Effects of technique variations on knee biomechanics during the squat and leg press

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Michael W. Krzyzewski Human Performance Laboratory, Division of Orthopaedic Surgery and Duke Sports Medicine, Duke University Medical Center, Durham, NC 27710; American Sports Medicine Institute, Birmingham, AL 35205; Department of Sports Health Science, Life University, Marietta, GA 30060; and Department of Exercise Science, Campbell University, Buies Creek, NC 27506

ABSTRACT

ESCAMILLA, R. F., G. S. FLEISIG, N. ZHENG, J. E. LANDER, S. W. BARRENTINE, J. R. ANDREWS, B. W. BERGEMANN, and C. T. MOORMAN, III. Effects of technique variations on knee biomechanics during the squat and leg press. *Med. Sci. Sports Exerc.*, Vol. 33, No. 9, 2001, pp. 1552–1566. **Purpose:** The specific aim of this project was to quantify knee forces and muscle activity while performing squat and leg press exercises with technique variations. **Methods:** Ten experienced male lifters performed the squat, a high foot placement leg press (LPH), and a low foot placement leg press (LPL) employing a wide stance (WS), narrow stance (NS), and two foot angle positions (feet straight and feet turned out 30°). **Results:** No differences were found in muscle activity or knee forces between foot angle variations. The squat generated greater quadriceps and hamstrings activity than the LPH and LPL, the WS-LPH generated greater hamstrings activity than the NS-LPH, whereas the NS squat produced greater gastrocnemius activity than the WS squat. No ACL forces were produced for any exercise variation. Tibiofemoral (TF) compressive forces, PCL tensile forces, and patellofemoral (PF) compressive forces were generally greater in the squat than the LPH and LPL, and there were no differences in knee forces between the LPH and LPL. For all exercises, the WS generated greater PCL tensile forces than the NS, the NS produced greater TF and PF compressive forces than the WS during the LPH and LPL, whereas the WS generated greater TF and PF compressive forces than the NS during the squat. For all exercises, muscle activity and knee forces were generally greater in the knee extending phase than the knee flexing phase. **Conclusions:** The greater muscle activity and knee forces in the squat compared with the LPL and LPH implies the squat may be more effective in muscle development but should be used cautiously in those with PCL and PF disorders, especially at greater knee flexion angles. Because all forces increased with knee flexion, training within the functional 0–50° range may be efficacious for those whose goal is to minimize knee forces. The lack of ACL forces implies that all exercises may be effective during ACL rehabilitation. **Key Words:** POWERLIFTING, KINETICS, PATELLOFEMORAL, TIBIOFEMORAL, ACL, PCL, COMPRESSIVE, SHEAR, REHABILITATION, FORCE, MUSCLE ACTIVITY, EMG

The dynamic squat and leg press (LP) exercises are common core exercises that are utilized by athletes to enhance performance in sport. These multi-joint exercises develop the largest and most powerful muscles of the body and have biomechanical and neuromuscular similarities to many athletic movements, such as running and jumping. Because the squat and LP are considered closed kinetic chain exercises (11,34), they are often recommended and utilized in clinical environments, such as during knee rehabilitation after anterior cruciate ligament (ACL) reconstruction surgery (17,23). Athletes and rehabilitation patients perform the squat and LP exercises with varying techniques according to their training or rehabilitation protocols. An athlete or patient with patellar chondromalacia, or recovering from ACL reconstruction, may prefer a squat or LP technique that minimizes patellofemoral compressive force or tibiofemoral anterior shear force. Athletes or patients typically choose a squat or LP technique according to personal preference and effectiveness. Furthermore, athletes often use varying techniques to develop specific muscles. Some prefer training the squat and LP with a narrow stance, whereas others prefer a wide stance. Similarly, some athletes prefer their feet pointing straight ahead, whereas others prefer their feet slightly turned out. In addition, some athletes prefer a high foot placement on the LP foot plate, whereas others prefer a low foot placement. However, the effects that these varying stances, foot angles, and foot placements have on knee forces and muscle activity is currently unknown.

During performance of the dynamic squat exercise, several studies have quantified tibiofemoral compressive forces (4,9,11,12,21,30,34), tibiofemoral shear forces (3,4, 9,11,12,21,30,32,34), patellofemoral compressive forces (9,11,21,25,35), and muscle activity about the knee (9,11, 15,19,20,26,27,30,34–37). There are two known studies that have quantified tibiofemoral forces, patellofemoral forces, and muscle activity during the dynamic LP (11,34). However, none of these squat or LP studies quantified knee forces while performing these exercises. Although there are a few studies that quantified muscle activity while performing the squat with varying foot positions (7,19,20,26,31),

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there are no known studies that have quantified muscle activity while performing the LP with varying foot positions. Having 10 subjects perform the squat and LP with their preferred stance width and foot angle, Escamilla et al. (11) reported a mean stance (distance between medial calcanei) of 40 ± 8 cm for the squat and 34 ± 14 cm for the LP, and a mean forefoot abduction of 22 ± 11° for the squat and 18 ± 12° for the LP. Although these stance and foot angle measurements are typical for athletes performing the squat or LP, many athletes prefer a more narrow or wide stance while performing the squat and LP. Therefore, it is important to understand how knee forces and muscle activity vary if the squat and LP are performed with a more narrow or wide stance, or with the feet turned out or in to a greater extent. Knee forces and muscle activity may also vary during the LP by placing the feet higher or lower on the foot plate. The specific aim of this project was to quantify tibiofemoral compressive forces, ACL/PCL tensile forces, patellofemoral compressive forces, and muscle activity about the knee while performing the squat and LP with varying stances, foot angles, and foot placements. We hypothesized that knee force and electromyographic (EMG) measurements would be significantly different among the squat, LP with high foot placement, and LP with low foot placement while employing these varying foot positions. This information will provide valuable insights to athletes, physicians, therapists, and trainers concerning which exercises and technique variations would be most effective for athletic training or knee rehabilitation.

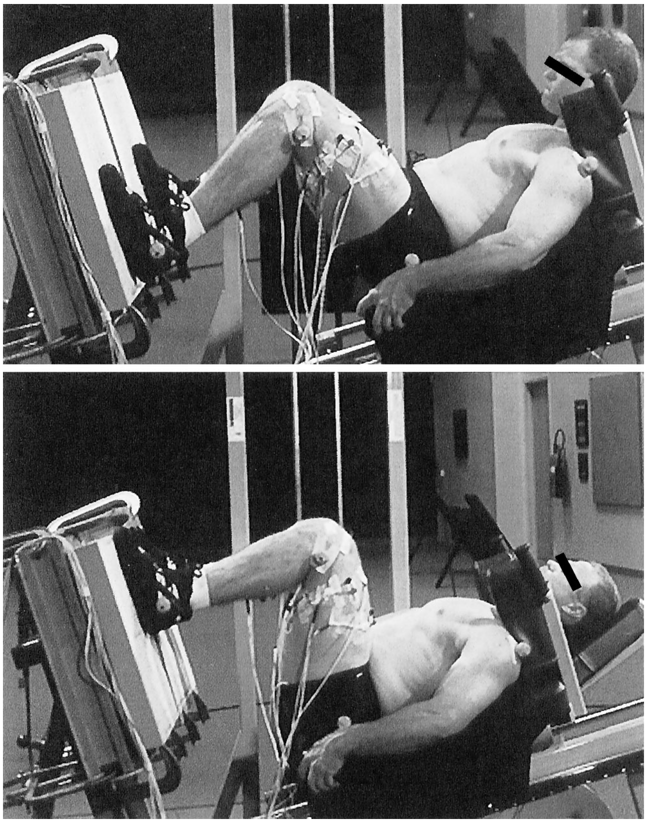

FIGURE 1—Performing the narrow stance leg press with a low foot placement (top) and a high foot placement (bottom).

METHODS AND MATERIALS

Subjects. Ten male lifters experienced in performing the squat and LP served as subjects. All subjects had previously performed the squat and LP regularly in their training regimens and employed varying stances, foot angles, and foot placements throughout a periodization yearly training cycle. The subjects had 10.1 ± 7.7 yr experience performing the squat and 9.0 ± 8.3 yr experience performing the LP. To accurately measure knee forces while performing squat and LP variations, it was important to have subjects who had experience in performing these exercises with varying techniques. The subjects had a mean height of 177.0 ± 8.5 cm, a mean mass of 93.5 ± 14.0 kg, and a mean age of 29.6 ± 6.5 yr. All subjects had no history of knee injuries or knee surgery. Before subjects participated in the study, informed consent was obtained.

Data collection. A pretest was given to each subject 1 wk before the actual testing session. The experimental protocol was reviewed, and the subjects were given the opportunity to ask questions. During the pretest, the subject's stance, foot angle, foot placement, and 12-repetition maximum (12 RM) were determined and recorded for the squat and LP. The subjects were first asked to perform the squat and LP with their preferred narrow and wide stances that they normally used in training. Because the subjects' preferred narrow stance for the squat and LP ranged between 24 and 31 cm when measured between their medial calcanei, and the mean distance between their anterior superior iliac spines (ASIS) was 28.6 ± 2.5 cm, the distance between each subject's ASIS was used to normalize and define the narrow stance. Because the subjects' preferred wide stance for the squat and LP ranged between 53 and 65 cm, and twice their mean ASIS distance was 57.2 cm, twice the distance between each subject's ASIS was used to normalize and define the wide stance. The subjects' mean foot angles measured during their preferred narrow stance squat and LP were 7.7 ± 7.6° and 7.2 ± 7.1°, respectively, whereas their mean foot angles measured during their preferred wide stance squat and LP were 36.6 ± 8.6° and 32.5 ± 6.3°, respectively. Because most of the subjects employed foot angles that ranged between 0 and 30° of forefoot abduction, the two foot positions defined for all exercises and stances were a) the feet pointing straight ahead, which was defined as 0° of forefoot abduction; and b) 30° of forefoot abduction.

