA. The DMSS is a comprehensive database of military injuries maintained by the US Army Center for Health Promotion and Preventive Medicine that captures all illness and injury events in the US armed forces resulting in a hospitalization or an ambulatory care facility visit to a military hospital or a military clinician. The DMSS was searched to identify people within the cohort whose medical record contained one of the following diagnosis codes (International Statistical Classification of Diseases and Related Health Problems, ninth edition [ICD-9]): 726.69 (unspecified knee enthesopathy), 726.64 (patellar tendonitis), 717.7 (patella chondromalacia), and 719.46 (unspecified disorder of joint in lower leg). After the DMSS search, people in the cohort who were identified with one of the listed ICD-9 codes underwent a medical record review by the first author within AHLTA.

Athletic injuries that are evaluated and treated by the certified athletic trainers at the USNA are not included in the medical records for midshipmen. The certified athletic trainers use SportsWare (Computer Sports Medicine, Inc, Stoughton, Massachusetts) to record the athletic injuries they evaluate and treat. A keyword search through SportsWare was performed to determine the

TABLE 2
Results From Univariate and Domain-Specific Poisson Regression Models[a]

		Unadjusted (Separate Models)				Domain-Specific Models (One Model Per Domain)				
Domain	Independent Variables	RR[b]	95% CI	CLR	*P* Value	RR[c]	95% CI	CLR	*P* Value	Model *P* Value
Kinematic variables	Hip flexion angle (°)	1.47	0.64,3.35	5.18	.36	0.89	0.25,3.25	13.10	.87	.83
	Hip adduction angle (°)	0.86	0.39,1.91	4.90	.71	0.77	0.30,1.97	6.51	.59	
	Hip internal rotation angle (°)	1.30	0.60,2.82	4.68	.50	1.99	0.72,5.50	7.66	.19	
	Knee flexion angle (°)	0.52	0.22,1.18	5.16	.12	0.38	0.11,1.37	12.71	.14	
	Knee valgus angle (°)	1.04	0.46,2.37	5.17	.92	0.71	0.23,2.20	9.59	.55	
	Knee internal rotation angle (°)	0.70	0.32,1.52	4.72	.37	0.63	0.28,1.41	5.02	.26	
Kinetic variables	Vertical ground-reaction force (%BW)	0.42	0.17,1.03	6.03	.06	0.42	0.15,1.21	8.26	.11	.66
	Hip abduction moment (%BW·ht)	1.19	0.51,2.79	5.52	.69	0.64	0.22,1.81	8.07	.40	
	Hip external rotation moment (%BW·ht)	1.75	0.69,4.42	6.37	.23	1.54	0.54,4.37	8.09	.42	
	Knee extension moment (%BW·ht)	2.00	0.79,5.05	6.38	.14	1.69	0.57,5.01	8.80	.34	
	Knee varus moment (%BW·ht)	1.00	0.46,2.19	4.75	.99	1.53	0.64,3.68	5.73	.33	
Muscle strength variables	Knee flexion torque (%BW)	0.30	0.13,0.68	5.20	.01	0.37	0.11,1.21	11.21	.10	.16
	Knee extension torque (%BW)	0.19	0.07,0.47	6.46	.01	0.13	0.03,0.52	16.85	.01	
	Hip extension torque (%BW)	0.48	0.20,1.18	5.95	.11	1.37	0.44,4.27	9.72	.59	
	Hip internal rotation torque (%BW)	0.42	0.18,0.97	5.37	.04	0.94	0.28,3.11	11.00	.92	
	Hip external rotation torque (%BW)	0.47	0.21,1.09	5.23	.08	3.34	0.88,12.67	14.42	.08	
	Hip abduction torque (%BW)	0.45	0.19,1.02	5.25	.06	0.90	0.29,2.84	9.86	.86	
Static alignment variables	Q angle (°)	0.99	0.47,2.09	4.42	.98	1.01	0.47,2.15	4.54	.98	.21
	Navicular drop (mm)	2.52	1.25,5.08	4.06	.01	2.52	1.25,5.08	4.06	.01	

[a]RR, rate ratio; 95% CI, 95% confidence interval; CLR, confidence limit ratio; %BW, percent body weight; ht, height.
[b]RR for all variables other than sex represents the effect of each variable at the 90th percentile of its distribution relative to the 10th percentile.
[c]Adjusted for all other variables in that domain.

varsity athletes who developed PFPS (keywords: anterior knee pain, patellofemoral pain, and patella maltracking). Injury records highlighted by the keyword search were evaluated by the first author to determine inclusion into the injured group.

