

PATELLOFEMORAL JOINT LOADING IN FEMALES DURING
BACK SQUATS OF VARYING DEPTH,
WEIGHT LOAD, AND STANCE WIDTH

by

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ABSTRACT

As a repetitive and loaded exercise, the back squat can lead to tissue injury. One concern is patellofemoral pain syndrome, a common knee diagnoses over twice as prevalent in females as in males. Patellofemoral joint stress is cited as a cause of the syndrome. To manage the syndrome, quadriceps strength is important. Although the back squat is a good exercise for quadricep strength, modifications to squat technique may be necessary to decrease patellofemoral joint stress. Two studies on female recreational athletes are addressed here: 1) how patellofemoral joint loading changes with squat depth and load and 2) how it changes with squat load and stance width. Depth-specific 1-repetition maximums were measured, and weight loads were based on percentages of the maximum. Peak knee extensor moments, patellofemoral joint reaction forces, and patellofemoral joint stresses were calculated using inverse dynamics and previously reported equations. First, participants squatted to 90° , $\sim 110^\circ$, and $\sim 135^\circ$ of knee flexion with loads of 0%, 50%, and 85% of 1RM. A depth-by-load interaction was found such that within each depth, moments increased as load increased, while decreasing with increased depth. Patellofemoral joint reaction force had main effects of load and depth such that as load increased or depth decreased, reaction force increased. Another depth-by-load interaction was found such that within each depth, as load increased the stress increased, while increasing with increased depth. From these results, squats to full depth or loaded squats to less than 90° of knee flexion are recommended to minimize patellofemoral joint stress. Second, when squatting to $\sim 110^\circ$ with loads of 35% and 85% and stance widths of 90%, 100%, 110%, and 120% of natural stance, there was a main effect of load for knee extensor moment, patellofemoral joint reaction force, and patellofemoral joint stress. Although altering stance width does not appear to change joint loading, some research suggests that there may be a relationship between foot turnout and joint loading. Continuing relatively simple studies, like these, reveal trends which more individualized approaches can later use, accounting for individuals' anatomy to fully understand patellofemoral joint loading during the back squat.

CHAPTER ONE

INTRODUCTION

Research Context

Squats are a foundational movement for both daily activities and athletics. Standing up from a chair, lifting an item from the ground, or climbing stairs all require the movements and muscles involved in a squat. For athletes, squats are used in strength training for the quadriceps and gluteal muscle groups and high strength in squat performance has repeatedly been linked to a higher level of sport performance.¹ One frequently used technique is the back squat, where a barbell rests on the trapezius muscles behind the neck. Whether unweighted or weighted, the back squat can be used for a wide range of abilities and strengths – from clinical populations to elite athletes – to improve lower body strength.²

The back squat is a repetitive movement that often involves a heavy loads. These two factors create a potential for knee injury as tissues must repeatedly support the increased forces due to the extra load.^{3,4} One common knee injury is patellofemoral pain syndrome (PFPS), which refers to general chronic pain in the patellofemoral joint of the knee.⁵ PFPS is most often attributed to high stress in the patellofemoral joint between the articular surface of the patella and the femoral sulcus (also called patellar surface) of the femur.^{4,6,7} Because of this patellofemoral joint stress (PFJS), concerns with PFPS are not

only chronic pain, but cartilage damage in the patellofemoral joint leading to osteoarthritis (OA).

Past studies found that PFPS accounts for 25-40% of knee injuries diagnosed in sports medical clinics.⁸ Although there is currently insufficient epidemiologic data about PFPS beyond military populations, the estimate of prevalence in the general population is up to 28% in adolescents and up to 15% in adults.⁹ Within this prevalence, one longitudinal study found that the rate of PFPS incidence in females is over two times that of males,¹⁰ which may be attributed to anatomic differences such as greater laxity in females' knees.^{11,12} Whatever the case, PFPS is a common diagnosis that is chronic, leading to limited activity, which leads to decreased strength, which furthers the risk for PFPS and the likelihood of recovery.⁶ With this cycle, it is necessary to understand strategies to strengthen musculature around the knee while not exacerbating the PFPS.

The back squat is a relatively simple, controllable exercise for strengthening the lower body. Altering back squat technique in order minimize PFJS can help manage PFPS by improving quadricep strength which helps the patellofemoral joint move correctly. Simple alterations to the back squat include how much weight is lifted, how deep the squat is in terms of knee flexion, how wide of a stance is taken, and to what degree of turnout the foot is placed. In consideration of PFPS and the back squat, the global goal of the present research project was to evaluate how PFJS changes with squat load, depth, and stance width and consequently what strategies can be used to minimize PFJS during the back squat. Because of a difference in males and female for both

epidemiologic PFPS data and anatomy, females who weightlift were the population for the study.

Purpose

The purpose of this research was to assess patellofemoral joint loading in female recreational weightlifters during the back squat when squat depth, weight load, and stance width are varied. In this paper, Chapter Two reviews the literature to provide a background for the research. Next, two related research questions were addressed in two separate studies. Chapter Three comprises the first study and deals with squat depth and load. Chapter Four comprises the second study and deals with squat load and stance width. The research questions and hypotheses for each study are as follows:

Research Question 1

How does patellofemoral joint loading vary with squat depth and weight load?

Hypothesis 1 Patellofemoral joint loading during the back squat will be higher for higher weight loads, and unchanged for different depths

Research Question 2

How does patellofemoral joint loading vary with squat weight load and stance width?

Hypothesis 2 patellofemoral joint loading during the back squat will be higher for higher weight loads, higher for narrower stance widths, and higher for both conditions together.

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CHAPTER TWO

BACKGROUND

The Patellofemoral Joint

The patellofemoral joint must be both mobile and stable and therefore provides high potential for pathomechanics that may lead to dysfunction or injury. The patellofemoral joint is part of the knee complex (the tibiofemoral and patellofemoral joints together) and acts like a pulley for the quadriceps muscles, extending the moment arm over which force is transmitted. Secondly, the placement of the patella between the quadriceps tendon and the femur reduces friction that would damage the tendon if not attached to the patella which slides on slick hyaline cartilage between the patella and femur.¹

The patellofemoral joint is one of the most incongruent joints in the body.¹ The patella itself is shaped like a “teardrop” with the point, the apex, facing inferiorly and the broader end, the base, facing superiorly (see Figure 1 for labelled image of patella²). On its posterior surface, the patella has two main facets – the medial and the lateral – separated by vertical ridge that is centered on the surface from the superior to the inferior aspect. Both

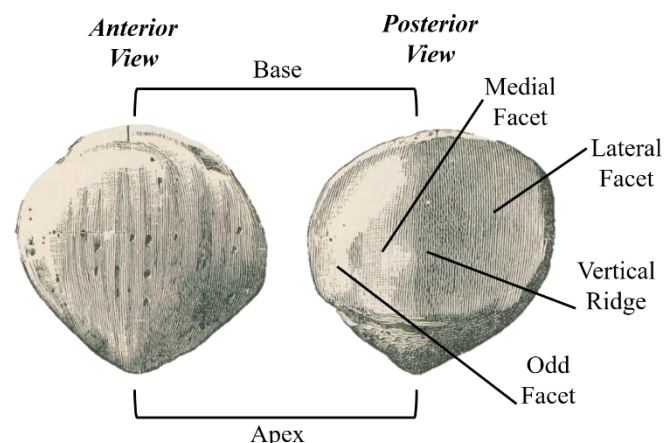


Figure 1. Anatomical features of a right patella bone. (Public Domain image from *Text-Book of Anatomy*.¹³ Labels added.)

the medial and lateral facets have their own articular surfaces and are slightly convex. At the medial edge of the medial facet, another vertical ridge separates the medial facet from a smaller facet, the odd facet.³ Throughout the joint's range of motion (ROM) the surface area and region of contact between the patella and the femur varies greatly.¹