To define high and low foot placements on the LP foot plate, each subject was asked to perform the LP with their preferred high and low foot placements. For their high foot placement, each subject's preference was to position their feet near the top of the foot plate so that their leg was near parallel with the back pad and near perpendicular to the foot plate at approximately 90–100° knee flexion (Fig. 1, bottom). For their low foot placement, the subjects preference was to move their feet down on the foot plate a mean distance of 20.1 ± 1.4 cm from their high foot placement (Fig. 1, top).

Each subject's 12 RM was determined for both the squat and LP utilizing the most weight they could lift for 12 consecutive repetitions. Because it was predetermined that the same 12 RM weight would be employed for all technique variations within an exercise, each subject's 12 RM was determined for the squat and LP by using a foot position halfway between their defined narrow and wide stances, halfway between their two defined foot angle positions (i.e., 15°) and halfway between their defined low and high foot placements on the LP foot plate. The mean 12 RM loads that were employed during testing were 133.4 ± 37.0 kg for the squat and 129.1 ± 26.8 kg for the LP.

The subjects reported for testing 1 wk after the pretest. Spherical plastic balls (3.8 cm in diameter) covered with reflective tape were attached to adhesives and positioned over the following bony landmarks: a) medial and lateral malleoli of the left foot, b) upper edges of the medial and lateral tibial plateaus of the left knee, c) posterior aspect of the greater trochanters of the left and right femurs, and d) acromion process of the left shoulder. In addition, a 1-cm^2 piece of reflective tape was positioned on the third metatarsal head of the left foot. Four electronically synchronized high-speed charged couple device video cameras were strategically positioned around each subject, and centroid images from the reflective markers were transmitted directly into a motion analysis system (Motion Analysis Corporation, Santa Rosa, CA).

EMG was utilized to quantify muscle activity and help estimate internal muscle forces (11). EMG data from quadriceps, hamstrings, and gastrocnemius musculature were quantified with an eight channel, fixed cable, Noraxon Myosystem 2000 EMG unit (Noraxon U.S., Inc., Scottsdale, AZ). The amplifier bandwidth frequency ranged from 15 to 500 Hz, with an input voltage of 12 VDC at 1.5 A. The input impedance of the amplifier was 20,000 kΩ, and the common-mode rejection ratio was 130 Db. The skin was prepared by shaving, abrading, and cleaning. A model 1089 mk II Checktrode electrode tester (UFI, Morro Bay, CA) was used to test the contact impedance between the electrodes and the skin, with impedance values less than 200 kΩ considered acceptable (11). Most impedance values were less than 10 kΩ .

Blue Sensor (Medicotest Marketing, Inc., Ballwin, MO) disposable surface electrodes (type N-00-S) were used to collect EMG data. These oval-shaped electrodes (22 mm wide and 30 mm long) were placed in pairs along the longitudinal axis of each muscle or muscle group tested, with a center-to-center distance between each electrode of approximately 2–3 cm. One electrode pair was placed on each the following muscles in accordance with procedures from Basmajian and Blumenstein (5): 1) rectus femoris, 2) vastus lateralis, 3) vastus medialis, 4) lateral hamstrings (biceps femoris), 5) medial hamstrings (semimembranosus/semitendinosus), and 6) gastrocnemius.

A standard 20.5-kg Olympic barbell, disks (Standard Barbell), and a Continental squat rack were used during the squat. Each subject squatted with his left foot on an Advanced Mechanical Technologies, Inc. (AMTI) force platform (Model OR6–6-2000, Advanced Mechanical Technologies, Inc., Watertown, MA) and his right foot on a solid block (Fig. 2). A variable-resistance LP machine (Model MD-117, Body Master, Inc., Rayne, LA) was used during the LP. An AMTI force platform for the left foot and a solid block for the right foot were mounted on a customized LP foot plate (Figs. 1 and 3). The force platform, solid block, and LP foot plate all remained stationary throughout the lift, while the body moved away from the feet.

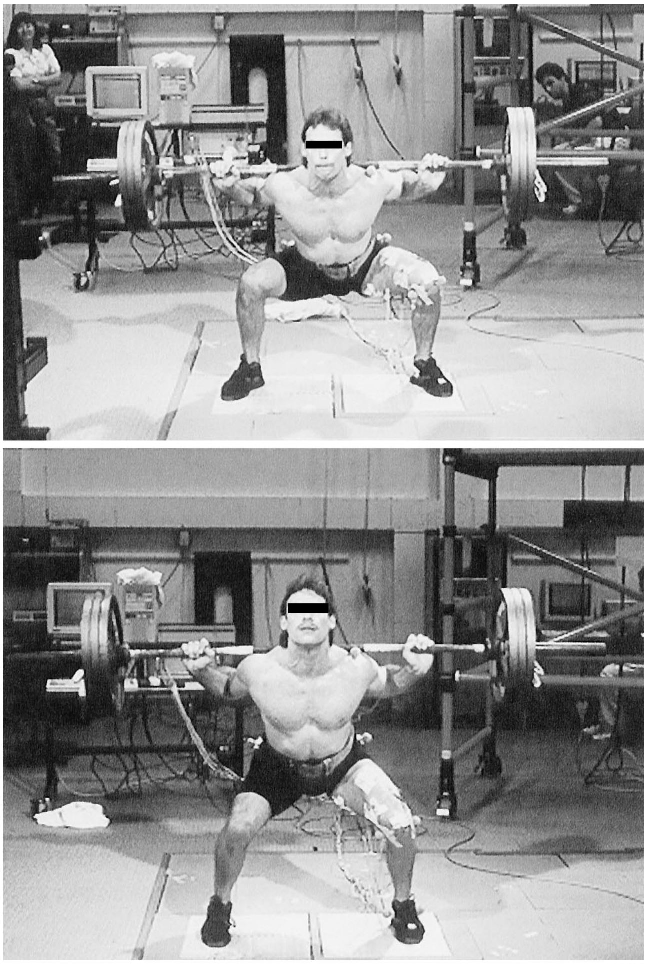

FIGURE 2—Performing the wide stance squat with 30° forefoot abduction (top) and with 0° forefoot abduction (bottom).

EMG, force, and video collection equipment were electronically synchronized, with EMG and force data sampled at 960 Hz and video data sampled at 60 Hz. Because bilateral symmetry was assumed, force, video, and EMG data were collected and analyzed only on the subject's left side (11). Each subject performed four variations of the squat (Fig. 2): a) narrow stance, 0° forefoot abduction; b) narrow stance, 30° forefoot abduction; c) wide stance, 0° forefoot abduction; and d) wide stance, 30° forefoot abduction. These same four variations were also performed during the LP (Fig. 3), with the feet placed both high and low on the LP foot plate (Fig. 1). Therefore, each subject performed a total of eight LP variations.

The order of performing the four squat variations and the eight LP variations was randomly assigned for each subject. All subjects performed two to three warm-up sets in preparation for testing. For all lifting variations, each subject used their 12 RM weights previously established for the

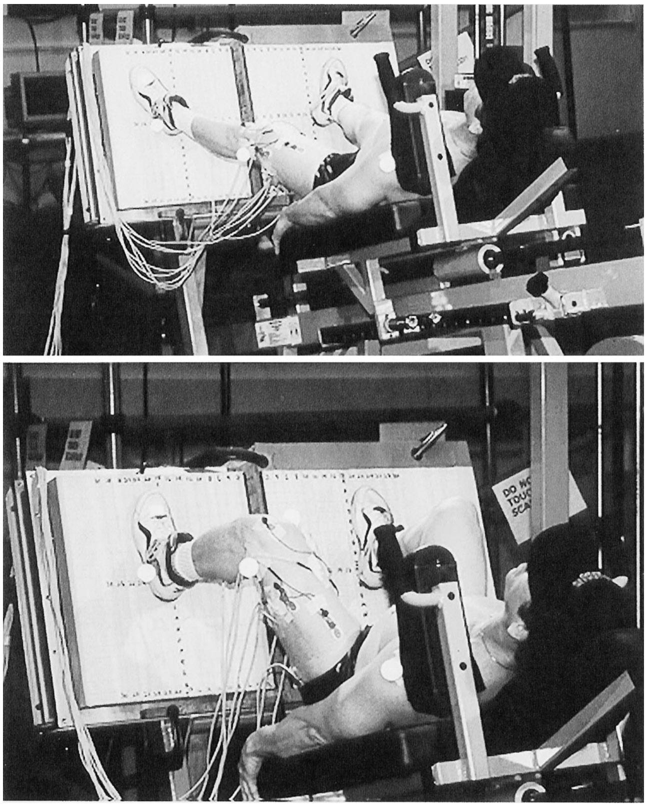

FIGURE 3—Performing the wide stance leg press with 30° forefoot abduction (top) and with 0° forefoot abduction (bottom).

squat and LP. To help the subjects determine their defined stance and foot placement for each exercise variation, a numerical grid was overlaid on the squat and LP force platforms (Figs. 2 and 3). A tester used a goniometer to help the subjects determine 0° and 30° of forefoot abduction. Once the feet were appropriately positioned for the squat and LP, a tester gave a verbal command to begin the exercise. The starting and ending positions for the squat and LP were with the knees in full extension, which was defined as 0° knee angle (KA). From the starting position, the subject flexed their knees to maximum KA (approximately 90–100°) and then extended their knees back to the starting position. Each exercise variation was performed in a slow and continuous manner according to a subject's preference. Due to the consistent cadence the subjects displayed for all exercise variations, cadence was not controlled, which allowed a subject to perform each exercise variation as they normally employed in training. Cadence was also similar among all subjects.

Each subject performed four repetitions for each exercise variation. Data collection was initiated at the end of the first repetition and continued throughout the final three repetitions of each set. Therefore, three distinct trials were collected for each of the 12 sets performed. Between each repetition, the subjects were instructed to pause approximately 1 s to provide a clear separation between repetitions. Each subject rested long enough between exercise variations to completely recover from the previous set (approximately 3–4 min). Fatigue was assumed to be minimal due to the submaximal weight lifted, the low lifting intensity, the low number of repetitions performed for each set, a sufficient rest interval between sets, and the high fitness level of the subjects. All subjects acknowledged that fatigue did not adversely affect their ability to perform any of the exercise variations.

