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# Patellofemoral Joint Stress During Weight-Bearing and Non–Weight-Bearing Quadriceps Exercises

uadriceps strengthening is a common component of the rehabilitation program for persons with patellofemoral pain (PFP) and typically includes weight-bearing and non-weightbearing exercises.<sup>1,9,12,18,27</sup> Both forms of exercise Ċ (

have their advantages with respect to quadriceps strengthening. Weightbearing exercises are more functional in nature<sup>7,11</sup> and incorporate contractions of multiple agonist and antagonist muscle groups.<sup>19-21,25</sup>

• STUDY DESIGN: Single-group, repeatedmeasures design.

 OBJECTIVE: To compare patellofemoral joint (PFJ) stress among weight-bearing and nonweight-bearing quadriceps exercises.

BACKGROUND: An important consideration when prescribing exercises to strengthen the quadriceps in persons with patellofemoral pain is to minimize PFJ loading. Currently, there is disagreement in the literature as to which exercises and ranges of motion best accomplish this goal.

• **METHODS:** Ten healthy subjects participated. Lower extremity kinematics, kinetics, and electromyography of the knee musculature were obtained during a weight-bearing squatting exercise and 2 non-weight-bearing knee extension exercises: (1) knee extension with variable resistance, and (2) knee extension with constant resistance. A previously described biomechanical model was used to estimate PFJ stress at 0°, 15°, 30°, 45°, 60°, 75°, and 90° of knee flexion. PFJ stress was compared among the 3 exercises using a 2-way analysis of variance with repeated measures. **RESULTS:** Compared to the 2 non-weightbearing exercises, the squat exercise produced significantly higher PFJ stress at 90°, 75°, and 60° of knee flexion. Conversely, the 2 non-weight-bearing exercises produced significantly higher PFJ stress at 30°, 15°, and 0° of knee flexion when compared to the squat exercise. The knee-extension-withvariable-resistance exercise produced significantly lower PFJ stress than the knee-extension-withconstant-resistance exercise at 90°, 75°, and 60° of knee flexion.

• CONCLUSION: To minimize PFJ stress while performing quadriceps exercises, our data suggest that the squat exercise should be performed from 45° to 0° of knee flexion and the knee-extensionwith-variable-resistance exercise should be performed from 90° to 45° of knee flexion. J Orthop Sports Phys Ther 2014;44(5):320-327. Epub 27 March 2014. doi:10.2519/jospt.2014.4936

• KEY WORDS: force, patella, pressure, rehabilitation

In contrast, nonweight-bearing knee extension exercises require less cocontraction of antagonist muscles thus provide better

quadriceps muscle isolation. $^{\scriptscriptstyle 5}$ 

When designing a quadricepsstrengthening program for individuals with PFP, it is important to select exercises that promote muscle loading and adaptation and minimize patellofemoral joint (PFJ) stress and pain. Steinkamp and colleagues17 first described the influence of weight-bearing status on PFJ stress. These authors reported a contrast in the pattern of PFJ stress during weight-bearing and non-weight-bearing exercises performed at 0° to 90° of knee flexion. During the weight-bearing task (leg press), PFJ stress increased linearly from 0° to 90° of knee flexion.<sup>17</sup> During the non-weight-bearing knee extension exercise, however, PFJ stress was greatest at 0° and decreased with knee flexion.17

The findings of Steinkamp et al<sup>17</sup> have been challenged by Escamilla and colleagues,<sup>6</sup> who quantified PFJ reaction forces during similar weight-bearing and non-weight-bearing tasks (squat and knee extension, respectively). These authors reported that the PFJ reaction

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Escamilla et al<sup>6</sup> can be explained by the types of knee extension exercises that were evaluated. Steinkamp et al<sup>17</sup> studied knee extension with a mass applied at the ankle (an ankle weight). As a result, the applied resistance was not perpendicular to the tibia throughout the range of knee extension. Consequently, the external knee flexion moment created by the ankle weight increased as the knee extended from 90° to 0°, because of the progressive increase in the moment arm of the external resistance (FIGURE 1A). In this scenario, the increasing external knee flexion moment would translate into increased quadriceps force and PFJ reaction forces. In contrast, Escamilla et al<sup>6</sup> evaluated knee extension on an exercise machine that applied external resistance perpendicular to the tibia. This resulted in a constant external moment arm throughout the range of knee extension (FIGURE 2A). In this scenario, the external knee flexion moment, quadriceps force, and PFJ reaction force would have been relatively constant during the exercise.