Articulating with the posterior surface of the patella, the femoral sulcus sits within the femoral condyles, dividing them into medial and lateral portions. The vertical ridge of the patella sits within the central groove of the sulcus. Throughout its ROM the patella's facets contact the femoral condylar surfaces in varying amounts.¹

The patellofemoral joint is supported by several tissues (Figure). The patellar ligament – some of which is a continuation of the quadriceps tendon – attaches the patella to the tibial tuberosity on the anterior tibia. Superiorly, the quadriceps connect the patella to the thigh segment and provides muscular control of the patella. Medial-laterally, a pronounced lip on the lateral femoral sulcus helps prevent lateral patellar displacement. The extensor retinaculum also holds the patella to its joint surface, with the superficial portion directly connecting the vastus medialis and vastus lateralis to the patella. The patellotibial ligaments within the retinaculum and joint capsule stabilize the patella longitudinally while the medial and lateral patellofemoral ligaments stabilize through their

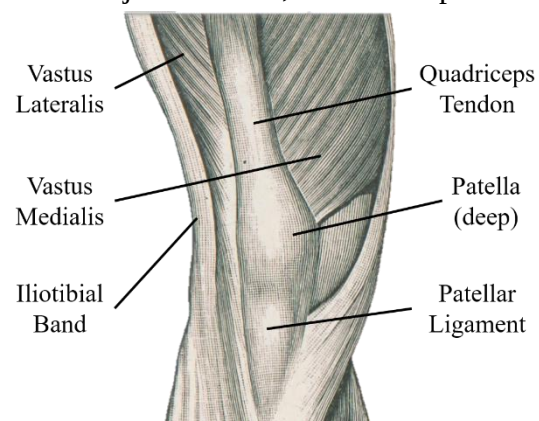


Figure 2. Key structures around the patellofemoral joint. (Public Domain image from *Text-Book of Anatomy*.¹³ Labels added.)

attachments to the adductor tubercle and iliotibial band, respectively.¹

In general, the knee complex is a stable joint in the kinetic mobility-stability continuum. Yet while the patella stabilizes the knee and enhances the use of the tibiofemoral joint, its role in mobility is evidenced by its lack of joint congruence and slick hyaline cartilage. Throughout knee ROM, the patella must glide inferiorly and superiorly, shift and tilt laterally and medially, and rotate medially and laterally about its apex, which is “fixed” to the tibial tuberosity via the patellar ligament. Patellar movements may be affected when muscle imbalances alter the direction of forces on the patella, or connective tissue restraints decrease mobility.

Patellofemoral Joint Movement and Contact Area

The patellofemoral joint follows a certain path or “tracks” along the femoral sulcus throughout tibiofemoral joint ROM. With tibiofemoral joint flexion, the patella glides inferiorly along the sulcus, between the condyles. With tibiofemoral joint extension, the patella glides superiorly. Yet the glide path is not perfectly superior-inferior; with initial flexion the patella shifts medially and then remains or shifts a small amount lateral through deeper flexion. With tibiofemoral joint flexion there is tibial medial rotation and because the patella is “anchored” to the tibial tuberosity, the patella also medially rotates. Thus, this patellar tracking must be intact for the function of the whole knee complex and, if it is not, is referred to as “maltracking.”¹

An understanding of normal patellar tracking helps explain how contact area amount and location changes throughout knee flexion. At full extension the patellofemoral joint is most unstable as the patella rests on the femoral sulcus and not

within the intercondylar groove. In this position, the contact area between the patella and femur is primarily at the inferior pole of the patella. With knee flexion, the patella glides inferiorly on the femoral sulcus and the sulcus deepens to the intercondylar groove, increasing joint congruency and therefore stability. At 10-20° of tibiofemoral joint flexion, the inferior margins of the medial and lateral facets of the patella contact the femur. From 20-90° the contact area begins to shift superiorly, still on both the medial and lateral facets. Around 90° the medial and lateral facets are in full contact with the femur while the odd facet is not. From 90° to full tibiofemoral joint flexion, the patellar contact shifts towards the lateral facet and at full flexion both the lateral and odd facets are in full contact with the femur, while the medial facet has little contact with the femur. In addition to patellar contact, the quadriceps tendon also contacts the femoral condyles, helping to distribute force.¹

Patellar maltracking describes patellar movement which deviates from the described pattern, especially during knee flexion. Maltracking can be due to quadriceps muscle imbalances or as a result of bone structure.¹ The effects of these features are highlighted in two research studies by Powers^{4,5} who described influences on patellar alignment in female subjects. In resisted knee extension from 45° of knee flexion, incremented steps throughout the movement assessed vastus lateralis and medialis muscle activity and correlated it with MRI data of medial-lateral displacement and patellar tilt. With higher vastus medialis activity there was greater lateral patellar displacement and lateral tilt, causing maltracking.⁴ Additionally, Powers assessed patellar groove depth and found that a shallow groove was predictive of lateral patellar displacement and lateral tilt.

Notably, the predictive ability for lateral displacement was for knee extension at or less than 27° and for lateral tilt less than 9° .⁵ In both studies, anatomical influences likely increased contact area and force on the lateral facet of the patella. Maltracking can alter the mechanics of the patellofemoral joint, bringing stress to different parts of the joint than would be expected.

Patellofemoral Joint Stress (PFJS)

Joint stress has two components: the forces in the joint and the joint surface contact area over which the force is distributed. Patellofemoral joint contact force is primarily influenced by the magnitude and direction of the quadriceps muscle force and the knee flexion angle. As knee flexion angle increases, there is a greater contact force within the patellofemoral joint as the quadriceps' direction of pull becomes more directly compressive.^{1,6} However, to maintain an equally high joint moment, at full extension the quadriceps must produce a high force to account for the small moment arm over which it is applied. In both scenarios, the patellofemoral joint undergoes high stress even though the line of pull of the quadriceps in one case is nearly orthogonal to that of the other because of joint position.¹ These variations in the application of quadriceps force while still producing high joint stress illustrate the other factor of joint stress: contact area.

As discussed in the previous section, there is little contact area between the patella and femur at tibiofemoral joint extension, but this contact area increases as flexion angle increases, with some variation in where the region of contact is on the patella as the joint progress to full flexion. As compressive joint contact force increases with knee flexion angle, so does the area over which that force is distributed. Even though the line of pull

of the quadriceps at degrees of flexion beyond 90° results in a large compressive force, the force is maximally distributed over the patella. In the full extension case, the inferior portion of the patella barely contacts the femur, so force is directed through a small area, creating high stress. The relationship between the force of the muscle, the line of pull for a given flexion angle, and the contact area for a given flexion area determine patellofemoral joint stress (PFJS).¹

Determining PFJS

There are several methods to calculating PFJS. The simplest uses inverse dynamics and mathematical models based on cadaveric data while the most complex methods optimize muscle forces via musculoskeletal modeling and perform discrete^{7,8} or finite element analysis⁹ to determine contact forces. In between, some studies use mathematical models, but get muscle forces through musculoskeletal models, optimizing muscle forces based on joint moments calculated from inverse dynamics.^{10,11} Unless for simulation purposes alone, all these methods acquire data with motion capture and force plates in order to calculate the knee extensor moment throughout the range of knee flexion angles.

Kernozek et al.¹¹ compared a purely inverse dynamics method and an inverse dynamics plus static optimization method for determining PFJS. The main difference in these methods was in determining the total quadriceps force on the patella. For the purely inverse dynamics method, quadriceps force was calculated based on the knee extensor

moment and then divided by the average quadriceps moment arm for a given knee flexion angle. For the inverse dynamics plus static optimization method with knee extensor data, a musculoskeletal model with 300 muscle tendon units estimated the maximum strength of each muscle and the associated moment arm throughout knee flexion.