Subsequent to completing all exercise trials, EMG data from the quadriceps, hamstrings, and gastrocnemius were collected during maximum voluntary isometric contractions (MVIC) to normalize the EMG data collected during the squat and LP variations (1,11). Three 3-s MVIC trials were collected in a randomized manner for each muscle group. The MVICs for the quadriceps and hamstrings muscles were performed in the seated position with approximately 90° hip and knee flexion, whereas the MVICs for the gastrocnemius were performed in a position of 0° hip and knee flexion with the feet halfway between the neutral ankle position and maximum plantar flexion. The methods and positions used during these MVICs have been previously described (11).

Data reduction. Video images for each reflective marker were automatically digitized in three-dimensional space with Motion Analysis ExpertVision software, utilizing the direct linear transformation method (11). Testing of the accuracy of the calibration system resulted in reflective balls that could be located in three-dimensional space with an error less than 1.0 cm. The raw position data were smoothed with a double-pass fourth-order Butterworth low-pass filter with a cut-off frequency of 6 Hz (11). A computer program was written to calculate joint angles, linear and angular velocities, and linear and angular accelerations during the squat and LP.

EMG data for each MVIC trial and each test trial were rectified and averaged in a 0.01-s moving window. Data for each test trial were then expressed as a percentage of the subject's highest corresponding MVIC trial. To compare muscle activity among the three exercises, between the narrow and wide stances, between the two foot angles, and between the knee flexing (KF) and knee extending (KE) phases, EMG data were averaged over both the KF and KE phases. Calculating EMG values over KF and KE phases is in accordance with procedures from McCaw and Melrose (19), who also examined how stance widths affect EMG during the squat. In addition, to determine where maximum quadriceps, hamstrings, and gastrocnemius activity occurred during the squat and LP, peak EMG values were calculated as a function of KA. Peak EMG values are important in order to compare peak muscle activity between muscles and determine where in the squat and LP range of motion these peak values occurred.

As previously described (11), resultant joint forces and torques acting on the foot and leg were calculated using three-dimensional rigid link models of the foot and leg and principles of inverse dynamics. Resultant forces at the knee were separated into three orthogonal components. However, due to the small magnitudes of mediolateral forces observed, only axial compressive and anteroposterior shear forces were further analyzed. Unfortunately, anterior and posterior shear force definitions are inconsistent among studies (11,12,17,21,29,30,34). In the current study, an anterior shear force was resisted primarily by the ACL, whereas a posterior shear force was resisted primarily by the PCL (8). Resultant torque applied by the thigh to the leg was separated into three orthogonal components. Due to the small magnitudes in valgus, varus, internal rotation, and external rotation torques, only flexion and extension torques were analyzed. Resultant force, torque, and EMG data were then expressed as functions of KA. For each squat and LP variation, data from the three exercise trials were averaged.

To estimate tibiofemoral compressive forces, cruciate tensile forces, and patellofemoral compressive forces, a biomechanical model of the sagittal plane of the knee was employed (11,38). Quadriceps, hamstrings, and gastrocnemius muscle forces ($F_{m(i)}$) were estimated by the following equation: $F_{m(i)} = c_i k_i A_i \sigma_{m(i)}[EMG_i/MVIC_i]$, where k_i was a muscle force-length variable defined as a function of knee and hip flexion angle, A_i was the physiological cross sectional area (PCSA) of the ith muscle, $\sigma_{m(i)}$ was MVIC force per unit PCSA for each muscle, EMG_i and $MVIC_i$ were EMG window averages during squat, LP, and MVIC variations, and c_i was a weight factor adjusted in a computer optimization program used to minimize errors in muscle force estimations due to nonlinear relationships between EMG and muscle force (11,38). Linear or near linear relationships between EMG and muscle force have been shown for the quadriceps and hamstrings (biceps femoris) during the static LP exercise (1). Muscle and ligament moment arms and lines of action angles were represented as polynomial functions of KA (13), whereas angles between the patellar tendon, quadriceps tendon, and patellofemoral joint were expressed as functions of KA, utilizing a mathematical model of the patellofemoral joint (33). All forces were calculated every 2°KA throughout the KF and KE phases.

Statistical analysis. To determine significant force and EMG differences among the exercise variations, a three-way repeated measures analysis of variance ($P < 0.05$) with planned comparisons was used, with exercise, foot angle, and stance comprising the three factors. The three exercises were the squat, LP with high foot placement (LPH), and LP with low foot placement (LPL). The two stances were narrow stance (NS) and wide stance (WS). The two foot angles were 0° and 30° forefoot abduction. For each of the three exercises, the NS with 0° forefoot abduction was compared with the NS with 30° forefoot abduction, the WS with 0° forefoot abduction was compared with the WS with 30° forefoot abduction, and the NS with 0° forefoot abduction was compared with the WS with 30° forefoot abduction. In addition, the three exercises were compared with each other for both the NS with 0° forefoot abduction and the WS with 30° forefoot abduction. PCL/ACL tensile force, tibiofemoral compressive force, and patellofemoral compressive force data were analyzed every 2° of KA during both the KF and KE phases (11). Because multiple comparisons were made, only significant force differences that occurred over five consecutive 2°KA intervals (i.e., a 10°KA interval) were reported in the result tables (11). For graphical presentation of knee forces, data for all subjects performing each type of exercise were averaged and presented as means and standard deviations.

RESULTS

Each squat and LP trial took approximately 3–3.5 s to complete. Across all squat trials for all subjects, the KF phase took 1.74 ± 0.36 s to complete, whereas the KE phase took 1.56 ± 0.29 s to complete. Across all LP trials for all subjects, the KF phase took 1.83 ± 0.40 s to complete, whereas the KE phase took 1.52 ± 0.25 s to complete. During both the KF and KE phases, each subject's lifting cadence displayed less than 10% variation among all exercises. Lifting cadences were also similar among the subjects, with lifting cadence variations generally less than 20%.

There were no significant force or EMG differences observed between the two foot angle positions for all exercise and stance variations. Because during the squat and LP pretest the subjects employed a foot angle near 0° forefoot abduction during their preferred NS and near 30° forefoot abduction during their preferred WS, all stance comparisons reported in the tables and figures are with 0° forefoot abduction for the NS and 30° forefoot abduction for the WS.

Normalized EMG values are shown in Table 1. No significant EMG differences were observed during the KF phase among exercise and stance variations. During the KE phase, the squat generated greater rectus femoris activity compared with the LPH and greater vasti activity compared with the LPH and LPL. There were no differences in quadriceps activity between the NS and WS. Lateral and medial hamstring activity were greater in the squat compared with the LPH and LPL, and greater in the WS compared with the NS for the LPH. Gastrocnemius activity was greater for the NS squat compared with the WS squat. Quadriceps, hamstrings, and gastrocnemius activity was generally greater during the KE phase compared with the KF phase.

Peak EMG activity during the squat and LP exercises (Table 2) occurred during the KE phase. Peak quadriceps activity occurred near maximum KA for the squat, LPH, and LPL. Peak hamstrings activity occurred at approximately 60°KA for the squat and near maximum KA for the LPH and LPL. Peak gastrocnemius activity occurred near maximum KA for the squat and at approximately 25°KA for the LPH and LPL. Peak quadriceps, hamstrings, and gastrocnemius activity were greater in the squat compared with the LPH and LPL. Peak hamstrings activity during the LPH and LPL were greater in the WS compared with the NS, whereas peak gastrocnemius activity during the squat was greater in the NS compared with the WS. Peak gastrocnemius activity was greater in the LPL compared with the LPH.

Significant knee force differences among the three exercises are shown in Table 3. Tibiofemoral (TF) compressive forces were on the average 32–43% greater in the squat compared with the LPH and LPL between 27 and 87°KA, and on the average 17% greater in the LPH compared with the squat between 79 and 91°KA. PCL tensile forces were on the average 18–131% greater in the squat compared with the LPH and LPL between 27 and 89°KA. ACL tensile forces were not produced during any exercise. Patellofemoral (PF) compressive forces were on the average 21–39% greater in the WS squat compared with the WS-LPH and

TABLE 1. Normalized (% MVIC) mean (±SD) EMG activity for the narrow stance (NS) and wide stance (WS) squat, leg press with high foot placement (LPH), and leg press with low foot placement (LPL).

		Knee Flexing Phase (5–95°)		Knee Extending Phase (95–5°)	
		NS	WS	NS	WS
Rectus femoris	SQUAT	28 ± 13	24 ± 10†	36 ± 14[a]	33 ± 12[a]†
	LPH	20 ± 9	17 ± 7	25 ± 11[a]	21 ± 8[a]
	LPL	23 ± 11	20 ± 9	29 ± 11	26 ± 11
Vastus lateralis	SQUAT	32 ± 7†	33 ± 7†	47 ± 6[ab]†	47 ± 7[ab]†
	LPH	27 ± 6†	26 ± 5†	38 ± 7[a]†	37 ± 6[a]†
	LPL	28 ± 6†	27 ± 6†	39 ± 7[b]†	37 ± 8[b]†
Vastus medialis	SQUAT	33 ± 7†	34 ± 5†	50 ± 9[ab]†	49 ± 9[ab]†
	LPH	29 ± 6†	28 ± 6†	42 ± 8[a]†	40 ± 7[a]†
	LPL	30 ± 6†	28 ± 7†	41 ± 7[b]†	39 ± 7[b]†
Lateral hamstrings	SQUAT	10 ± 5†	10 ± 4†	26 ± 11[ab]†	28 ± 13[ab]†
	LPH	7 ± 2†	8 ± 2†	10 ± 2[a]*†	12 ± 2[a]*†
	LPL	6 ± 2†	7 ± 2†	8 ± 2[b]†	10 ± 3[b]†
Medial hamstrings	SQUAT	10 ± 5†	12 ± 5†	22 ± 9[ab]†	25 ± 10[ab]†
	LPH	9 ± 5	10 ± 6	10 ± 3[a]*	13 ± 3[a]*
	LPL	7 ± 3	8 ± 3	8 ± 2[b]	10 ± 3[b]
Gastrocnemius	SQUAT	12 ± 5†	13 ± 6	17 ± 3*†	14 ± 3*
	LPH	10 ± 4	9 ± 3†	13 ± 5	12 ± 3†
	LPL	10 ± 3†	9 ± 3†	15 ± 5†	14 ± 5†

[a] Significant differences ($P < 0.05$) between squat and LPH.
[b] Significant differences ($P < 0.05$) between squat and LPL.
† Significant differences ($P < 0.05$) between knee flexing and knee extending phases.
* Significant differences ($P < 0.05$) between NS and WS.