Cohort Selection

The total number of participants enrolled in this investigation was 1597 (632 women and 965 men). Seventy-two of these participants (26 women and 46 men) did not complete 1 or more of the baseline testing stations and were eliminated from the cohort. None of the eliminated participants received a diagnosis of PFPS during the follow-up period. Additionally, 206 participants (93 women and 113 men) reported a history of PFPS in the previous 6 months on the baseline questionnaire and were eliminated from the cohort. We eliminated these participants because, at the time of baseline assessment, their performance on the jump-landing task and strength tests could have been influenced by the presence of prior PFPS.

Statistical Analysis

Means and standard deviations were computed for the injured and noninjured groups. Differences between these groups were assessed using analysis of variance, with sex included in all models. Separate Poisson regression analyses were performed for each risk factor variable. Additionally, multivariate Poisson regression models were used to model the rate of PFPS as a function of domain-specific risk factors. Domain-specific models were developed to determine the risk factors associated with PFPS when adjusting for the other risk factor variables within each domain. Table 1 lists the dependent variables within each domain. Based on the findings from the domain-specific Poisson regression models, 2 final multivariate models were developed, including the risk factors across multiple domains. The risk factors that were included in the 2 final multivariate models had $P < .20$ in the domain-specific models. All rate ratios (RRs) were scaled so that each RR represents the effect of each variable at the 90th percentile relative to the 10th percentile of the distribution of the variable in the cohort (injured and noninjured groups combined). All statistical analyses were performed using SAS 9.1 software (SAS Institute, Inc, Cary, North Carolina). An a priori alpha level for all analyses was set at .05.

RESULTS

A total of 40 participants (24 women and 16 men) with complete baseline testing and no history of PFPS developed PFPS during the follow-up period and met the inclusion criteria for the injured group. The noninjured group included 1279 participants (489 women and 790 men). The

TABLE 3
Results From the 2 Final Multivariate Poisson Regression Models[a]

Final Models	Independent Variables	10th Percentile	90th Percentile	RR[b]	95% CI	CLR	*P* Value	Model *P* Value
Model 1:	Hip internal rotation angle (°)	–3.15	18.19	1.38	0.59,3.23	5.47	.46	.04
Kinematic/	Knee flexion angle (°)	63.21	99.48	0.32	0.12,0.86	7.23	.02	
kinetic/	Vertical ground-reaction force (%BW)	1.92	4.02	0.28	0.10,0.79	7.87	.02	
posture	Navicular drop (mm)	4.00	10.67	3.39	1.62,7.11	4.39	.01	
	Sex[c]	N/A	N/A	1.92	1.00,3.68	3.68	.05	
Model 2:	Knee flexion torque (%BW)	0.19	0.32	0.34	0.11.1.06	9.80	.06	.02
Muscle	Knee extension torque (%BW)	0.37	0.69	0.18	0.04,0.70	15.5	.01	
strength/	Hip external rotation torque (%BW)	0.16	0.28	4.02	1.03,15.72	15.29	.04	
posture	Navicular drop (mm)	4.00	10.67	2.73	1.36,5.49	4.03	.01	
	Sex[c]	N/A	N/A	1.62	0.76,3.45	4.56	.21	

[a]RR, rate ratio; 95% CI, 95% confidence interval; CLR, confidence limit ratio; %BW, percent body weight.
[b]Adjusted for all other variables in that model. Rate ratio for all variables other than sex represents the effect of each variable at the 90th percentile of its distribution relative to the 10th percentile.
[c]Female compared with male (reference category).

overall risk of PFPS was 3% in this population and the incidence rate was 22 injuries/1000 person-years (95% confidence interval: 15/1000 person-years, 29/1000 person-years). No significant sex × group (injured vs noninjured) interactions were found after the analysis of variance procedures ($P > .05$). Results for injured and noninjured group comparisons are presented in Table 1.