Given the discrepancies in the existing literature, the purpose of this study was to determine the influence of weightbearing status on PFJ stress. To investigate this, we examined a weight-bearing squat exercise and 2 non-weight-bearing knee extension exercises: (1) knee extension with variable resistance (EXT-VR), and (2) knee extension with constant



**FIGURE I.** (A) Free-body diagram for the knee extension exercise evaluated by Steinkamp et al.<sup>a</sup> The external moment arm increases with decreasing knee flexion angle  $(L_1>L_2>L_3)$ , resulting in an increasing external flexion moment and quadriceps demand as the knee extends. (B) Free-body diagram for knee extension with variable resistance. Abbreviations:  $\alpha$ , knee flexion angle; d, distance from the lower-leg center of mass to knee axis of rotation; F, ankle-weight resistance; KFM, knee flexor moment; I, distance from knee center to ankle weight; L<sub>1</sub>, moment arm of the external load at 0° of knee flexion; L<sub>2</sub>, moment arm of the external load at 45° of knee flexion; L<sub>3</sub>, moment arm of the external load at 90° of knee flexion; SIMM, Software for Interactive Musculoskeletal Modeling; W, weight of shank and foot.

resistance (EXT-CR). The EXT-VR exercise was similar to that described by Steinkamp et al,<sup>17</sup> whereas the EXT-CR exercise was similar to that evaluated by Escamilla and colleagues.<sup>6</sup> Data obtained from this study will be useful in clarifying the best methods to promote quadriceps strengthening while minimizing PFJ loading during rehabilitation.

## METHODS

#### **Participants**

EN HEALTHY, PAIN-FREE INDIVIDUALS (5 men, 5 women) between 24 and 40 years of age participated. The men had a mean  $\pm$  SD age of 32.4  $\pm$  4.7 years, height of 177.6  $\pm$  5.5 cm, and mass of 72.7  $\pm$  5.7 kg; the women had an age of 25  $\pm$ 1.0 years, height of 167.8  $\pm$  4.3 cm, and mass of 56.5  $\pm$  4.5 kg. The participants were physically active and were recruited from the graduate student population at the University of Southern California. Specific exclusion criteria included (1) history of knee pathology or trauma, (2) current knee pain or effusion, and (3) knee pain with any recreational activities or activities of daily living. Prior to participation, the purpose of the study, procedures, and risks were explained to each participant,

and informed consent was obtained per the study protocol, which was approved by the Institutional Review Board of the University of Southern California.

#### **Procedures**

Subjects participated in 2 testing sessions. The purpose of the first session was to establish the resistance for each exercise. The second session consisted of biomechanical testing of each exercise. Only the dominant limb of each participant was evaluated (as determined by the preferred limb used to kick a ball). All testing was performed at the University of Southern California.

**Determination of Exercise Resistance** To provide a valid comparison of PFJ stress between the 3 exercises, an attempt was made to use a resistance for the 2 nonweight-bearing knee extension exercises that would result in a quadriceps demand similar to that of the squat exercise. To accomplish this goal, each participant underwent an electromyographic (EMG) analysis of the vastus lateralis while performing each exercise. The vastus lateralis electrode was placed over the muscle belly at the level of the mid thigh.<sup>8</sup> Vastus lateralis activity was recorded at 1560 Hz, using a preamplified surface electrode

(Motion Lab Systems, Inc, Baton Rouge, LA). The vastus lateralis EMG signal was band-pass filtered (50-200 Hz) and processed using a root-mean-square smoothing algorithm (75-millisecond window).