WS-LPL between 43 and 87°KA, and on the average 18–19% greater in the NS-LPH and NS-LPL compared with the NS squat between 77 and 95°KA. No significant PF or TF compressive forces were observed among the NS squat, NS-LPH, and NS-LPL during the KF phase.

Significant knee force differences between the two stances are shown in Table 4. TF compressive forces were on the average 15–16% greater during the WS squat compared with the NS squat between 19 and 89°KA, but on the average 7 and 12% less during the NS-LPH and NS-LPL compared with the WS-LPH and WS-LPL between 21 and 95°KA. There were no significant differences in PCL tensile forces between WS and NS squats. PCL tensile forces were on the average 11–13% greater during the WS-LPH compared with the NS-LPH between 33 and 85°KA, and on the average 9–11% greater during

TABLE 2. Normalized (% MVIC) peak (±SD) EMG activity among the narrow stance (NS) and wide stance (WS) squat, leg press with high foot placement (LPH), and leg press with low foot placement (LPL).

		NS	WS	Knee Angle (°) at Peak EMG
Rectus femoris	SQUAT	52 ± 14[a]	45 ± 13[a]	95 ± 6
	LPH	39 ± 13[a]	33 ± 10[a]	92 ± 6
	LPL	46 ± 9*	37 ± 10*	95 ± 7
Vastus lateralis	SQUAT	57 ± 8[ab]	54 ± 8	89 ± 5
	LPH	47 ± 9[a]	50 ± 8	86 ± 6
	LPL	48 ± 10[b]	50 ± 11	95 ± 7
Vastus medialis	SQUAT	58 ± 10[b]	58 ± 11[b]	95 ± 7
	LPH	52 ± 8	50 ± 9	93 ± 5
	LPL	50 ± 6[b]	48 ± 7[b]	95 ± 6
Lateral hamstrings	SQUAT	41 ± 12[ab]	38 ± 11[ab]	62 ± 7
	LPH	13 ± 2[a]*	16 ± 2[a]*	82 ± 6
	LPL	12 ± 3[b]	12 ± 3[b]	95 ± 7
Medial hamstrings	SQUAT	31 ± 4[ab]	31 ± 7[ab]	63 ± 6
	LPH	15 ± 6[a]*	20 ± 5[a]*	91 ± 7
	LPL	11 ± 2[b]*	15 ± 4[b]*	95 ± 6
Gastrocnemius	SQUAT	23 ± 6[a]*	18 ± 4*	95 ± 8
	LPH	14 ± 3[ac]	15 ± 2[c]	25 ± 6
	LPL	22 ± 4[c]	22 ± 4[c]	28 ± 3

[a] Significant differences ($P < 0.05$) between squat and LPH.
[b] Significant differences ($P < 0.05$) between squat and LPL.
[c] Significant differences ($P < 0.05$) between LPH and LPL.
* Significant differences ($P < 0.05$) between NS and WS.
All peak EMG values occurred during the knee extending phase.

TABLE 3. Tibiofemoral compressive, PCL tensile, and patellofemoral compressive forces (N) among the narrow stance and wide stance squat, leg press with high foot placement (LPH), and leg press with low foot placement (LPL).

Stance and Force	Knee Flexing or Extending Phase	Knee Angle Range (deg) in Which Significant Force Differences ($P <$ 0.05) Were Found	Exercise Comparisons and Mean ± SD Percent Increase over Given Knee Angle Range
Narrow stance			
Tibiofemoral compressive forces	Flexing	None	None
	Extending	79–91	LPH > SQUAT (17 ± 1%)
		27–37	SQUAT > LPL (32 ± 3%)
		27–37	SQUAT > LPH (37 ± 6%)
PCL tensile forces	Flexing	27–65	SQUAT > LPL (74 ± 29%)
		27–43	SQUAT > LPH (70 ± 15%)
	Extending	27–71	SQUAT > LPL (131 ± 40%)
		27–71	SQUAT > LPH (93 ± 25%)
Patellofemoral compressive forces	Flexing	None	None
	Extending	77–95	LPL > SQUAT (18 ± 2%)
		77–95	LPH > SQUAT (19 ± 1%)
Wide stance			
Tibiofemoral compressive forces	Flexing	27–87	SQUAT > LPH (36 ± 4%)
		27–87	SQUAT > LPL (34 ± 4%)
	Extending	27–63	SQUAT > LPH (41 ± 13%)
		27–81	SQUAT > LPL (43 ± 23%)
PCL tensile forces	Flexing	27–89	SQUAT > LPL (49 ± 28%)
		61–89	SQUAT > LPH (18 ± 7%)
	Extending	27–75	SQUAT > LPL (103 ± 28%)
		27–75	SQUAT > LPH (73 ± 21%)
Patellofemoral compressive forces	Flexing	43–87	SQUAT > LPH (28 ± 6%)
		43–87	SQUAT > LPL (21 ± 5%)
	Extending	43–55	SQUAT > LPL (39 ± 1%)

the WS-LPL compared with the NS-LPL between 31 and 73°KA. PF compressive forces during the squat were only significant during the KF phase, which on the average were 15% greater during the WS compared with the NS between 21 and 79°KA. PF compressive forces were on the average 10–18% greater in the NS-LPH and NS-LPL compared with the WS-LPH and WS-LPL between 19 and 95°KA.

Peak knee forces during the squat, LPH, and LPL are shown in Table 5. Peak TF compressive forces were the only knee forces significantly different among the three exercises, with the WS squat generating 30–40% greater

TABLE 4. Tibiofemoral compressive, PCL tensile, and patellofemoral compressive forces (N) between the narrow stance (NS) and wide stance (WS) squat, leg press with high foot placement (LPH), and leg press with low foot placement (LPL).

Exercise and Force	Knee Flexing or Extending Phase	Knee Angle Range (deg) in Which Significant Force Differences ($P <$ 0.05) Were Found	Stance Comparison and Mean ± SD Percent Increase over Given Knee Angle Range
SQUAT			
Tibiofemoral compressive forces	Flexing	19–83	WS > NS (16 ± 5%)
	Extending	59–89	WS > NS (15 ± 1%)
PCL tensile forces	Flexing	None	None
	Extending	None	None
Patellofemoral compressive forces	Flexing	21–79	WS > NS (15 ± 4%)
	Extending	None	None
LPH			
Tibiofemoral compressive forces	Flexing	21–91	NS > WS (11 ± 5%)
	Extending	71–91	NS > WS (7 ± 3%)
PCL tensile forces	Flexing	33–69	WS > NS (13 ± 5%)
	Extending	55–85	WS > NS (11 ± 2%)
Patellofemoral compressive forces	Flexing	19–91	NS > WS (18 ± 6%)
	Extending	39–91	NS > WS (10 ± 3%)
LPL			
Tibiofemoral compressive forces	Flexing	21–95	NS > WS (9 ± 3%)
	Extending	23–91	NS > WS (12 ± 4%)
PCL tensile forces	Flexing	37–69	WS > NS (9 ± 4%)
	Extending	31–73	WS > NS (11 ± 5%)
Patellofemoral compressive forces	Flexing	19–95	NS > WS (16 ± 9%)
	Extending	19–95	NS > WS (15 ± 7%)

TABLE 5. Maximum PCL tensile, tibiofemoral compressive, and patellofemoral compressive forces during the narrow stance (NS) and wide stance (WS) squat, leg press with high foot placement (LPH), and leg press with low foot placement (LPL); for each parameter, the mean ± SD force (N) is shown at the corresponding mean ± SD knee angle.

Force	Knee Flexing or Extending Phase	NS SQUAT	WS SQUAT	NS-LPH	WS-LPH	NS-LPL	WS-LPL
Tibiofemoral compressive forces	Flexing	3009 ± 741 @71 ± 14°	3413 ± 749^{ab} @72 ± 13°	2705 ± 433 @85 ± 6°	2488 ± 478^{a} @80 ± 11°	2778 ± 480 @84 ± 8°	2507 ± 456^{b} @79 ± 9°
	Extending	2944 ± 1005 @64 ± 16°	3428 ± 838^{b} @65 ± 16°	3073 ± 457 @78 ± 13°	2821 ± 500 @74 ± 10°	2994 ± 481 @81 ± 10°	2646 ± 470^{b} @81 ± 11°
PCL tensile forces	Flexing	1469 ± 438 @88 ± 14°	1710 ± 506 @81 ± 25°	1404 ± 261 @95 ± 0°	1376 ± 341 @94 ± 2°	1462 ± 246 @95 ± 0°	1463 ± 299 @95 ± 1°
	Extending	2066 ± 881 @77 ± 19°	2212 ± 801 @76 ± 16°	1703 ± 358 @94 ± 3°	1726 ± 553 @88 ± 6°	1690 ± 303 @95 ± 0°	1726 ± 368 @95 ± 0°
Patellofemoral compressive forces	Flexing	4246 ± 1047 @85 ± 3°	4674 ± 1195 @82 ± 4°	4316 ± 832 @87 ± 2°	3761 ± 880 @87 ± 5°	4541 ± 785 @87 ± 2°	4000 ± 829 @86 ± 3°
	Extending	3958 ± 1105 @85 ± 10°	4313 ± 1201 @80 ± 11°	4809 ± 954 @88 ± 5°	4389 ± 1085 @84 ± 4°	4813 ± 978 @88 ± 5°	4224 ± 950 @90 ± 5°

[a] Significant differences ($P < 0.05$) between squat and LPH.
[b] Significant differences ($P < 0.05$) between squat and LPL.

peak forces than the WS-LPH and WS-LPL. Peak TF compressive forces in the current study were approximately 3.75 times body weight (BW) for the squat at 65°KA, approximately 3.35 times BW for the LPH at 78°KA, and approximately 3.25 times BW for the LPL at 81°KA. Significant differences in knee forces between the KF and KE phases are shown in Table 6, with knee forces generally significantly greater during the KE phase.