Table 2 includes RR, confidence limit ratios (CLRs), and *P* values for the separate Poisson regression models for each variable. Table 2 also includes the RR, CLR, and *P* values for each variable in the domain adjusting for the other variables in the model, and the *P* value for the domain-specific model. A significantly predictive Poisson regression model was found for each of the following variables: knee flexion torque, knee extension torque, hip internal rotation torque, and navicular drop. There were no significant domain-specific models ($P > .05$).

Because of the small number of subjects in the injured group (n = 40), we could not include all risk factor variables in 1 model. Therefore, 2 final models were created with 5 or fewer variables to assess the risk factors across multiple domains. The 2 final models were a kinematics/kinetics/posture model and a muscle strength/posture model. The independent variables included in the kinematics/kinetics/posture model were hip internal rotation angle, knee flexion angle, vertical ground-reaction force, navicular drop, and sex. The independent variables included in the muscle strength/posture model were knee flexion peak torque, knee extension peak torque, hip external rotation peak torque, navicular drop, and sex. Sex was included in both models because of the inherent differences between men and women for many of the independent variables in the models. Navicular drop was also included in both models because navicular drop was the most predictive variable.

Table 3 provides the RR, CLR, and *P* values for the kinematic/kinetic/posture model and the muscle strength/posture model. Each model significantly predicted the development of PFPS ($P < .05$). The RR in Table 3 represents the effect of each factor at its 90th percentile relative to the 10th percentile. Examples of how these results can be interpreted are as follows: Based on model 1, the rate of development of PFPS was 3.4 times greater for the subjects with navicular drop at the 90th percentile (10.7 mm) relative to those at 10th percentile (4.0 mm) when adjusting for all other variables in the model. Additionally, the rate of development of PFPS was 3.1 (RR: 0.32^{-1}) times greater for the people with knee flexion angle at the 10th percentile (63.2°) relative to those at the 90th percentile (99.5°) when adjusting for all other variables in the model.

DISCUSSION

The main objective of this investigation was to determine the biomechanical risk factors for PFPS. On the basis of the descriptive analysis, people who developed PFPS were significantly weaker on measures of hip abduction, knee flexion, and knee extension strength. Additionally, people who developed PFPS had significantly lower vertical ground-reaction force, knee extension moment, and hip external rotation moment, and displayed significantly more navicular drop at baseline assessment than those who did not develop PFPS. Based on the final Poisson regression models, decreased peak knee flexion angle and decreased peak vertical ground-reaction force during the jump-landing task were risk factors for the development of PFPS. For the strength variables, decreased knee flexion and extension strength, and increased hip external rotation strength were risk factors for the development of PFPS. Finally, increased navicular drop and female sex were significant risk factors for the development of PFPS.

Although there are not many investigations for comparison of our results, previous investigations have theorized many of the biomechanical variables we assessed as risk factors for PFPS.[7,21,26] The findings of decreased knee flexion and extension strength, increased navicular drop, decreased knee flexion angle, and increased hip internal

rotation angle support the theorized biomechanical risk factors. However, increased hip external rotation strength and decreased vertical ground-reaction force are not in agreement with the theorized risk factors. The next few paragraphs will provide a brief explanation of the following variables as risk factors for PFPS.

Excessive foot pronation has been theorized to predispose people to PFPS due to the associated internal rotation of the tibia with foot pronation.[27] Tiberio[27] proposed that for the knee to extend with the tibia in an internally rotated position, the femur must also internally rotate. This internal rotation of the femur is thought to lead to malalignment of the patella within the femoral trochlea and compression of the lateral patellar facet.[27] Previous research supports the theory that femoral internal rotation causes an increase in contact pressures on the lateral facets of the patella[13]; therefore, excessive pronation has previously been proposed as a risk factor for the development of PFPS.

Muscle imbalances, including decreased strength of the hip and knee musculature, have also been proposed to be risk factors for PFPS. In vivo assessments of the vastus lateralis and vastus medialis oblique muscles have confirmed their role as the primary dynamic stabilizers of the patella[12,14]; therefore, weakness in these muscles may lead to maltracking of the patella. The exact relationship between decreased hamstring strength and the development of PFPS is not clearly understood; however, decreased hamstring strength may be due to an overall weakness of the thigh musculature in people who develop PFPS.