Notably, the purely inverse dynamics method cannot account for co-contraction with the quadriceps, unlike the inverse dynamics plus static optimization method. Differences in quadricep force and consequently PFJS for running and squatting were 30-106% greater for the inverse dynamics plus static optimization method.¹¹ The smaller percent difference was associated with squatting where the inverse dynamics plus static optimization method found a 30.1% difference between quadricep force estimates, with the greatest differences at greater squat depths. As discussed by the authors, the lesser difference is likely because of co-contraction.¹¹ During the back squat there is little activation of the hamstrings¹² so the quadriceps are primarily responsible for patellofemoral joint forces. Although there still is a difference in methods, it is not as extreme as for more dynamic exercises and so for slow non-locomotive movements like the back squat, determining quadriceps force based on inverse dynamics alone is a reasonable approach.

Once the force due to the quadricep is determined, joint reaction force is found using the quadricep moment arm dependent on knee flexion angle. Moment arm data may be derived from the musculoskeletal model¹¹ or incorporated in the form of a mathematical model fit to cadaveric data.¹³⁻¹⁶ Finally, the joint reaction force of the

patellofemoral joint is divided by the patellofemoral contact area, both dependent on the angle of knee flexion.

The present study used the purely inverse dynamics approach to find the force of the quadriceps and found PFJS through the mathematical models described by Salem & Powers¹⁶ and Wallace et al.¹³ First, the quadriceps force (QF) was calculated by:

$$QF = \frac{M}{L}$$

where M is the knee extensor moment and L is the effective moment arm of the quadriceps muscle, and varies with knee joint angles (θ) according to an equation described by van Eijden et al., accounting for 0°-120° degrees of knee flexion:¹⁷

$$L = 8.0E^{-5}\theta^3 - 0.013\theta^2 + 0.28\theta + 0.046$$

Second, to find patellofemoral joint reaction force (PFJRF), QF was multiplied by a constant k , which also varies with knee joint angle as described by van Eijden et al., accounting for 0°-120° degrees of knee flexion.:¹⁸

$$k = \frac{4.62E^{-1} + 1.47E^{-3}\theta^2 - 3.84E^{-5}\theta^2}{1 - 1.63E^{-2}\theta + 1.55E^{-4}\theta^2 - 6.98E^{-7}\theta^3}$$

Finally, to get PFJS, the PFJRF was divided by the contact area (CA) of the patella on the femur. Contact areas are dependent on the knee joint angle and were determined by fitting a third order polynomial ($R^2=0.99$) to cadaveric data described by Matsuda et al.¹⁹ As opposed to other commonly used cadaveric data,^{6,20} this particular contact area data

was used as it provided patellofemoral contact areas at degrees of knee flexion up to 135°. Once contact area was determined, PFJS was calculated as:

$$\text{PFJS} = \frac{\text{PFJRF}}{\text{CA}}$$

Concerns with Calculating PFJS for Squats

All cadaveric data for the mathematical calculation of PFJS are based on pure sagittal plane tibiofemoral joint flexion. However, in the back squat, stance width and foot turnout bring the knee out of the sagittal plane and introduce rotation at femoroacetabular and tibiofemoral joints. In using the calculation methods described^{13,16} to find PFJS during squats – particularly with differing stance widths - it is assumed that stance width and foot turnout do not influence total patellar contact.

Hefzy et al.²¹ used cadaver knees to determine patellar-femoral contact areas as tibial rotation angle changes during knee extension from 90° of knee flexion with differing resistance. Until about 30° of knee flexion, greater external tibial rotation results in more lateral displacement and lateral tilt. Contact area results compared to other studies of contact area during knee flexion;²⁰ however, though total contact area was the same, the region of the patella in contact with the femoral sulcus differed. For example, increased external tibial rotation throughout knee flexion there was associated with increased contact area on the lateral patellar articular surface (and the opposite true for internal tibial rotation).²¹ The implications of these results are that 1) even with varied stance foot turnout during a squat, the same contact area values may be used and 2) modifications in foot placement may be able to relieve some of the contact force between

patella and femur in certain compartments. Therefore, together with the review of PFJS calculation methods discussed earlier, there is no strong reason to assume that the described equations and mathematical calculation methods cannot be used for the calculation of PFJS with variations of the back squat.

Patellofemoral Pain Syndrome (PFPS)

High patellofemoral joint stress is often referenced as the contributor to PFPS and patellofemoral osteoarthritis. Though PFPS is a broad term, the associated pain is typically regarded as the result of damage to subchondral bone, which may occur with degradation of joint cartilage due to high joint stress.¹ PFPS is one of the most common sports orthopedic knee injuries. As previously described, it is often seen in adolescent populations and occurs over two times more in females than in males.²² Chronic PFPS can cause severe pain in a multitude of daily activities both sedentary and non-sedentary. Moreover, once PFPS begins to limit an individual's activities, they are prone to further problems as the strength and muscle balance to control the patella can decrease.^{1,23}

Recommendations to manage PFPS involve monitoring knee flexion angle in weight-bearing and non-weight-bearing exercises.²⁴ The goal is to avoid high quadriceps forces at full extension non-weight-bearing as well as high compressive contact forces with deep knee flexion in weight-bearing scenarios. Although open kinetic chain exercises are often criticized for rehabilitation of PFPS, in a randomized study on 5-week physical therapy programs for PFPS, no difference was found between open kinetic chain and closed kinetic chain treatments for PFPS over a follow-up time of 5-years.²⁴

Consequently, management of PFPS tends to be vague, relying on the primary goal of working within pain-free limits.

There have been several observations of differences between patellar movement in healthy populations versus those with PFPS. A primary theory is that patellar maltracking changes the PFJS because of altered contact areas over which compressive forces are transferred. For instance, tibiofemoral rotation and patellar width have been shown to explain 46% of patellar contact area variation in individuals with PFP. Contrary to other studies, this case did not find any explanation of variance due to patellar tilt, but found that wider patellae tend to have increased contact area and that an increase in internal tibiofemoral rotation decreases contact area.²⁵ However, the role of tibiofemoral rotation has been previously theorized and studied, with debate as to the consistency and true effect of this phenomenon.²⁶

Another study assessed tibiofemoral rotation by computationally modeling PFJS with the assumption that greater cartilage stress is directly related to the greater PFJS that causes pain of the subchondral bone. In individuals with PFPS, greater PF joint cartilage stress was found when squatting at 15° and 45° of knee flexion relative to other degrees of flexion.²⁷ Building on that finding, the authors then associated internal rotation of the femur with greater cartilage stress.²⁸ Whether due to patellar, patellofemoral, or both pathomechanics, in study of individualized measures of effective quadriceps moment arm and patellofemoral joint reaction force (PFJRF) in PFPS and healthy populations, the PFPS population had 15% greater PFJRF.²⁹ Therefore, there is a known difference in joint forces in PFPS patients, which must occur from dysfunction of the joint.

Issues like tibiofemoral rotation and general patellar control may guide rehabilitation protocols, but there are also known strength deficits of concern in PFPS patients. In a series of functional tasks, Souza and Powers³⁰ found that increased hip internal rotation, decreased hip muscle strength, and increased gluteus maximus activation indicated compensatory pattern, linking PFPS and hip strength in females performing functional tasks. In a more recent study, individuals with PFPS had decreased concentric and eccentric quadricep strength, which was related to pain and function scores.³¹ As previously discussed, there is a spiral pattern with PFPS: pain leads to inactivity, inactivity to weakness, and weakness to poor patellar control and worsening symptoms. It is a necessity to determine a controllable, effective method of strengthening patients with PFPS while minimizing PFJS.