First, the level of vastus lateralis activation was established for the squat exercise. Participants assumed a comfortable stance position (feet shoulder-width apart and toes straight ahead) and were instructed to execute the squat from a starting position of 0° of knee flexion to a depth of 90° (as determined by a plastic goniometer) and to return to the start position. To ensure that 90° of knee flexion was achieved, a stool with an adjustable seat height was placed behind each participant to serve as the target for desired squat depth. Participants descended by flexing the hips and knees until the posterior aspect of the thighs was in contact with the stool. The velocity of the squatting maneuver was controlled by a metronome, such that the knee angular velocity was approximately 30°/s. Three squat trials were performed. With the participant still connected to the EMG unit, the vastus lateralis EMG time integral during the concentric phase of the squat cycle was calculated for each trial and averaged.

Next, the external loads for the EXT-VR and EXT-CR exercises were determined. This was done by matching the vastus lateralis EMG time integral for each non-weight-bearing exercise to that calculated for the squat. The EXT-VR exercise was performed with each participant sitting on a chair (90° of hip and knee flexion), with an ankle weight secured to the distal end of the tibia (superior to the malleolus). The EXT-CR exercise was performed on a dynamometer (Kin-Com; Isokinetic International, Harrison, TN). As with the EXT-VR exercise, participants were positioned in 90° of hip and knee flexion and the resistance pad was secured to the distal end of the tibia (superior to the malleolus). The Kin-Com dynamometer allows for the resistance pad to be applied perpendicular to the tibia, thus providing a constant external



moment via a fixed lever arm throughout the range of motion. The dynamometer was set to isotonic mode, allowing the resistance to be adjusted as necessary.

For both the EXT-VR and EXT-CR exercises, participants performed 3 knee extension trials (90°-0° of knee flexion). As with the squat exercise, the knee angular velocity for both non-weight-bearing exercises was controlled by a metronome (30°/s). After each set of 3 trials, the vastus lateralis EMG time integral during the concentric phase of each exercise was calculated for each trial and averaged. If the calculated vastus lateralis EMG time integral did not fall within 95% to 105% of the value established during the squat exercise, the external resistance was adjusted accordingly and 3 additional trials were collected. This process was repeated until the  $\pm 5\%$  difference threshold was achieved for both non-weight-bearing exercises. On average, the 3 trials were repeated 5 times to achieve this threshold. Using this procedure, the average  $\pm$ SD resistance was  $4.4 \pm 3.5$  kg for the EXT-VR exercise and  $4.1 \pm 2.2$  kg for the EXT-CR exercise.

**Biomechanical Testing** After determining the resistance for the EXT-VR and the EXT-CR exercises, biomechanical testing of each exercise commenced. The purpose of this testing was to calculate the knee extensor moment (KEM) during each exercise, which was the key input variable of a PFJ model to estimate PFJ stress. The KEM during the squat exercise was determined using inversedynamics equations. The KEM during the EXT-VR and EXT-CR exercises was estimated using free-body diagrams (see below for details).

Although the net KEM provides a reasonable estimate of the demands placed on the knee extensors, the true quadriceps force would be underestimated in the presence of muscle cocontraction. To account for the potential influence of muscle cocontraction, an estimate of the knee flexor moment (KFM) was obtained during each exercise by using an EMGdriven musculoskeletal model (see below for details).

Using a previously described marker set,<sup>13</sup> lower extremity kinematics during the squat exercise was assessed with an 8-camera, Vicon motion analysis system at a sampling frequency of 250 Hz (OMG plc, Oxford, UK). Ground reaction forces were obtained with 2 force platforms at a rate of 1500 Hz (Advanced Mechanical Technology, Inc, Watertown, MA). Using



the instrumentation described above, EMG signals were obtained from the medial and lateral hamstrings and the medial and lateral heads of the gastrocnemius. The electrodes for the medial and lateral hamstrings were placed over the respective muscle bellies, midway between the ischial tuberosity and the epicondyles of the femur.<sup>8</sup> The electrodes for the medial and lateral gastrocnemius were placed over the upper one third of the respective muscle bellies.<sup>8</sup>

The procedures for the squat exercise were identical to those described above. Participants were positioned such that each foot fell within the boundaries of one of the adjacent force platforms. Once 3 trials of the squat exercise had been completed, the motion markers were removed and 3 trials of the EXT-VR and EXT-CR exercises were obtained using the previously established resistance. A sufficient rest (approximately 10 minutes) was provided between exercise conditions to minimize fatigue.