The hip musculature has also been theorized to have an influence on the positioning of the patella within the femoral trochlea.[21] The hip abductors and external rotators play a major role in controlling transverse and frontal plane motion of the femur. Weakness of the hip external rotators is proposed to cause an increase in hip internal rotation and knee valgus angles during dynamic tasks and, in turn, increase the lateral compressive forces at the patellofemoral joint.[11,13,21] In this investigation, increased hip external rotation strength was a risk factor for PFPS, which does not agree with the theorized risk factors for this injury. We hypothesize that, because of the increased hip internal rotation angle displayed during the jump-landing task, subjects who developed PFPS were commonly using their hip external rotators to counteract the increased hip internal rotation angle during dynamic tasks. If this hypothesis are true, these people may have developed increased hip external rotation strength over time in an attempt to counteract the increased hip internal rotation.

As mentioned previously, evidence does support increased patellofemoral joint contact pressures in various malaligned positions of the lower extremity. Lee et al[13] reported that more than 30° of femoral internal rotation causes a significant increase in patellofemoral joint contact pressures. Although none of the participants in this investigation displayed greater than 30° of hip internal rotation, we speculate that, over time, the increased hip internal rotation may have led to the development of PFPS.

Many case-control investigations have reported that those with PFPS display decreased knee flexion angles during functional tasks.[3,19,22] Researchers have speculated that this is a compensatory strategy to decrease the amount of contact pressure of the patella to decrease pain.[3,19,22] However, the findings in this investigation support decreased knee flexion angles as a risk factor for the development of PFPS, not a compensation to PFPS. We speculate that if people who ultimately develop PFPS also have lateral patellar malalignment due to the increased femoral internal rotation, the patellofemoral contact stress may be even more increased at the smaller knee flexion angles because of the decreased contact area at these decreased knee flexion angles.

Research has previously shown that decreased knee flexion angles during dynamic tasks leads to increased vertical ground-reaction forces[23,30]; however, we found the opposite in this investigation. We assessed peak vertical ground-reaction force and peak knee flexion angle over the stance phase of the jump-landing task. The peak vertical ground-reaction force occurs much earlier than the peak knee flexion angle; therefore, we took steps to try to understand the decreased vertical ground-reaction force in those who developed PFPS. We evaluated knee flexion and hip flexion displacement during the stance phase to determine if people who developed PFPS had a decreased amount of displacement, which may mean they do not efficiently absorb the vertical ground-reaction force; however, there was no difference in the knee flexion and hip flexion displacements between the injured and noninjured groups. Additionally, we assessed the knee flexion and hip flexion angles at initial contact during the jump-landing task. Those who developed PFPS had significantly less knee flexion angle at initial contact compared with those who did not develop PFPS ($P < .05$). There was no significant difference in hip flexion angle at initial contact between the 2 groups. Furthermore, we evaluated anterior/posterior and medial/lateral ground-reaction forces to determine if people who developed PFPS may have increased ground-reaction forces in other directions to compensate for the decreased vertical ground-reaction force. We did not find any differences in peak anterior/posterior or medial/lateral ground-reaction forces between the 2 groups. Based on our additional analysis, decreased vertical ground-reaction force as a risk factor for PFPS warrants further investigation.

To understand how all of the risk factors described here may interact with each other and lead to the development of PFPS, we have developed a conceptual model (Figure 1). When performing a dynamic task, people who have decreased quadriceps strength may display decreased knee flexion angles because the tasks demand a large amount of eccentric force from the quadriceps musculature and the quadriceps are weak in these people. Although increased or decreased knee extension moment did not predict the development of PFPS, the descriptive analysis showed that people who developed PFPS had significantly less knee extension moment during the jump-landing task. Decreased knee extension moment and decreased quadriceps strength may lead to decreased dynamic control of the patella. Additionally, an increase in hip internal rotation, possibly resulting from the increased navicular drop, may lead to a laterally aligned patella. The combination of increased hip internal rotation angle and decreased knee flexion angle will most likely increase the patellofemoral