The Back Squat

As previously defined by Comfort et al.,³² an optimal back squat provides performance benefits through training the lower extremity musculature with maximum muscle activation, while minimizing injury risk. There is an abundance of evidence to support the relationship between back squat strength and athletic performance.³² The most recent recommendations for back squat technique recommends allowing a stance width that is roughly shoulder-width with a foot turnout at whatever is most natural for the individual.³² Considering safety and exercise effectiveness, squat depth should be until proper technique can no longer be maintained.³²

Varying the Back Squat

The back squat is an easily modified exercise. Some of the simplest variations are changes to squat depth, load, stance width, and foot turnout. By adjusting these factors, athletes or clinicians can change the intensity of the exercises as well as how forces act upon the body. In patients with PFPS, modifying the back squat with these variations could allow them to perform this adaptable exercise in order to strengthen their lower body and while allowing less PFJS. However, little research has addressed how PFJS changes with these variations.

Depth and Load

Depending on the sport or lifting philosophy, the squat is commonly performed at three different depths. In training and clinical settings, squat depth is often limited to 90° of knee flexion (above parallel). Second, parallel depth is used in powerlifting competitions and refers to the thigh segment being parallel to the ground, such that the inguinal crease is just below the base of the patella.³³ Finally, full range of motion squats are defined by the hamstrings contacting the gastrocnemii.

Variations in back squat load are used to accomplish different strength goals. For strength adaptation with low repetitions, athletes typically use 75-85% of an individual's one repetition maximum (1RM). For power training, athletes may use 50-65% of their 1RM.³⁴ Finally, novice athletes or patients in clinical setting frequently use bodyweight squats.¹ In strength program design for clinical and athletic settings, it is important to understand how variations in squat depth and the corresponding weight load will affect the patient's or athlete's knee health.

Previous research has evaluated how peak knee extensor moment (KEM) changes with differing depths and loads during the back squat. One study found a main effect of load,¹³ while others found this effect as well as a depth-by-load interaction such that within each depth as load increased, peak KEM also increased.^{35,36} Another study looked at different squat depths with a heavy load and found no main effect of depth.¹⁶ These studies used a range of depths and weights, but a key methodological difference was how the 1RM was measured. In the studies that observed an interaction, the loads were calculated as percentages of depth-specific 1RM values tested by the researchers.^{35,36} In the study that focused on load, 35% of each participant's bodyweight was used, which does not account for variations in body composition, strength, or neuromuscular abilities.¹³ In the study that used a high load for three different depths, the load was 85% 1RM from the previous month's training, with no indication of depth tested.¹⁶ The issue with this range of methodologies is that the 1RM measured at each depth may be significantly different from each other such that 85% 1RM for 90° may be a much larger percentage of 1RM for a parallel depth. Consequently, comparison across these studies becomes difficult. Perhaps only an effect of load was seen in the study of three depths because the load relative to the depth was increasing with increased depth.¹³

Only a couple of studies determined patellofemoral joint reaction force (JRF) and patellofemoral joint stress (PFJS) during the back squat. Possibly related to the 1RM testing methodology, in the Salem et al.¹⁶ paper, there was no differences for JRF between different depths. For PFJS, a main effect of load was found when squatting to 90° unloaded and with a 35% of bodyweight load.¹³ Altogether, PFJS and related joint

loading is primarily affected by weight load rather than squat depth. The primary benefit of a deeper squat is to increase gluteal muscle activation³⁷ and increased patellofemoral joint loading with depth is not a concern.

Stance Width and Turnout

Anthropomorphic and mobility characteristics can influence range of motion (ROM) during the back squat. Using only unloaded conditions, Demers et al.³⁸ used motion capture to assess joint angles when back squatting at three different widths based on pelvic width. The authors found that for wider stance widths there was less joint ROM for ankle, knee, and hip flexion, with the greatest influence on dorsiflexion.³⁸ Thus, dorsiflexion is the limiting factor in squat depth, but using a wider stance width lessens the amount of dorsiflexion required. Anthropometrically, as length ratio of trunk/thigh increased, shifting the center of mass anteriorly, knee flexion and ankle dorsiflexion decreased. As thigh/shank ratio increased, shifting the center of mass posteriorly, knee flexion and ankle dorsiflexion increased.³⁸ Therefore, those with relatively long thigh segments or short trunks can benefit from a wider stance if they need to perform a deeper squat.

Overall, muscle activity in the quadriceps does not change with stance width and foot turnout, though gluteal activation does increase with a wider stance.^{32,39,40} Large stance widths can decrease knee and hip moments during bodyweight squats,⁴¹ though one study suggested that these differences are not clinically relevant.⁴² In squatting to the same depth with a wide or narrow stance, more knee flexion angle is observed in narrow

stances and a greater hip joint moment relative to the knee joint moment is seen with the wide stance.⁴³ Lorenzetti et al.⁴⁴ reported that a wide stance (two times ASIS-ASIS width) with high turnout (42°) resulted in a greater knee moment in the sagittal plane as compared to a medium and a narrow stance, each measured for three turnout angles: 0°, 21°, and 42°. From these results, squats should be performed with caution in positions of extreme foot turnout and/or extreme stance widths.⁴⁴ Ideally, follow the recommendations from Comfort et al.³² and perform the back squat in a natural stance and turnout position.

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CHAPTER THREE

PATELLOFEMORAL JOINT LOADING IN FEMALES WHEN
USING DIFFERENT DEPTHS AND LOADS
IN THE BACK SQUAT

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Patellofemoral joint stress in females when using different depths and loads during the back squat

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Abstract

Back squats are a common strengthening exercise for knee and hip musculature. However, the repetitive loaded movement can result in high patellofemoral joint loading and therefore may contribute to the development overuse injuries. Thus, it is important to understand how changing parameters such as depth or load influences knee loading during the squat. This study investigated how knee loading changes when experienced female lifters squat to three depths (above parallel, parallel, and below parallel) and with three commonly used loads (unloaded, 50%, 85% of depth-specific one repetition maximums). Patellofemoral joint reaction forces and stresses were calculated from the knee extensor moments and joint angles. Knee extensor moments displayed a depth-by-load interaction such that within each depth, as load increased, peak knee extensor moment increased. However, within each load, the effects of depth were different. Patellofemoral joint reaction force had main effects of load and depth such that as load increased or depth decreased, peak joint reaction forces also increased. Patellofemoral joint stress displayed a depth-by-load interaction such that within each depth, as load increased the joint stress also increased ($p = .029$). However, within each load, the effects of depth varied. Unloaded squats with full range of motion or loaded squats to less than 90° of knee flexion are recommended for strengthening knee and hip musculature via the back squat while minimizing patellofemoral joint stress.

Keywords: patellofemoral joint kinematic and kinetics, patellofemoral pain syndrome, joint contact force

Word Count: 3765

Introduction

The squat is a foundational exercise for developing lower limb strength.¹ One common variation of the squat is the back squat technique where the barbell is held behind the neck resting on the trapezius muscle. Depending on the sport or lifting philosophy, the back squat is commonly performed to three different depths. Above parallel squats are typically limited to less than 90° of knee flexion and result in the thigh being above parallel to the ground at the bottom of the squat. Above parallel depths are commonly used in clinical settings as this depth limits the amount of compressive force applied to the patellofemoral joint.² In powerlifting competitions legal squat depth requires the inguinal crease to be below the base of the patella, resulting in approximately 110° of knee flexion and the thigh being parallel to the ground.^{3,4} Finally, full depth squats to 120 - 130° of knee flexion with the back of the thigh contacting the calves, are commonly prescribed for athletic performance or Olympic weight lifting.^{2,3} In strength program design for both clinical and athletic performance settings it is important to understand how variations in squat depth impact a patient's or athlete's knee health.