DISCUSSION

The aim of this project was to quantify knee forces and muscle activity about the knee while performing the squat and LP with varying stances, foot angles, and foot placements. Both the KF and KE phases of each exercise were examined. Muscle activity and force for all major knee muscles were quantified over the entire KF and KE ranges of motion. Muscle forces served as input into a biomechanical knee model that calculated PF and TF compressive forces, and ACL/PCL tensile forces.

Exercise intensity was normalized by each subject employing a 12 RM intensity for each exercise variation, which is approximately equivalent to 70–75% of each subject's 1 RM (11). Performing 8–12 repetitions is a common repetition scheme that many physical therapy, athletic training, and athletic programs utilize for strength development and rehabilitation. Because the same relative weight was used

TABLE 6. Tibiofemoral compressive, PCL tensile, and patellofemoral compressive forces (N) between the knee flexing (KF) and knee extending (KE) phases of the narrow stance (NS) and wide stance (WS) squat, leg press with high foot placement (LPH), and leg press with low foot placement (LPL).

Exercise and Force	Stance	Knee Angle Range (deg) in Which Significant Force Differences ($P < 0.05$) Were Found	Phase Comparison and Mean ± SD Percent Increase over Given Knee Angle Range
SQUAT			
Tibiofemoral compressive forces	NS	41–61	KE > KF (17 ± 6%)
		77–95	KF > KE (10 ± 2%)
	WS	19–55	KE > KF (17 ± 6%)
		71–95	KF > KE (9 ± 4%)
PCL tensile forces	NS	29–95	KE > KF (66 ± 37%)
	WS	29–95	KE > KF (57 ± 30%)
Patellofemoral compressive forces	NS	27–63	KE > KF (21 ± 7%)
	WS	37–49	KE > KF (16 ± 2%)
		79–95	KF > KE (8 ± 3%)
LPH			
Tibiofemoral compressive forces	NS	51–95	KE > KF (11 ± 1%)
	WS	37–95	KE > KF (15 ± 3%)
PCL tensile forces	NS	29–95	KE > KF (36 ± 12%)
	WS	29–95	KE > KF (37 ± 5%)
Patellofemoral compressive forces	NS	63–95	KE > KF (11 ± 1%)
	WS	47–95	KE > KF (16 ± 3%)
LPL			
Tibiofemoral compressive forces	NS	81–95	KE > KF (7 ± 3%)
	WS	None	None
PCL tensile forces	NS	25–95	KE > KF (28 ± 8%)
	WS	27–95	KE > KF (30 ± 9%)
Patellofemoral compressive forces	NS	None	None
	WS	None	None

for each exercise variation, knee forces and muscle activity were able to be compared among the squat, LPH, and LPL. The propensity of the subjects in the current study was to employ smaller foot angles during their preferred NS squat (7.7 ± 7.6°) and NS-LP (7.2 ± 7.1°) and larger foot angles during their preferred WS squat (36.6 ± 8.6°) and WS-LP (32.5 ± 6.3°). This implies that forefoot abduction increases as stance width increases during the squat (10) and LP.

Muscle activity. Because the quadriceps cross the knee anteriorly and the hamstrings and gastrocnemius cross the knee posteriorly, co-contractions from these muscle groups are very important in enhancing anteroposterior knee stability. Co-contractions between the hamstrings and quadriceps have been shown to be an important factor in minimizing stress to the ACL (22). Co-contractions from the quadriceps, hamstrings, and gastrocnemius were observed in the current study, with the largest magnitudes occurring in the squat during the KE phase. The greater quadriceps (20–60%) and hamstrings (90–225%) activity generated in the squat compared with the LPH and LPL implies that the squat may be a more effective exercise for quadriceps and hamstring development compared with the LPH and LPL. Moderate hamstring activity has been reported in previous studies that employed the barbell squat using a 60–75% 1RM lifting intensity similar to the current study (11,19,34,37). Similar to other studies (11,34), low hamstring activity occurred during the LP. The comparable gastrocnemius activity between squat and LP exercises is in agreement with Escamilla et al.(11), who reported no significant differences in gastrocnemius activity between the squat and LP. Because there were no significant EMG differences in any of the muscles tested between the LPH and LPL, except the LPL demonstrated greater peak gastrocnemius activity compared with the LPH, either exercise appears equally effective in quadriceps and hamstrings, and gastrocnemius development may be enhanced during the LPL.

A few studies have examined how stance width during the squat affects knee musculature (2,19,31). Subjects from McCaw and Melrose (19) used relative loads between 60 and 75% of their 1 RM, which is similar to the relative loads used in the current study. In addition, the three different stance widths employed by their subjects were shoulder width, 75% shoulder width (NS), and 140% shoulder width (WS). Although the mean stance width distances in McCaw and Melrose (19) were not reported in absolute measurements, it can be inferred that their defined NS and WS were very similar to the defined NS and WS in the current study. In the current study, there were no significant differences in quadriceps activity between NS and WS squats, which is in agreement from EMG data from McCaw and Melrose (19) and Anderson et al.(2), and magnetic resonance imaging (MRI) data from Tesch (31).

Similar to several other studies (11,34–36), vasti activity was 30–90% greater than rectus femoris activity in the squat and LP exercises. This implies that squat and LP exercises may be more effective in vasti development compared with rectus femoris development. Within the squat, LPH, and LPL exercises, the VM and VL produced approximately the same amount of activity, which is in agreement with squat and LP data from several studies (11,27,34).

Because there were also no differences in quadriceps activity between the NS-LPH and WS-LPH, and between the NS-LPL and WS-LPL, stance variations during the LPH and LPL do not appear effective in producing differences in quadriceps development during these exercises. There were also no differences in hamstring activity between the NS squat and WS squat, which is in agreement with data from Tesch (31) and McCaw and Melrose (19). However, a small but significant increase in hamstring activity was observed in the WS-LPH compared with the NS-LPH, which implies that the WS-LPH may be slightly more effective in hamstrings development compared with the NS-LPH. In addition, a small but significant increase in gastrocnemius activity was observed in the NS squat compared with the WS squat, which implies that the NS squat may be slightly more effective in gastrocnemius development compared with the WS squat.

When comparing muscle activity between the KF and KE phases, quadriceps activity was 25–50% greater in the KE phase during the squat, LPH, and LPL. Hamstring activity was 100–180% greater in the KE phase during the squat, but only 10–50% greater in the KE phase for the LPH and LPL. Gastrocnemius activity was 5–55% greater in the KE phase during the squat, LPH, and LPL. Greater muscle activity in the KE phase compared with the KF phase has been previously reported during the squat, especially in the hamstrings (11,19,20,30,34). Because the hamstrings are biarticular muscles, it is difficult to determine if these muscles act eccentrically during the KF phase and concentrically during the KE phase, as commonly is believed. They may actually be working nearly isometrically during both the KF and KE phases (19), because they are concurrently shortening at the knee and lengthening at the hip during the KF phase and lengthening at the knee and shortening at the hip during the KE phase. If they are indeed working eccentrically during the KF phase and concentrically during the KE phase, then data from the current study would be in accord with data from Komi et al. (16), who reported decreased activity during eccentric work and increased activity during concentric work. In any case, the hamstrings probably do not change length much throughout the squat, LPH, and LPL. Hence, in accordance with the length-force relationship in skeletal muscle, a constant length in the hamstrings will allow them to be more effective in generating force throughout the entire lifting movement. It is interesting that although peak quadriceps EMG values during the squat occurred near maximum knee flexion at the beginning of the ascent, peak hamstrings EMG values during the squat occurred at approximately 1/3 of the way up (approximately 60°KA) from the beginning of the ascent. The hamstrings may need to work harder at 60°KA during the ascent to compensate for attenuated force generation from the gluteus maximus due to muscle shortening. In contrast, the quadriceps (especially the vasti muscles) are most effective in generating force at maximum knee flexion, which may