### Data Analysis

Kinematic and kinetic data obtained during the squat exercise were processed using Visual3D software (C-Motion, Inc, Germantown, MD). Marker trajectories were low-pass filtered at 6 Hz using a fourth-order Butterworth filter. As described above, EMG signals were bandpass filtered (50-200 Hz) and processed using a root-mean-square smoothing algorithm (75-millisecond window). EMG data were normalized to the EMG data acquired during a maximal voluntary isometric contraction.

Estimate of KFM To account for cocontraction during the 3 exercises evaluated, an estimate of the KFM was required. The KFM was obtained from SIMM modeling software (Motion Analysis Corporation, Santa Rosa, CA). The SIMM lowerlimb model contains musculotendon actuators with information about peak isometric muscle force, optimal musclefiber length, pennation angle, and tendon slack length for the muscles of the lower extremity.4 In the SIMM software, muscles are represented as a series of 3-D vectors that are constrained to wrap over underlying structures. Using a Hill-based model, the SIMM software estimated the KFM based on the individual's lower extremity kinematics, speed of movement, and flexor muscle EMG. The estimated KEM derived from SIMM software has been found to be comparable to the KEM calculated with inverse-dynamics equations.10

To obtain a more accurate assessment of the KEM during the squat exercise, the KFM calculated by SIMM was added to the net KEM as estimated from the inverse-dynamics equations. This resulted in an adjusted KEM that accounted for antagonist muscle activation throughout the squat cycle: adjusted KEM = [net KEM (inverse dynamics) + KFM (SIMM)]. The adjusted KEM during the EXT-VR exercise was calculated based on the following equation: adjusted KEM =  $[(W \times d + F \times l)(\cos \alpha) + \text{KFM (SIMM)}]$ , where *W* is weight of shank and foot (6.0% of total body weight),<sup>26</sup> *d* is distance from the lower-leg center of mass to the knee axis (43.3% of distance between knee axis and medial malleolus),<sup>26</sup> *F* is ankle-weight resistance, *l* is the distance from knee center to ankle weight, and  $\alpha$  is the knee flexion angle (**FIGURE 1B**).

The adjusted KEM during the EXT-CR exercise was calculated based on the following equation:  $[(W \times d \times \cos \alpha) + (F \times l) + \text{KFM (SIMM)}]$ , where *W* is weight of shank and foot (6.0% of total body weight),<sup>26</sup> *d* is distance from the lowerleg center of mass to the knee axis (43.3% of distance between knee axis and medial malleolus),<sup>26</sup> *F* is ankle-weight resistance, *l* is the distance from knee center to ankle weight, and  $\alpha$  is the knee flexion angle (**FIGURE 2B**).

# Biomechanical Model to Estimate PFJ Stress

A previously described model was used to quantify PFJ stress (**FIGURE 3**).<sup>2,3,22,24</sup> Input variables included participant-specific parameters (ie, knee joint flexion angle and adjusted KEM) and data obtained from the literature (ie, PFJ contact area,<sup>14</sup> quadriceps effective lever arm,<sup>14</sup> and the relationship between quadriceps force and PFJ reaction force).<sup>23</sup>

Step 1 of the algorithm was to approximate the quadriceps force. First, the effective lever arm for the quadriceps muscle



**FIGURE 4.** Patellofemoral joint stress profiles of the 3 exercises evaluated in the current study. \*Significant difference from EXT-VR. <sup>†</sup>Significant difference from EXT-CR. Abbreviations: EXT-CR, knee extension with constant resistance; EXT-VR, knee extension with variable resistance.