In addition to depth, the weight used during the squat is an important variable, as the addition of load on the bar increases forces and stresses in the knee. Given the repetitive nature of the squat, such increased knee loading creates an environment for possible injury.^{5,6} Of particular concern is how changing squat depth or load affects the patellofemoral joint. Patellofemoral pain syndrome is one of the most common knee diagnoses in active populations, affecting up to 30% of active adults and 45% of active adolescents.⁷ Patellofemoral pain syndrome is attributed to increased patellofemoral joint

stress (pfJS) due to poor distribution of the joint contact force between the femur and the patella.^{6,8-10} High pfJS has also been associated with articular cartilage degradation and development of chronic knee pain.¹¹ The incidence of patellofemoral pain syndrome is over two times higher in females than in males.¹² This is due to a host of possible factors including: greater femoral internal rotation and valgus knee alignment,^{13,14} greater tibiofemoral joint laxity,¹⁵ or quadriceps dominant movement patterns.^{6,16} Considering these epidemiologic and anatomical factors, it is especially important to understand how depth and load combinations influence patellofemoral joint loading in female weight lifters.

To date, only a few previous studies have assessed patellofemoral joint forces, moments, or stresses during back squats in female weight lifters. In a mixed gender study which included nine females, Wallace *et al.* had participants squat to a depth of 110° knee flexion in unloaded and 35% 1RM conditions and observed that peak knee extensor moment (KEM), patellofemoral joint reaction force (pfJRF), and pfJS all increased with the addition of load, and also increased as participants progressed from 0° to 110° of knee flexion.¹⁷ However, the authors did not analyze male and female participants separately. Salem and Powers evaluated patellofemoral joint kinetics in five female collegiate athletes when squatting to three different depths using 85% of their 1RM and observed that peak KEM, pfJRF, and pfJS did not change with increasing depth.¹⁸ Most recently, Flores *et al.* evaluated 19 experienced female weight lifters while squatting to above parallel, parallel, and below parallel depths using unloaded, and 50% and 85% of depth specific 1RM loads.¹⁹ They observed a depth-by-load interaction such that peak KEMs

increased with increasing load for a given depth, but depended on the depth of the squat within a given load.¹⁹ While Flores *et al.* suggested the increased KEM could be used as a surrogate for pfJS¹⁹, this assumption should be interpreted cautiously as calculations of pfJS are based on not only KEM, but on changes to the patella contact area and pfJRF throughout the squat.^{17,18,20,21} However, to date, no studies have investigated the effects of commonly used depth and load combinations on pfJS in the back squat.

Given this gap, this study sought to build on the work of Flores *et al.*¹⁹ by assessing peak KEMs, pfJRFs, and pfJS in experienced female weight lifters squatting to above parallel, parallel, and below parallel depths while unloaded, and when using 50% and 85% of a depth specific 1RM. We hypothesized that peak KEM, pfJRF, and pfJS would all increase with load, but not with depth.

Methods

Twenty recreationally active females were recruited from the university campus and community (age: 24.9 ± 5.7 years, mass: 62.9 ± 10.0 kg, squat experience: 3.9 ± 2.5 years). All participants were healthy with no history of surgery or ligamentous injuries on either limb, and, during visual assessment of squat technique, were deemed capable of using proper back squat technique to a full depth, as indicated by maintaining heels on the ground and a neutral lumbar spine. Participants were asked to avoid intense physical activity for the 24 hours prior to visiting the laboratory. Upon arrival for the study, participants were briefed on the procedures and then provided written informed consent. All study procedures were approved by the Institutional Review Board.

The study involved two laboratory visits per participant: the first for depth-specific 1RM measurements and the second for the full data collection with 3-dimensional motion capture. At the 1RM visit, participants were provided 10 minutes to perform their normal, self-selected warm-up routine. The National Strength and Conditioning Association's 1RM procedure was followed to find the participant's 1RM, increasing barbell weight by 10-20% of bodyweight until the participant could not complete a squat.²² Depth-specific 1RM values were found for full depth ($\sim 125^\circ$ of knee flexion), parallel ($\sim 110^\circ$ of knee flexion), and above parallel ($\sim 90^\circ$ of knee flexion), in that order. Depth-specific 1RMs were used specifically because 1RM has been shown to decrease with increased depth.²³ For full depth, the hamstrings were required to contact the calves, as is used in weightlifting practice. For parallel, the thigh segment must be parallel to the floor, defined by USA Powerlifting as when the inguinal crease falls below the proximal patella.²⁴ For above parallel, depth was set using a goniometer to measure 90° of knee flexion. Between attempts there was a rest period of one to two minutes and all participants were verbally encouraged in their attempts.

To ensure proper depth was reached, a custom photocell device audibly and visually cued participants when they reached the bottom of their squat, where they paused for one second to minimize rebounding. The photocell had a field laser (Banner Engineering Corp., Minneapolis, MN) and a piezo light switch (Banner Engineering Corp., Minneapolis, MN), which provided auditory feedback. The height of the field laser for each depth was recorded and replicated for the second day of data collection.

Similarly, tape was used to mark the lateral and posterior borders of the participants' shoes so that stance width and foot position could be replicated between days.

After at least 24 hours and no more than one week, participants returned to the laboratory for the second session. A 12-camera motion capture system (Qualisys Inc., Gothenburg, Sweden) collected 3-dimensional kinematic data at 250 Hz while two force plates (Model 600900-10, Bertec Corp., Columbus, OH), one under each foot, collected ground reaction forces at 1000 Hz. A total of nine conditions based on the 1RM maximum results were recorded, with two consecutive squats performed per condition. At each depth, participants squatted unloaded, with 50%, and with 85% of their depth-specific 1RM. The order of conditions was randomized for each participant.

Reflective markers were placed bilaterally on the acromioclavicular joints, anterior superior iliac spines (ASIS), posterior superior iliac spines (PSIS), lateral and medial epicondyles, lateral and medial malleoli, second metatarsal heads, and the posterior calcanei. Additional tracking markers were placed on the iliac crests, mid-point between iliac crests and PSISs, base of fifth metatarsal, manubrium, and positioned on a headband between the ears. Lastly, rigid plastic marker clusters of four non-colinear markers were placed on the lateral shanks and thighs, and four markers were placed linearly along the barbell.

Marker trajectories and ground reaction forces were exported to Visual 3D (C-Motion, Inc., Rockville, MD) where they were filtered using fourth order, zero-lag Butterworth filters with cutoff frequencies of 8 Hz and 15 Hz, respectively, as determined by residual analysis.²⁵ Joint angles were calculated using a Cardan rotation sequence

corresponding to flexion/extension, ab/adduction, and internal/external rotation. Internal joint moments were calculated using Newton-Euler equations of motion and expressed in the proximal segment coordinate system. The sagittal plane knee joint angles and KEMs were exported to a custom Matlab (Mathworks, Natick, MA) program to calculate pfJRFs and pfJSs utilizing a previously described approach.^{17,18,20}

First, the quadriceps force (F) was calculated by:

$$F = \frac{M}{L}$$

where M is the KEM and L is the effective moment arm of the quadriceps muscle, and varies with knee joint angles (θ) according to an equation described by van Eijden *et al.*, accounting for 0°-120° degrees of knee flexion:²⁶

$$L = 8.0E^{-5}\theta^3 - 0.013\theta^2 + 0.28\theta + 0.046$$

Second, pfJRFs were calculated by multiplying F by a constant k ,^{20,27} which also varies with knee joint angle based on data from another study by van Eijden *et al.*, accounting for 0°-120° degrees of knee flexion:²⁸

$$k = \frac{4.62E^{-1} + 1.47E^{-3}\theta^2 - 3.84E^{-5}\theta^2}{1 - 1.63E^{-2}\theta + 1.55E^{-4}\theta^2 - 6.98E^{-7}\theta^3}$$

Finally, to get pfJS, the pfJRF was divided by the contact area (CA) of the patella on the femur. Contact areas are dependent on the knee joint angle and were determined by fitting a third order polynomial ($R^2=0.99$) to the cadaveric data described by Matsuda

et al.²⁹ This particular study for CA was used as it provided patellofemoral CAs at high degrees of knee flexion. Once CA was determined, pfJS was calculated as:

$$\text{pfJS} = \frac{\text{pfJRF}}{\text{CA}}$$

Statistical Analysis

Differences in 1RM values at each depth were compared using a one-way repeated measure analysis of variance (ANOVA). Within each participant, mean values for each condition and depth were calculated for peak KEMs, pfJRFs, and pfJSs. Differences between conditions and depths were evaluated using a 3x3 repeated measures ANOVA. For all ANOVAs, in the event of a significant omnibus test, pairwise comparisons were conducted using a Bonferroni correction. To aid in interpretation of results effect sizes (d ; mean difference divided by average standard deviation) were calculated for all pairwise comparisons. Ranges of < 0.2 , around 0.6, and > 1.2 , were interpreted as small, moderate, and large effects, respectively.^{30,31} All statistical tests were performed using Statistical Package for the Social Sciences (SPSS, Version 25; IBM Corp., Armonk, NY).