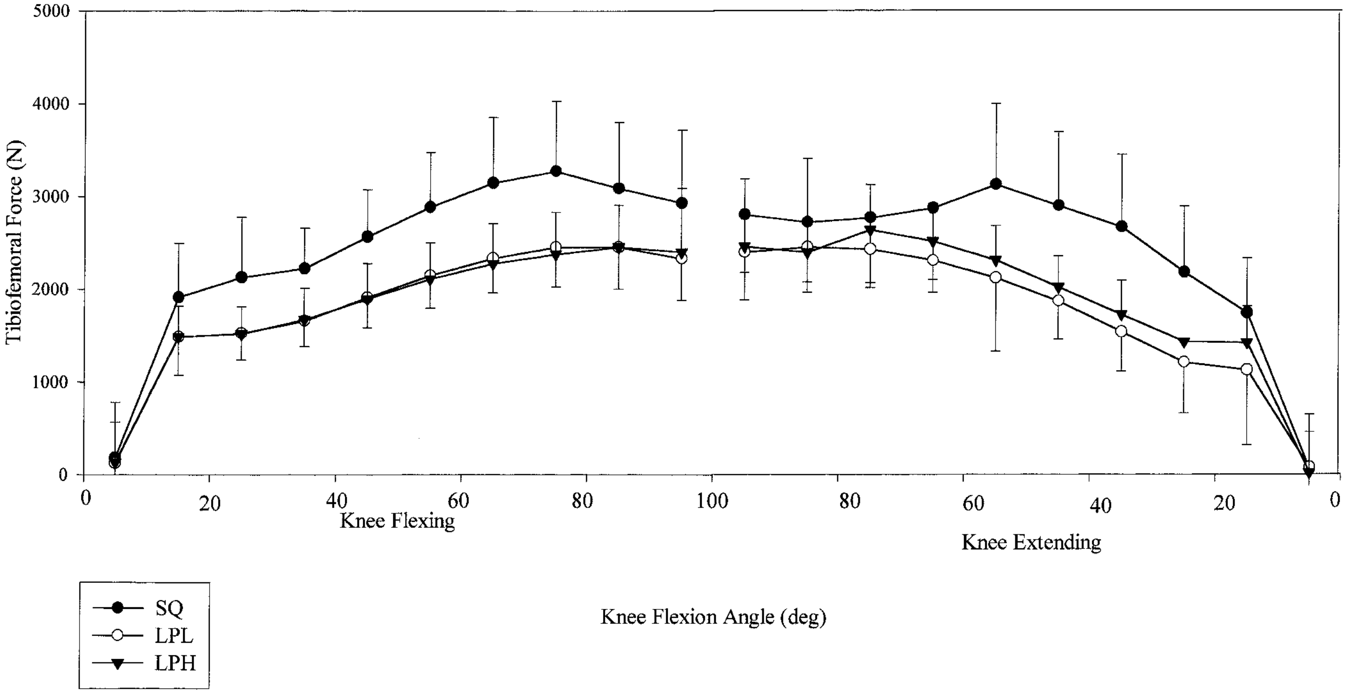

FIGURE 4—Mean and SD of tibiofemoral compressive forces during the wide stance squat, leg press with low foot placement (LPL), and leg press with high foot placement (LPH).

reflect the higher peak EMG values at this point, because as these muscles shorten, their ability to generate force diminishes.

The nonsignificant differences in muscle activity between 0 and 30° of forefoot abduction imply that employing varying foot angles is not effective in altering muscle recruitment patterns during the squat, LPH, and LPL. This is in agreement with data from other squat studies (7,20,26), which demonstrated that employing varying foot angles during the squat did not affect quadriceps or hamstrings activity.

Tibiofemoral (TF) compressive forces. TF compressive forces have been demonstrated to be an important factor in knee stabilization by resisting shear forces and minimizing tibia translation relative to the femur (18). Comparing among exercises (Table 3), the greater TF compressive forces in the NS squat compared with the NS-LPH and NS-LPL between 27 and 37°KA implies that the NS squat may provide enhanced knee stability between this smaller KA range. In contrast, the greater TF compressive forces in the NS-LPH compared with the NS squat between 79 and 91°KA implies that the NS-LPH may provide enhanced knee stability between this larger KA range. In addition, knee stability may be greater in the WS squat compared with the WS-LPH and WS-LPL between 27 and 87°KA. The generally greater TF compressive forces observed during the squat compared with the LPH and LPL are primarily due to the greater quadriceps and hamstrings activity generated in the squat compared with the LPH and LPL, because these muscles generate large TF compressive forces at the knee (11,34). It has been demonstrated that during a maximum voluntary contraction of the quadriceps the force generated ranges from 2000 to 8000 N, depending on KA (33). Maximum resistance to tibiofemoral shear forces may occur at peak TF compressive forces (Table 5), which occurred at approximately 65–70°KA during the squat and approximately 75–80°KA during the LPH and LPL. These KA ranges for peak TF compressive forces are near but slightly less than the KA ranges for peak PCL tensile forces, which occurred at approximately 75–80°KA for the squat and approximately 85–95°KA for the LPH and LPL. Although TF compressive forces may enhance knee stability and resist tibiofemoral shear forces, it is currently unknown if these large peak forces (between 3.25 and 3.75 times BW) may excessively load knee menisci and articular cartilage and cause degenerative changes in these structures. Unfortunately, it is currently unknown at what magnitude TF compressive force becomes injurious to knee structures.

TF compressive forces generally progressively increased as the knees flexed and decreased as the knees extended (Figs. 4 and 5), which is in agreement with several other squat studies (9,11,12,21,30,32). The larger TF compressive forces generated during the KE phase compared with the KF phase is not surprising considering muscle activity was greater during the KE phase, which helps generate TF compressive forces. When comparing TF compressive forces between stances (Table 4), the greater TF compressive forces in the WS squat compared with the NS squat between 19 and 89°KA implies that the WS squat may provide enhanced knee stability between this KA range. In contrast, knee stability may be greater in the NS-LPH and NS-LPL compared with the WS-LPH and WS-LPL between 21 and 95°KA. The greater TF compressive force in the NS-LPH compared with the WS-LPH was surprising, because hamstrings activity was greater in the WS-LPH. However, the difference in hamstring activity between the NS-LPH and WS-LPH is very small, although significant, as were the differences in TF compressive forces between these two exercises.

PCL tensile forces. It has been reported by Butler et al. (8) that the ACL provides 86% of the total restraining force to anterior drawer and the PCL provides 95% of the total restraining force to posterior drawer. An interesting result was that there were no ACL forces observed during the squat, LPH, and LPL throughout the KF and KE phases. However, this was not surprising because several studies have demonstrated PCL tensile forces exclusively during squat and LP exercises (9,11,17,30,34). Additional squat studies have reported moderate PCL tensile forces between 50 and 130°KA and minimum ACL tensile forces between 0 and 50°KA (12,21,28,32). Small ACL forces during the body weight squat have also been reported *in vivo* by Beynnon et al.(6), who inserted strain transducers into the anteromedial bundle of the ACL in eight subjects immediately after arthroscopic knee meniscectomies and debridements. Minimal ACL strain ($<$4%) was observed at less than 70°KA during both the KF and KE phases, with ACL strain greatest at full extension and progressively decreasing as the knees flexed to 90°. However, because this study was performed immediately after surgery, it difficult to extrapolate these results to the barbell squat as performed by healthy athletes in the current study.

The absence of ACL forces in the current study may in part be due to force contributions from the hamstrings, which have been shown to unload strain on the ACL (23). Quadriceps activity also affects cruciate ligament strain. Quadriceps force, via the patella tendon, exerts an anterior shear force on the leg when the knee is flexed less than 50–60°KA, and a posterior shear force when the knee is flexed greater than 50–60°KA (6,13). In addition to muscle forces, inertial forces and the effects of gravity based on technique variations also affect ACL and PCL loading. When muscle and inertial forces acting on the leg are greater in the posterior shear direction than the anterior shear direction, the PCL is loaded. Because the ultimate strength of the PCL has been estimated up to 4000 N for young active people (24), the peak PCL tensile forces of approximately 2000 N (Table 5) observed during the squat, LPH, and LPL are probably not of great enough magnitude to be injurious to the healthy PCL.

During PCL rehabilitation, in which the initial goal is to minimize PCL strain, the LPH and LPL may be preferred over the squat, because the squat generated greater PCL tensile forces than the LPL and LPH over a large KA range (Table 3). In addition, the NS-LPH and NS-LPL may be preferred over the WS-LPH and WS-LPL, because the NS-LPH and NS-LPL generated smaller forces than the WS-LPH and WS-LPL over a large KA range. Performing the squat, LPH, and LPL within the functional range of 0–50°KA may be preferred for PCL rehabilitation, because PCL tensile forces generally increased as the knees flexed and decreased as the knees extended (9,11,12,21,30,32), peaking near maximum KA (Figs. 6 and 7).

Patellofemoral (PF) compressive forces. Excessive PF compressive forces and stresses, or repetitive occurrences of lower magnitude forces and stresses, may contribute to patellofemoral degeneration and pathologies, such as patella chondromalacia, osteoarthritis, and osteochondritis dissecans. There are primarily three forces acting on the patella during the squat, LPH, and LPL: 1) quadriceps tendon force, 2) patellar tendon force,

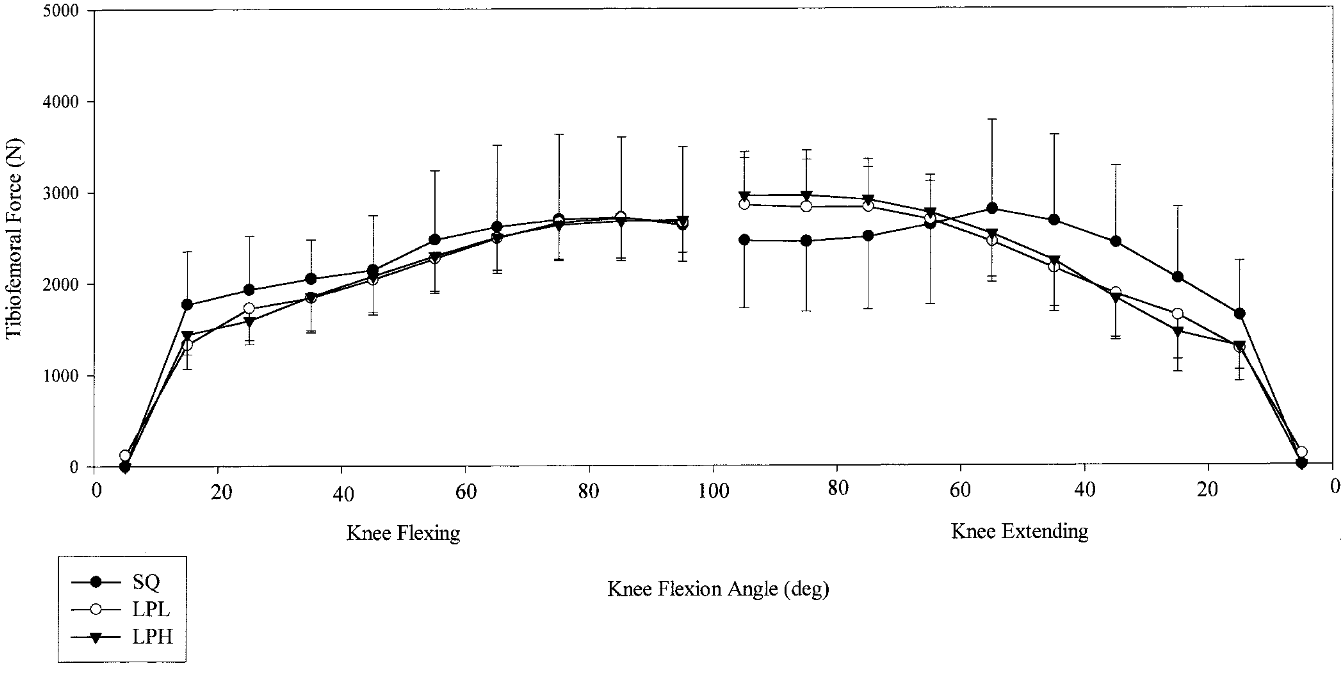

FIGURE 5—Mean and SD of tibiofemoral compressive forces during the narrow stance squat, leg press with low foot placement (LPL), and leg press with high foot placement (LPH).