TABLE		Patellofemoral Joint Stresses Among 3 Exercises at 7 Knee Flexion Angles*					
	0°	15°	30°	45°	60°	75°	90°
EXT-VR	8.4 ± 1.6	5.6 ± 1.0	4.7 ± 0.6	4.2 ± 0.8	$3.6\pm0.8$	2.6 ± 0.8	$0.5\pm0.5$
EXT-CR	7.9 ± 1.6	$5.6\pm1.6$	$5.1\pm1.5$	$5.0\pm1.5$	$5.2\pm1.6^{\dagger}$	$6.0\pm2.0^{\dagger}$	$6.5\pm2.6^{\dagger}$
Squat	$0.3\pm0.8^{\dagger\dagger}$	$0.9\pm0.9^{\dagger\dagger}$	$1.9\pm0.9^{\dagger\ddagger}$	3.9 ± 1.3	$6.7\pm1.4^{\circ}$	$10.5\pm1.6^{\rm tp}$	$12.3\pm1.6^{\ddagger}$
Abbrevia variable *Values †Signific *Signific	itions: EXT-Cl resistance. are mean ± SL ant difference j ant difference ;	R, knee extens ) MPa. from EXT-VR from EXT-CR	ion with const (P<.016). (P< 016).	tant resistand	ce; EXT-VR, k	nee extension	with

was determined at each degree of knee flexion by fitting a nonlinear equation to the data of van Eijden and colleagues.<sup>22</sup> Next, the quadriceps force was calculated by dividing the adjusted KEM calculated during each exercise by the effective lever arm. Step 2 of the algorithm was to estimate the PFJ reaction force. This was accomplished by multiplying the quadriceps force by a constant established by van Eijden and colleagues<sup>23</sup> that defined the relationship between quadriceps force and PFJ reaction force as a function of knee flexion angle. The third step of the algorithm was to calculate PFJ stress. The PFJ joint reaction force established in step 2 was divided by the PFJ contact area. PFJ contact area was determined for each knee flexion angle using a secondorder polynomial curve fit to the data of Powers et al.<sup>14</sup> The model output was PFJ stress as a function of knee flexion angle.

#### **Statistical Analysis**

PFJ stress was compared among the 3 exercises at 0°, 15°, 30°, 45°, 60°, 75°, and 90° of knee flexion using a 2-factor (exercise by knee flexion angle) analysis of variance (ANOVA) with repeated measures. If a significant interaction was found, separate 1-way ANOVAs using a Bonferroni correction were used to assess differences in PFJ stress between exercises at each knee flexion angle. If a post hoc ANOVA was found to be significant, then a second level of post hoc testing was employed (paired t tests with a Bonferroni correction). Statistical analysis was performed using SPSS Version 18.0 statistical software (SPSS Inc, Chicago, IL).

### RESULTS

HE PFJ STRESS RESULTS FOR THE different exercises are presented in FIGURE 4 and the TABLE. The results of the 2-factor ANOVA revealed a significant exercise-by-angle interaction (P < .001). The post hoc 1-way ANOVAs revealed that PFJ stress differed significantly among the 3 exercises at 0°, 15°, 30°, 60°, 75°, and 90° of knee flexion (P < .001). No differences in PFJ stress were detected between the 3 exercises at  $45^{\circ}$  of knee flexion (P = .126). As a result of the significant 1-way ANOVAs, secondary post hoc t tests were performed to test the differences among 3 exercises at 0°, 15°, 30°, 60°, 75°, and 90° of knee flexion.