Results

Participants' 1RM were significantly different between depths ($F_{2,38} = 10.968$, $p < .001$, $\eta^2 = 0.366$), with the above parallel 1RM (74.03 ± 20.25 kg) being greater than 1RM values at either parallel (65.1 ± 19.04 kg, $p = .015$, $d = 0.454$) or below parallel (60.72 ± 19.87 kg, $p = .008$, $d = 0.663$) depths. The parallel depth was also greater than the below parallel depth ($p = .031$, $d = 0.225$). Peak knee flexion during the squat also

changed with depth ($F_{2,38} = 235.18$, $p < .001$, $\eta^2 = 0.925$) and was greater during squats to the below parallel depth ($127.37 \pm 0.28^\circ$) than either the parallel ($103.85 \pm 2.62^\circ$, $p < .001$, $d = 16.232$) or above parallel ($87.91 \pm 2.16^\circ$, $p < .001$, $d = 32.364$) depths. Knee flexion was also greater at the parallel depths than the above parallel depths ($p < 0.001$, $d = 6.665$).

There was a significant depth by load interaction for peak KEM ($F_{4,76} = 6.34$, $p < .001$, $\eta^2 = 0.250$; Figure 1). Within each depth, as load increased, so did peak KEM. Within the unloaded condition, peak KEMs were not different between depths (above vs. parallel $p = .999$, $d = 0.081$; above vs. below $p = .364$, $d = 0.160$; parallel vs below $p = .999$, $d = 0.072$). Within the 50% 1RM condition, peak KEMs were higher in the below parallel depth than in either the parallel ($p = .012$, $d = 0.439$) or above parallel depths ($p = .026$, $d = 0.438$). Finally, in the 85% 1RM condition, peak KEMs were higher in the below parallel depth than the parallel depth ($p = .013$, $d = 0.679$), but not different between above and below parallel depths ($p = .088$, $d = 0.446$).

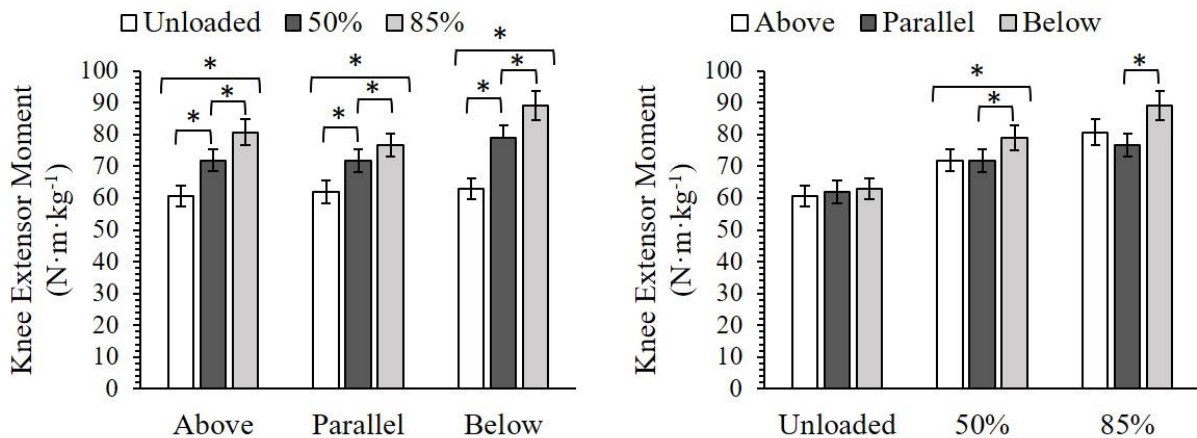


Figure 3. Mean values for peak KEMs increasing with load at each squat depth (left), and some increasing with depth for the 35% and 85% loads (right). * indicates significantly different at the $p < .05$ level.

For peak pfJRF there were significant main effects of both depth ($F_{2,38} = 8.413$, $p < .001$, $\eta^2 = 0.307$) and load ($F_{2,38} = 85.904$, $p < .001$, $\eta^2 = 0.819$; Figure 2). Pairwise comparisons revealed peak pfJRFs were higher at the above parallel depth than either the parallel ($p = .002$, $d = 0.418$) or below parallel ($p = .045$, $d = .301$) depths. As load increased, so too did peak pfJRFs (unloaded vs 50% 1RM $p < .001$, $d = 5.84$; unloaded vs 85% 1RM $p < .001$, $d = 3.597$; and 50% 1RM vs 85% 1RM $p < .001$, $d = 9.038$).

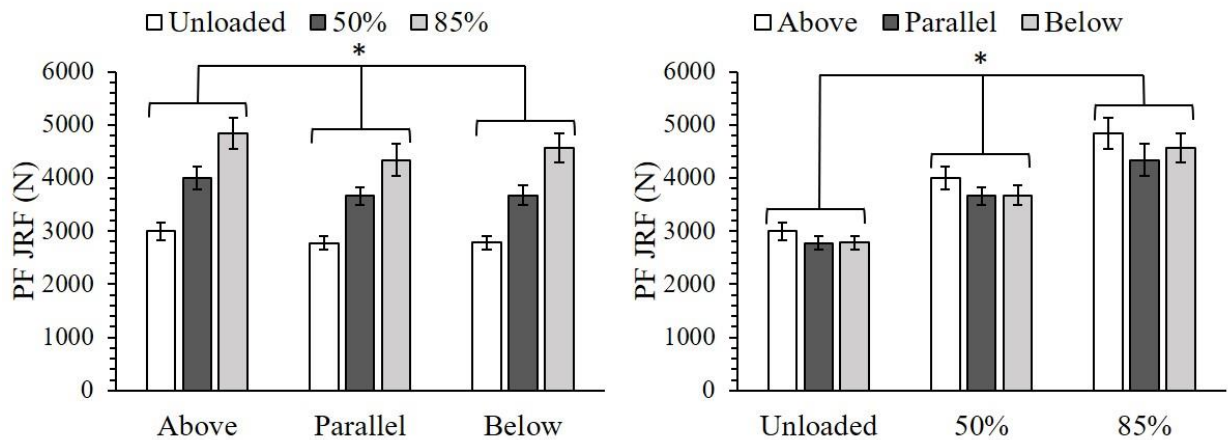


Figure 4. Mean values for peak pfJRF increasing with load at each squat depth (left), and some decreasing with depth for each load (right). * indicates significantly different at the $p < .05$ level.