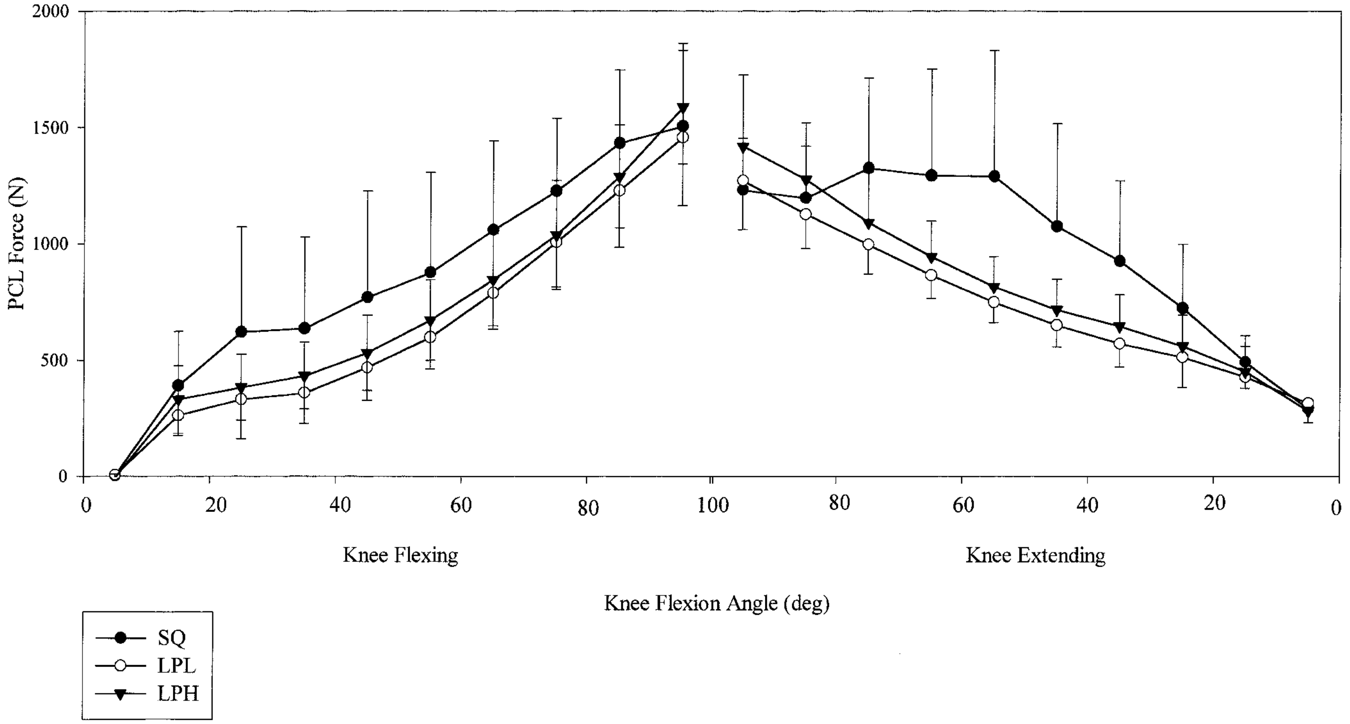

FIGURE 6—Mean and SD of PCL tensile forces during the wide stance squat, leg press with low foot placement (LPL), and leg press with high foot placement (LPH).

and 3) PF compressive force. PF compressive forces arise from contact between the undersurface of the patella and the patellar surface of the femur and vary according to KA. Patellofemoral joint contact areas are also affected by KA. From full extension to full flexion, the patella moves caudally approximately 7 cm, with femoral contact on the patella moving cranially as the knee flexes (14). Patellofemoral contact has been reported to initially occur between 10 and 20°KA (14), which is when the patella begins to glide onto the patellar surface of the femur. The femur makes contact with the medial and lateral inferior facets between approximately 20–30°KA, with the medial and lateral middle facets between approximately 30–60°KA, with the medial and lateral

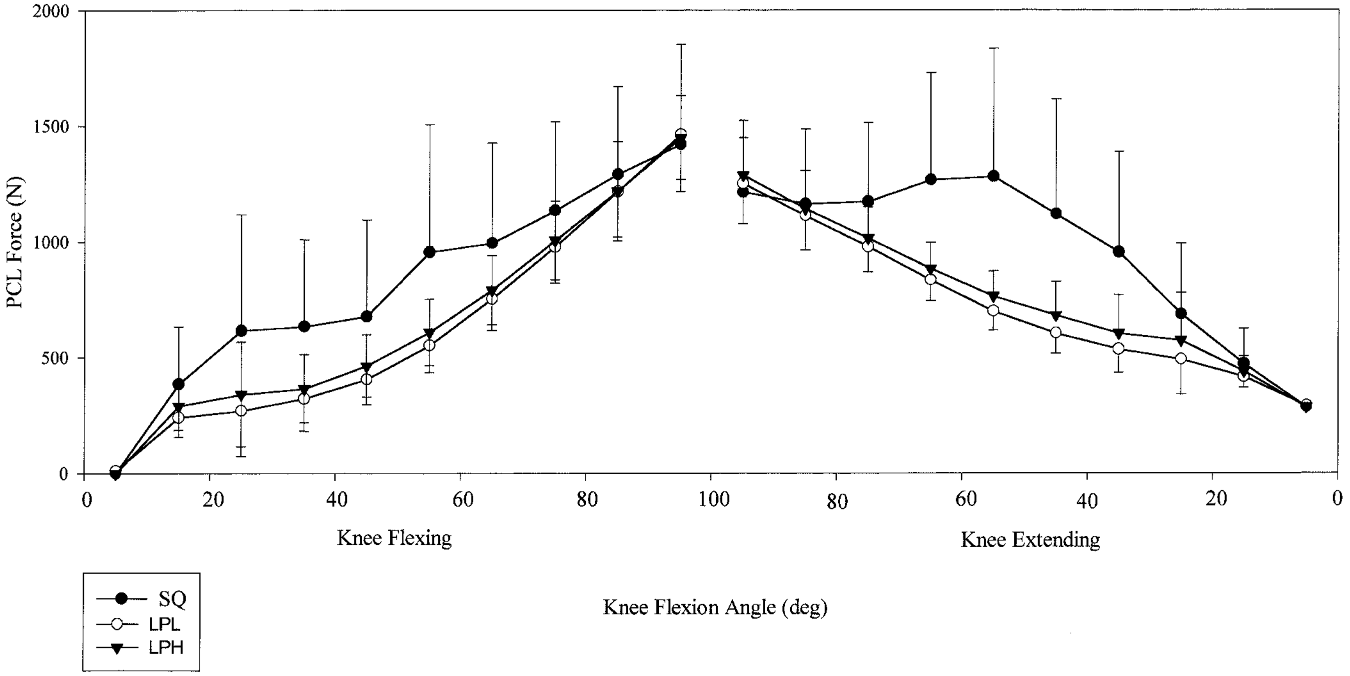

FIGURE 7—Mean and SD of PCL tensile forces during the narrow stance squat, leg press with low foot placement (LPL), and leg press with high foot placement (LPH).

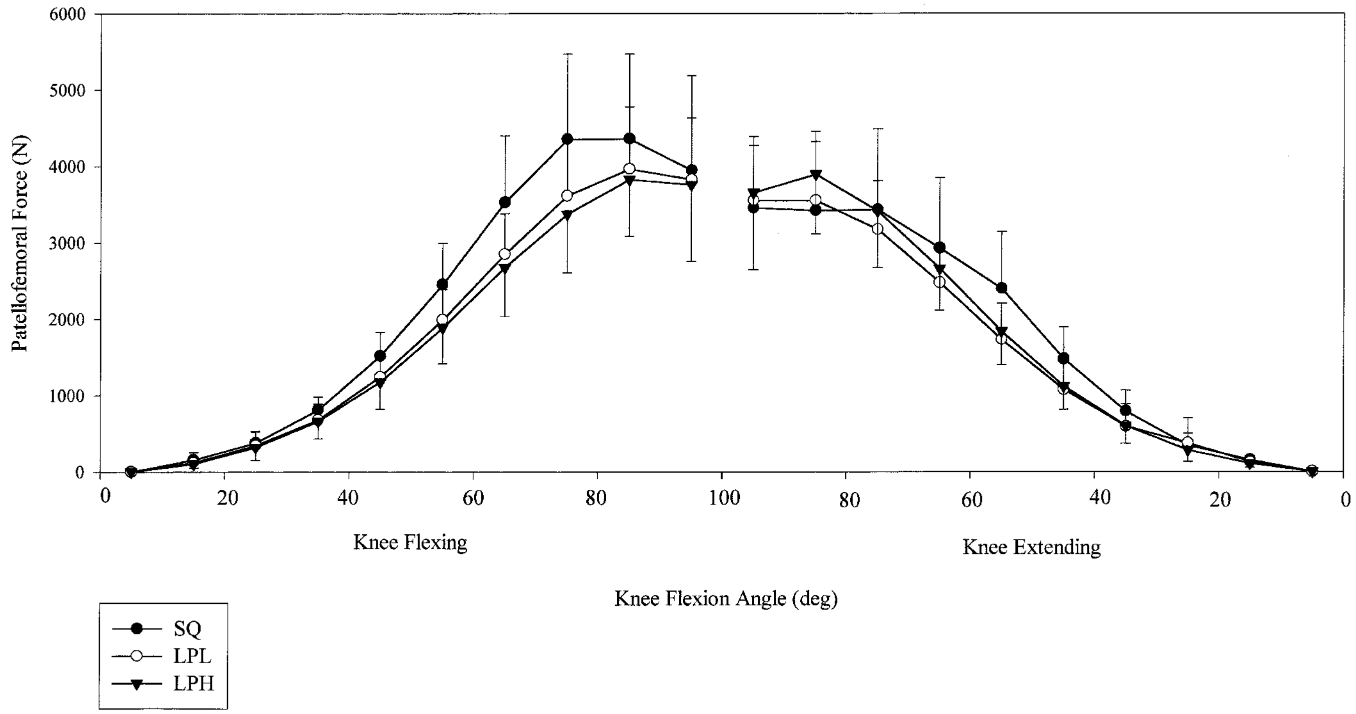

FIGURE 8—Mean and SD of patellofemoral compressive forces during the wide stance squat, leg press with low foot placement (LPL), and leg press with high foot placement (LPH).

superior facets between approximately 60–90°KA, and with the medial vertical "odd" facet and lateral superior facet between approximately 90 and 135°KA (14). At approximately 90°KA, the "odd" facet for the first time makes contact with the lateral margin of the medial condyle (14).