At 0°, 15°, and 30° of knee flexion, the average PFJ stress for both the EXT-VR and EXT-CR exercises was significantly greater than the squat exercise (P<.001). No difference in average PFJ stress was found between the EXT-VR and EXT-CR exercises at 0°, 15°, and 30° of knee flexion (FIGURE 4, TABLE). At 60° of knee flexion, the average PFJ stress for both the EXT-CR and squat exercises was significantly greater than that for the EXT-VR exercise (P<.001). No difference in average PFJ stress was found between the EXT-CR and squat exercises at 60° of knee flexion (P = .062). At 75° and 90° of knee flexion, the average PFJ stress for the squat exercise was significantly greater than that for the EXT-CR (P<.001) and EXT-VR (P<.001) exercises. In addition, the average stress for the EXT-CR exercise was significantly greater than that for the EXT-VR exercise at 75° and 90° of knee flexion (P<.001) (**FIGURE 4**, **TABLE**).

### DISCUSSION

HE RESULTS OF THE CURRENT STUDY revealed that PFJ stress profiles varied considerably among the 3 exercises evaluated. In general, the PFJ stress during the squat exercise was greatest at 90° of knee flexion (12.3 MPa) and steadily decreased as the knee extended (FIGURE 4, TABLE). In contrast, the PFJ stress during the EXT-VR exercise was lowest at 90° of knee flexion and steadily increased as the knee extended, achieving a maximum value of 8.4 MPa at 0°. PFJ stress during the EXT-CR exercise was relatively constant throughout the range of motion, with peak stress (7.9 MPa) occurring at 0° of knee flexion (FIGURE 4, TABLE).

The PFJ stress profiles for the EXT-VR and squat exercises in the current study are in close agreement with the findings of Steinkamp and colleagues.17 In their study, Steinkamp et al<sup>17</sup> reported that PFJ stress during the weight-bearing exercise was greater than that during the non-weight-bearing exercise at knee flexion angles greater than 45°. Conversely, these authors reported that PFJ stress during the non-weight-bearing exercise was greater than that during the weightbearing exercise at knee flexion angles less than 45°.17 Interestingly, our data revealed that the stress profiles for squat and EXT-VR exercises also diverged at 45° of knee flexion (FIGURE 4).

Despite the similarities between the stress profiles in the current study and those reported by Steinkamp and colleagues,<sup>17</sup> peak stress values varied considerably. For example, Steinkamp et al<sup>17</sup> reported peak PFJ stresses for nonweight-bearing (knee extension) and weight-bearing (leg press) exercises of 22.8 and 24.3 MPa, respectively, compared to 8.4 and 12.3 MPa in the current study. This discrepancy can be explained by the fact that Steinkamp et al<sup>17</sup> used greater external loads, which resulted in knee extensor torques of approximately 205 Nm for their weight-bearing and non-weight-bearing exercises. In contrast, the external loads used in the current study resulted in external knee extensor torques of 67.5, 67.2, and 64 Nm for the EXT-VR, EXT-CR, and squat exercises, respectively.

The PFJ stress profile for the EXT-CR exercise in the current study was similar to the external knee flexion moment curve reported by Escamilla and colleagues.<sup>6</sup> Between 90° and 0° of knee flexion, the PFJ stress for the EXT-CR exercise was relatively constant. However, as PFJ stress was not computed by Escamilla et al,<sup>6</sup> direct comparisons to the current study are not possible.

As mentioned previously, the differences in PFJ stress profiles between the 2 non-weight-bearing knee extension exercises can be explained by how the resistance was applied to the tibia. For the EXT-CR exercise, the moment arm for the external load was maintained throughout knee flexion/extension. whereas the moment arm of the external load increased with knee extension in the EXT-VR exercise. For the EXT-VR exercise, the maximum external knee flexion moment at 0° of knee flexion resulted in the peak PFJ stress occurring at full knee extension. For the EXT-CR exercise, the constant external knee flexion moment from 90° to 0° of knee flexion resulted in a relatively consistent PFJ stress pattern throughout the range of motion.