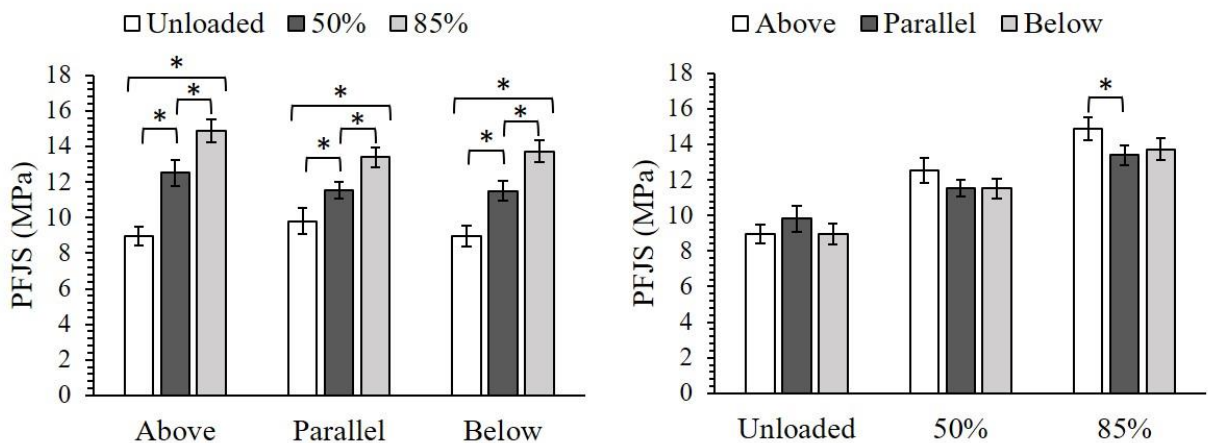


Figure 5. Mean values for peak pfJS increasing with load at each squat depth (left), and decreasing from above to parallel depths for the 85% load (right). * indicates significantly different at the $p < .05$ level.

For peak pfJS, there was a significant depth by load interaction ($F_{4,76} = 2.849$, $p = .029$, $\eta^2 = 0.130$, Figure 3). Within each depth, as load increased, so did peak pfJS. Within the unloaded condition, peak pfJS was not different between depths (above vs parallel $p = .688$, $d = 0.291$; above vs below $p = .999$, $d = 0.001$; parallel vs below $p = .958$, $d = 0.279$). Similarly, within the 50% 1RM condition, there were no differences between depths (above vs parallel $p = 0.342$, $d = 0.362$; above vs below $p = .422$, $d = 0.352$; parallel vs below $p = .999$, $d = 0.012$). However, within the 85% 1RM condition, peak pfJS was higher at the above parallel depth than the parallel depth ($p = .004$, $d = 0.546$), but not different between above parallel and below parallel depths ($p = .326$, $d = 0.402$) or parallel and below parallel depths ($p = .999$, $d = .126$).

Discussion

The aim of this study was to evaluate how KEM, pfJRF, and pfJS change in females during the back squat when depth and load are varied. It was hypothesized that there would be a main effect of load, but not depth, for KEM, pfJRF, and pfJS. The results partially supported the hypothesis as with increasing load within each depth, both peak KEM and pfJS increased. However, pfJRF had a main effect of both load and depth. The overall findings align with previous research suggesting that knee loading is influenced by both depth and load used during the squat.

In agreement with previous studies,^{19,23} peak KEMs displayed a depth by load interaction. As load increased within a given depth so too did peak KEM. This finding is consistent with Wallace et al.¹⁷ who reported that peak KEMs were higher when loaded then unloaded at 30°, 45°, 60°, 75°, and 90° of knee flexion. As load increases the force

generated by the quadriceps muscles must also increase to resist (eccentrically) or move (concentrically) the load. Since the quadriceps moment arm changes with joint angle but not with load, there would be larger peak KEMs with increasing load. However, the current study also found there were differences between squat depths when squatting with a given load. This result is in contrast to those of Salem and Powers,¹⁸ who reported no differences between shallow, medium, and deep depth squats when performed using loads of 85% 1RM. Partially, this might be explained by methodology differences between the two studies. Salem and Powers calculated load based on 1RM from the previous month of training, but they did not describe how the 1RM was determined and for what squat depth.¹⁸ In the present study, the barbell was loaded based on depth-specific 1RM values and, in agreement with Flores et al.,¹⁹ there was a significant difference between each depth-specific 1RM and a depth by load interaction for peak KEMs. Cotter et al.²³ also used depth specific 1RM values, and observed a depth-by-load interaction for peak KEM, though their study was in male athletes. Combined these results highlights the importance of 1RM loads which are specific to the depths that will be used in training or research as the resulting absolute load will vary significantly. For example, if 85% 1RM from the above parallel condition was used for the below parallel condition, the weight would be 104% of the below parallel 1RM.

While the 1RM methodology may explain differences between studies, it does not explain why only the below parallel KEMs were greater in the 50% and 85% 1RM loaded conditions. In absolute terms, the 85% 1RM at below parallel was the lightest load used. However, the decrease in load was not enough to offset the increase in peak KEM

from increasing depth. Increased peak KEMs at full depth despite lower loads was also observed by Flores et al.¹⁹ and Cotter et al.²³, in female and male populations, respectively. One possible explanation is that during loaded squats at full depths the lifter may change their posture to utilize a more upright trunk position, thus increasing the moment arm from center of mass to the knee joint center and creating a larger knee moment. Such a change in position would allow the weight to be more directly moved by the hip musculature and may be one reason why the gluteal muscles are more active during squats to deep depths compared to shallow depths.³² More investigation of how load changes deep squat mechanics may provide further understanding of this hypothesis.

A depth-by-load interaction was observed in peak pfJS such that within a given depth, pfJS increased with adding load. However, within a given load there were minimal differences in pfJS between depths. The singular exception was that the above parallel depth had greater peak pfJS at 85% of 1RM compared to parallel. This is not surprising given that the calculation of pfJS is dependent on both pfJRF and patellofemoral CA, the latter of which varies with knee angle. The patellofemoral CA gradually increases from full extension up to 90° of knee flexion.^{29,33–36} The highest peak pfJRF was observed during the above parallel depth with 85% 1RM. This highest pfJRF in this combination makes sense as, in absolute terms, this was heaviest load lifted during the trials. However, in this position patellofemoral CA area is relatively small. Thus, the combination of large pfJRF and small CA should result in a large pfJS.

The dependence of patellofemoral CA on knee flexion angle helps also helps explain how pfJS changes during the squat. As knee angle increases, CA also increases

until around 40-50° of knee flexion. From there, CA essentially plateaus, with only slight increases thereafter until about 90°. ²⁹ Consequently, patellofemoral CA maximizes after about 50° and changes in pfJS thereafter are more dependent on increases in pfJRF. However, in discussing patellofemoral CA, there are necessary considerations about methodology as well as implications. The CA equation used in the current study was modelled based on data from Matsuda *et al.* because it was the only report of CAs in deep knee flexion ranges. ²⁹ However, these are cadaveric data and may not accurately represent *in vivo* values. Moreover, a generalized equation may not be completely accurate as an individual's patellofemoral CA may differ based on bony morphologies and/or muscle imbalances. Studies using weight bearing open magnetic resonance imaging have reported that people with PFPS may have decreased CAs, which would increase pfJS. ^{33,37} However, determining individualized estimations of patellofemoral CA requires experimental facilities such as MRI which are not readily available. Lacking such facilities, the more general equations can be applied provide insight into factors influencing pfJS.