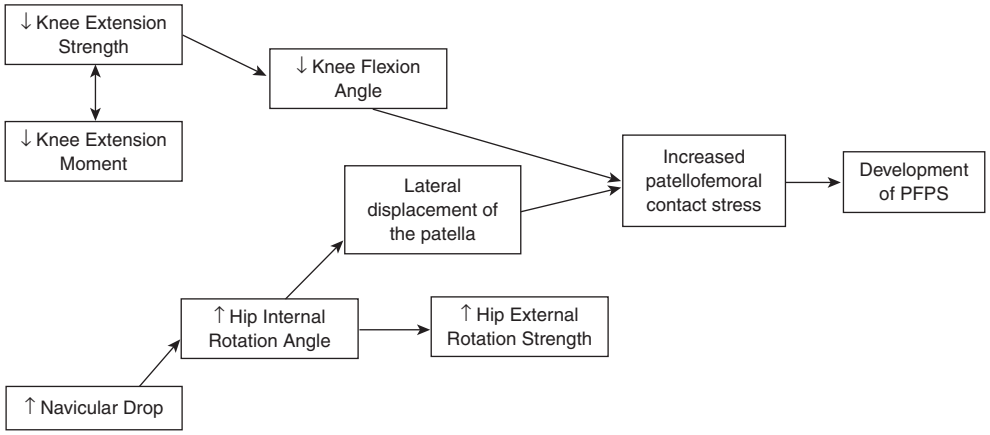

Figure 1. Conceptual model for the development of patellofemoral pain syndrome.

contact pressures and, over time, repetitive movements in this position may lead to the development of PFPS.

As mentioned previously, we speculate that the increased hip external rotation strength is due to people constantly having to control the increased hip internal rotation angles during dynamic tasks. However, the finding of increased hip internal rotation angle along with the increased hip external rotation strength leads us to believe this may be a neuromuscular control issue, meaning that people do not know when to recruit the hip external rotators during dynamic tasks, leading to the increased hip internal rotation angle.

A limitation of this investigation is that this cohort population is not representative of the general population, and results should be generalized only to young, active people. Another limitation was the small number of people who met the criteria to be included in the injured group (n = 40) and the decreased amount of follow-up time for the 2007 cohort. Possible explanations for the low incidence of PFPS in this investigation include a lack of information in the medical record to be included in the injured group, medical record charts not available for review, self-treatment for PFPS, and diagnosis by a physician outside the USNA. It is very uncommon for midshipmen to see a physician outside the USNA; therefore, we do not believe that this had a large effect on the number of diagnoses of PFPS. Additionally, only 5% of the people with an ICD-9 code in which we were interested did not have enough information in the medical record; therefore, this most likely did not significantly affect the number of people diagnosed with PFPS. A more plausible explanation is that 21 people who had an ICD-9 code that we were interested in did not have a medical record chart that was available for review during the follow-up time for this investigation. This is a limitation of this study; however, only 12% of the medical records that we reviewed that did have an ICD-9 code for PFPS were actual cases that met our criteria. It is unlikely that this drastically decreased the number of people who were included in the injured group.

The most reasonable explanation for the decreased incidence of PFPS in this investigation is self-treatment. People who developed PFPS may have learned ways to compensate during activities to decrease the pain in their knee. Also, people may have been able to withstand the pain, making a visit to a physician unnecessary. Future investigations may attempt to follow people more closely with the use of questionnaires to determine those who may self-treat for PFPS.

Another limitation of this investigation includes the large variability in some of the risk factor variables. For example, hip external rotation strength has a CLR of 15.29 in the final model. A measure is thought to be precise if the confidence interval is narrow, decreasing the CLR.[20] Very few of the variables in this investigation had a narrow confidence interval; therefore, the results of this investigation should be interpreted with caution. A final limitation was the assessment of only the peak kinematic and kinetics during the jump-landing task. We chose to assess the peak kinematics and kinetics because theory supports that the peak transverse and frontal plane angles are the factors that may be leading to the development of PFPS. Future investigations should determine if kinematics and kinetics during various periods of a dynamic task are risk factors for the development of PFPS.

CONCLUSION

This is the first large-scale prospective investigation to assess structural alignment, muscle strength, and dynamic movement patterns as risk factors for PFPS. The findings of this investigation support strengthening of the quadriceps and hamstring musculature along with teaching the proper technique for performing dynamic tasks (decrease hip internal rotation angle, increase knee flexion) as components of effective injury prevention programs, specifically for PFPS. Future research should investigate biomechanical risk factors in the general population and across multiple age groups to determine if these risk factors may differ from the young adult military population.

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