Patellofemoral contact area has been reported to be 2.6 ± 0.4 cm^2 at 20°KA, 3.1 ± 0.3 cm^2 at 30°KA, 3.9 ± 0.6 cm^2 at 60°KA, 4.1 ± 1.2 cm^2 at 90°KA, and 4.6 ± 0.7 cm^2 at 120°KA (14). When PF compressive forces are distributed over patellofemoral contact areas, patellofemoral stress is produced. Consider the KF phase in Figure 9, in which there were no patellofemoral differences among the squat, LPH, and LPL. Mean PF compressive forces collapsed across exercises were 238 N at 20°KA, 615 N at 30°KA, 2731 N at 60°KA, and 4186 N at 90°KA. By using these PF compressive force data from the KF phase of Fig. 9, and the patellofemoral contact areas given above, patellofemoral stress at 20°, 30°, 60°, and 90°KA would be 0.92 MPa, 1.98 MPa, 7.00 MPa, and 10.21 MPa, respectively. Consequently, during the squat, LPH, and LPL, PF stresses increase as knee flexion increases, peaking near 80–90°KA. Increasing PF stresses as the knees flex and decreasing PF stresses as the knees extend is in agreement with several other studies (9,11,21,25,35). From these data, it can be inferred that individuals with patellofemoral disorders should avoid performing the squat, LPH, and LPL at higher knee flexion angles. Furthermore, squat and LP data from Escamilla et al. (11) and the current study illustrate that the rate of increase in PF stress appears maximum between approximately 50 and 80°KA, thus generating proportionately greater PF stress between 50 and 80°KA compared with 0 and 50°KA. Therefore, performing the squat, LPH, and LPL within the functional range of 0–50°KA may be most effective for athletes or patients with patellofemoral pathologies.

Although the loads lifted in the current study (approximately 1.5 times BW) are higher than most rehabilitation patients will experience, they are typical loads for strength and power athletes while performing the squat and LP exercises. However, performing the squat, LPH, and LPL at greater knee flexion angles may not be problematic for athletes with healthy knees, as long as heavy loads are not used excessively. Interestingly, PF compressive forces have been shown to remain relatively constant or slightly decrease beyond 85–90°KA (11,21) (Figs. 8 and 9). Hence, patellofemoral stress may decrease with greater than 90°KA, because patellofemoral contact area continues to increase as knee flexion increases (14). Nevertheless, training with excessive loads can be a potential problem for powerlifters and football players, who often train with heavy loads for long periods of time. Unfortunately, it is currently unknown how much PF compressive force and stress is detrimental to the patellofemoral joint while performing squat and LP exercises.

When normalized by body weight and load lifted, and expressed as a percentage, mean peak PF compressive force in the current study was 210 ± 54% BW for the squat. This is similar to the 180 ± 93% BW from Wretenberg et al. (35) and the nearly 200% BW from Nisell and Ekholm (21), whose subjects also performed the barbell squat with a similar lifting intensity (65–75% 1 RM) as the current study. Surprisingly, the remaining two studies that quantified PF compressive forces during the dynamic squat found normalized values in excess of 700% BW (9,25). Because both of these studies examined PF compressive forces during the body weight squat, which requires relatively little effort and muscle activity compared with

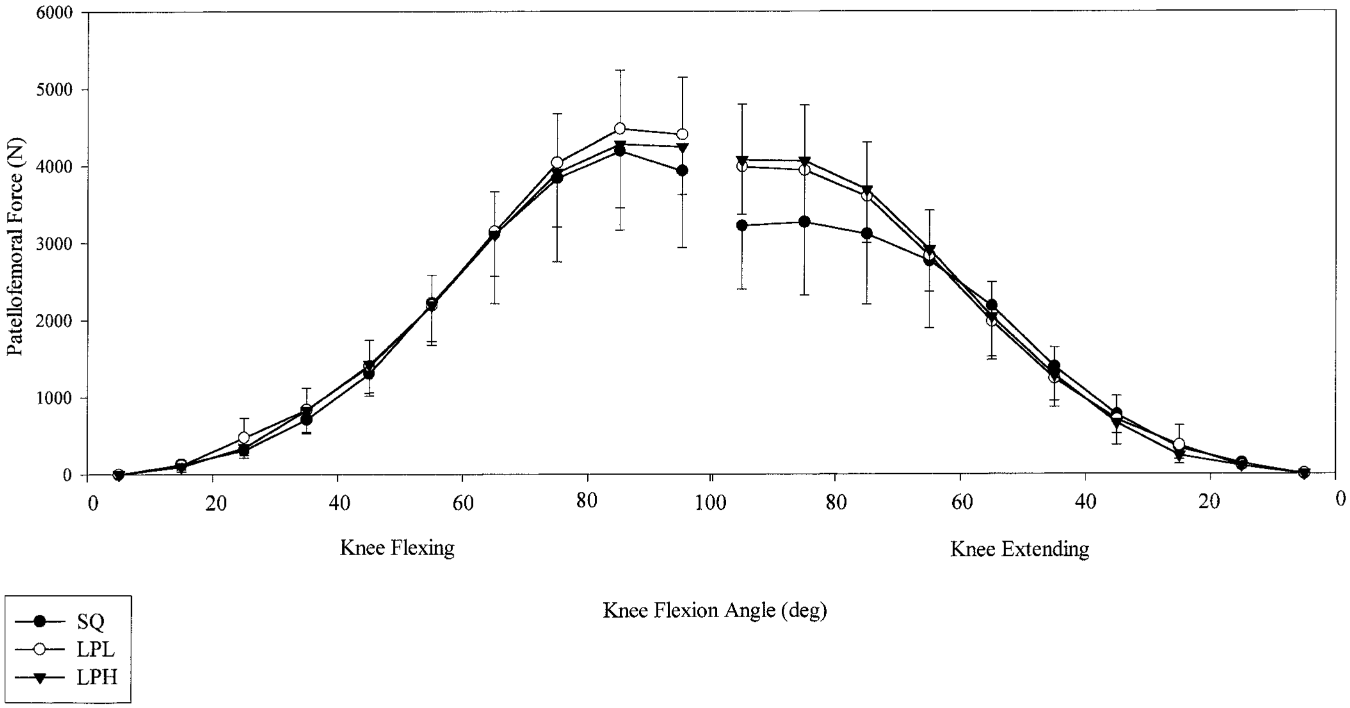

FIGURE 9—Mean and SD of patellofemoral compressive forces during the narrow stance squat, leg press with low foot placement (LPL), and leg press with high foot placement (LPH).

the barbell squat, these discrepancies may be due to methodological differences among studies.

Escamilla et al. (11) conducted the only known studied that quantified PF compressive forces during the dynamic LP. Using a 12 RM lifting protocol, these authors reported similar PF compressive forces as in the current study. Performing an isometric LP with a 10 RM lifting intensity, Steinkamp et al. (29) reported a mean peak PF compressive force of excess of 10,000 N. Because these authors did not specify the mean weight lifted, it is not possible to compared normalized values between their study and the current study. Steinkamp et al. (29) also quantified patellofemoral stress during the LP. They reported a patellofemoral stress of 0.8 MPa at 0°KA, 6.1 ± 1.4 MPa at 30°KA, 16.5 ± 3.9 MPa at 60°KA, and 29.5 ± 7.0 MPa at 90°KA. Like the current study, these authors found patellofemoral stresses progressively increased with greater knee flexion angles, although their magnitudes of patellofemoral stress were greater. These discrepancies in patellofemoral stress magnitude between Steinkamp et al. (29) and the current study may be due to mechanical differences between leg press machines employed, as well as differences between isometric versus dynamic exercise.

CONCLUSIONS

Because varying foot angles did not affect muscle activity or knee forces during the squat and LP, it is recommended that athletes or rehabilitation patients employ a foot angle that is most comfortable for them. Regarding stance width, the NS squat is preferred over the WS squat for enhanced gastrocnemius involvement, whereas the WS-LPH is preferred over the NS-LPH for greater hamstrings involvement. Either a WS or NS appears equally effective in quadriceps involvement. From our data, the squat is more effective than the LP in enhancing quadriceps and hamstrings activity. Because the WS squat generated the highest tibiofemoral compressive forces, the WS squat may be the most effective in minimizing tibiofemoral shear forces. Because ACL tensile forces were not found in the current study, all exercise and stance variations seem appropriate for rehabilitation patients whose goal is to minimize ACL stress. For rehabilitation patients whose goal is to minimize PCL tensile forces, the LP is preferred over the squat, the NS squat is preferred over the WS squat, and the WS-LPH and WS-LPL is preferred over the NS-LPH and NS-LPL. Furthermore, training in the functional range between 0 and 50°KA minimizes PF compressive forces.

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