The differences in PFJ stress profiles between the EXT-VR and squat exercises can be explained by the varied interaction between PFJ reaction force and PFJ contact area while performing these 2 tasks. The PFJ contact area used in our model was smallest at 0° and steadily increased with knee flexion.<sup>14</sup> During the EXT-VR exercise, the progressive increase in PFJ reaction force, combined with the simultaneous decrease in contact area as the knee extended from 90° to 0°, resulted in an overall increase in PFJ stress. In contrast, the PFJ reaction force during the squat exercise steadily decreased as the knee extended from 90° to 0°. The decrease in the PFJ reaction force was more pronounced than the decrease in contact area, resulting in an overall decrease in PFJ stress as the knee extended.

It is important during the initial stages of PFJ rehabilitation to select quadriceps exercises and external loads that minimize PFJ stress. The findings of the current study provide a general rehabilitation guideline to accomplish this goal. To strengthen the quadriceps through a 90° range of motion and to keep PFJ stress to a minimum, our data suggest that a combination of weight-bearing and non-weight-bearing exercises could be utilized. For example, performing the squat exercise from 0° to 45° of knee flexion and the EXT-VR exercise from 45° to 90° of knee flexion would keep PFJ stress to a minimum (below 4 MPa). Although it is not known how much stress causes PFP or constitutes "overloading" of the PFJ, it has been reported that the peak PFJ stress during stair ambulation (a common pain-inducing activity) is approximately 4 MPa.15 As such, keeping PFJ stress values below this threshold during the initial stages of PFJ rehabilitation would appear to be prudent. It should be noted that the EXT-CR exercise resulted in PFJ stress values greater than 4 MPa throughout the entire range of motion evaluated, and thus should be used with caution.

The present study has several limitations that should be acknowledged. First, only healthy participants were evaluated. As such, caution should be taken when generalizing the current results to patients with PFP. For instance, it has been shown that persons with PFP have smaller contact areas when compared with healthy persons.<sup>16</sup> Although smaller contact areas would lead to higher PFJ stresses, the general trends for each of the exercises evaluated in the current study

likely would be similar. Second, the absolute PFJ stress values reported here should be viewed with caution, as our PFJ model has not been validated against a gold standard. However, any error in PFJ stress estimates would be similar across conditions, making comparisons between exercises valid. Third, we did not control the trunk position during the squat exercise. This could have influenced the magnitude of the KEM and therefore the PFJ stress during this task. In addition, despite our attempt to standardize the resistance across exercises, PFJ stress may vary based on the magnitude of external loads applied (regardless of the exercise performed). Fourth, segmental accelerations during the non-weight-bearing exercises were considered to be negligible and were not considered in the calculations of PFJ stress. As such, the absolute values presented for these tasks should be viewed with caution. Last, we only reported data for the concentric phase of each exercise. Further research is necessary to determine whether differences in PFJ stress exist between the concentric and eccentric phases of a given exercise.

## CONCLUSION

UR RESULTS PROVIDE GENERAL guidelines with respect to quadriceps strengthening for persons with PFP. To keep PFJ stress to a minimum, our data suggest that the squat exercise should be performed between 0° and 45° of knee flexion and the EXT-VR exercise should be performed between 45° and 90° of knee flexion. Throughout the range of motion evaluated, the EXT-CR exercise generated a level of PFJ stress comparable to climbing stairs (ie, greater than 4 MPa), and thus should be used with caution. •

#### KEY POINTS

**FINDINGS:** When compared to the 2 non–weight-bearing exercises, the squat exercise produced significantly higher PFJ stress at 60°, 75°, and 90° of knee flexion. Conversely, the 2 non–weightbearing exercises produced significantly higher PFJ stress at 0°, 15°, and 30° of knee flexion when compared to the squat exercise. The EXT-VR exercise produced significantly lower PFJ stress than the EXT-CR exercises at 90°, 75°, and 60° of knee flexion.

**IMPLICATIONS:** To keep PFJ stress to a minimum, our data suggest that the squat exercise should be performed between 0° and 45° of knee flexion and the EXT-VR exercise should be performed between 45° and 90° of knee flexion. **CAUTION:** As only healthy participants were evaluated, caution should be taken when generalizing the current results to persons with PFP.

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