The results of this study have implications for using squats in clinical and athletic settings. In clinical settings, research has shown that both open and closed kinetic chain exercises are effective for patellofemoral pain syndrome rehabilitation. ³⁸ Within those exercises, strengthening programs that target the hip and knee musculature are more successful and result in longer last improvements in pain, function, and activity levels than programs that only address knee musculature. ³⁹⁻⁴¹ As such, the squat would be especially beneficial as it is a closed-chain exercise that involves both the knee and hip

musculature. The results of the current study suggest unloaded full-depth squats or loaded squats to a maximum depth of parallel could both be used for rehabilitation while minimizing pfJS. In athletic settings, using the whole knee range of motion increases gluteal engagement.³² In a specific comparison between squats and resisted open-chain knee extension for strengthening knee extensors while minimizing pfJS, Powers found squats to have a lower pfJS for 0°-45° of knee flexion and resisted knee extension for 45°-90°.⁴² However, a previous study compared quadricep, hamstring, and gluteal muscle activation at different squat depths and reported greater gluteal activation with deeper squats.³² These findings suggest deeper squat depth is necessary to engage hip musculature, which is an important part of patellofemoral pain syndrome rehabilitation.⁴³⁻⁴⁵ Simultaneously, greater weight can be used with lesser squat depth, which will strengthen knee musculature. As a good exercise for developing hip and knee muscle strength,¹ these squat modifications can allow athletes to continue to build strength while managing patellofemoral pain syndrome.

There are several factors which must be considered when interpreting the results of this study. First, bar position (high bar vs low bar) during the squat was not controlled. While only three participants used the low-bar lifting style, this alternative bar-positioning has been shown to increase hip flexor moments,⁴ and thus could possibly affect knee loading. Second, shoe-type was not controlled and most participants used tennis shoes. However, one participant used lifting shoes designed with a raised heel. It has been shown previously that lifting shoes affect knee and hip kinetics by decreasing the ankle dorsiflexion angle.⁴⁶ Third, participants squatted at a self-selected pace, which

may influence forces and moments. Fourth, the study was designed to minimize “bouncing” at the bottom of the squat by using a 1-second pause at full depth. This style of squat is not commonly used during training and may also influence forces and moments. Fifth, as previously mentioned, the equations utilized and CA cited are generalized and not based precisely on the individual and thus variations in actual effective quadriceps moment arm and CA values would be expected. Finally, it is important to remember that this study is primarily assessing the patellofemoral joint and so results should not be interpreted for the whole knee.

In summary, when back squatting to different depths with various loads, pfJS in recreationally active females changes with load. In consideration of the patellofemoral joint, the depth of the squat does not influence pfJS, though has some influence on pfJRF. If pfJS is a concern, to engage the hip musculature a lighter weight load should be paired with back squatting to full depth. To target knee musculature while keeping pfJS low, a heavier weight load should be used for squat depths less than 90° of knee flexion.

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CHAPTER FOUR

PATELLOFEMORAL JOINT LOADING IN FEMALES
DURING BACK SQUATS WITH
VARYING STANCE WIDTHS

Contribution of Authors and Co-Authors

Manuscript in Chapter 4

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Contributions: Thesis advisor; oversaw study design, data analysis, and writing

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Introduction

Back squats are a foundational exercise to strength and conditioning programs in athletics.¹ Whether for rehabilitation or training, the exercise helps develop knee and hip musculature – particularly the quadriceps and gluteal groups. Concerns about sport-specific strength requirements and knee safety have led to a variety of philosophies about squat technique.² The back squat technique refers to holding a barbell behind the neck, resting on the trapezius muscles. Common back squat variations include the depth to which a squat is performed, and the weight, stance width, or foot turnout used during the squat. In rehabilitation settings, squats are often unweighted and restricted to less than 60° of knee flexion. In athletics, sport specificity brings a wide variation with loads from 50-85% of a 1-repetition maximum (1RM) and common depths of full (hamstrings to gastrocnemius), parallel (thigh segment parallel to the ground), or 90° of knee flexion. No matter the environment, the back squat is used to strengthen lower extremity musculature, often involving a weight load and many repetitions.

The loaded, repetitive movement nature of the back squat raises concerns regarding the potential for overuse tissue injury.^{3,4} One specific concern is risk to the patellofemoral joint from increasing patellofemoral joint stress (PFJS). Patellofemoral pain syndrome is linked to increased PFJS,^{5,6} is the most common orthopedic knee injury in active populations, and is over two times more prevalent in females than males.⁷ The syndrome can chronically cause pain during both sedentary and non-sedentary daily activities.⁸ Furthermore, patellofemoral pain syndrome is difficult to manage because if pain is limiting activity, loss of strength in hip and knee musculature – especially the

quadriceps – can make the symptoms worse.⁴ To treat patellofemoral pain syndrome, exercises are needed to strengthen the musculature around the knees and hips, while not exacerbating symptoms.

Previous research has assessed how PFJS changes in females when alterations are made to how the back squat is performed. Several studies have assessed squat depths and squat loads and discovered that PFJS is affected most by load.^{9–11} However, stance width may also change PFJS during the back squat. Although difference in knee flexion and moments with varying width have been reported,^{12–16} at present, we are not aware of any published literature that addresses PFJS and stance width. In bodyweight squats, one study found that a large stance width can decrease sagittal plane moments at the knee and hip.¹³ In research by Lorenzetti et al.,¹⁵ a wide stance with 42° of foot turnout produced greater knee moments than a medium or narrow stance in any of the tested foot turnouts (0°, 21°, and 42°). Whether these results translate to traditional squats is debatable as, the amount of turnout as natural and recommended turnout during squatting is typically between 0° and 30°.¹⁷ Finally, another study showed how at different stance widths there was a change in relative joint angles of the ankle, knee and hip such that wider stances decreased the amount of flexion at each joint.¹² Inherently, shifting how joint angles change relative to one another may alter the force distribution and moment arms during the squat, possibly affecting PFJS.

Given that the back squat is a common exercise for knee and hip strengthening, is a key component of many conditioning or rehabilitation programs, and that relatively little is known about how altering stance width affects patellofemoral joint loading, the

purpose of this study was to evaluate how stance width and load impact knee extensor moments (KEM), patellofemoral joint reaction forces (JRF), and PFJS in recreational females athletes during the squat. Four stance widths (natural and 90%, 110%, and 120% of natural) with foot turnout held constant and two loads (35% and 85% of each participant's 1RM) were used. It was hypothesized that the widest (120%) and narrowest (90%) stances would have the highest PFJS and that PFJS would increase with added load.

Methods

Twenty-six recreational weight-lifting females were recruited from the university campus and community (age: 23.1 ± 3.6 years, mass: 64.77 ± 8.67 kg; height: 1.66 ± 0.07 m; 1RM: 157.9 ± 33.1). Participants were physically active, had at least 1-year total of back squat experience, and no back or lower extremity injuries in the past 1 year. Participants were visually assessed during the 1RM measurement session and included in the study if they could squat to a depth where the inguinal crease aligned with the base of the patella (thigh segment parallel to the ground) while maintaining a neutral spine position and without visible valgus knee collapse.¹⁷ Participants were asked to avoid intense activity 24 hours prior to their laboratory visits. Prior to participation all participants provided written informed consent and the university's Institutional Review Board approved all study procedures.

Two laboratory visits were conducted per participant: first for a 1RM measurement and second for the data collection with motion capture. A pair of minimalist

running shoes was provided for each participant to control for footwear. At both sessions, participants warmed up by jogging for 2 minutes and then performed 10 body-weight squats and squats with an unloaded barbell. In the first visit, the 1RM was determined using protocols recommended by the National Strength and Conditioning Association.¹⁷ A warmup of three squats at approximately 50% and at 70% of the estimated 1RM were completed and then single-squat attempts for 1RM began, increasing load by 10-20% of bodyweight until failure. Participants rested for at least two minutes between attempts. All 1RM attempts were performed to thighs parallel to the ground ($\sim 110^\circ$ knee flexion), so that the inguinal crease aligned with the base of the patella as described earlier. Safety bars were set to ensure a consistent depth such that participants lightly touched the barbell to the safety bars when full depth was reached. Following the 1RM measurement, participants' natural stance width and foot turnout were recorded.

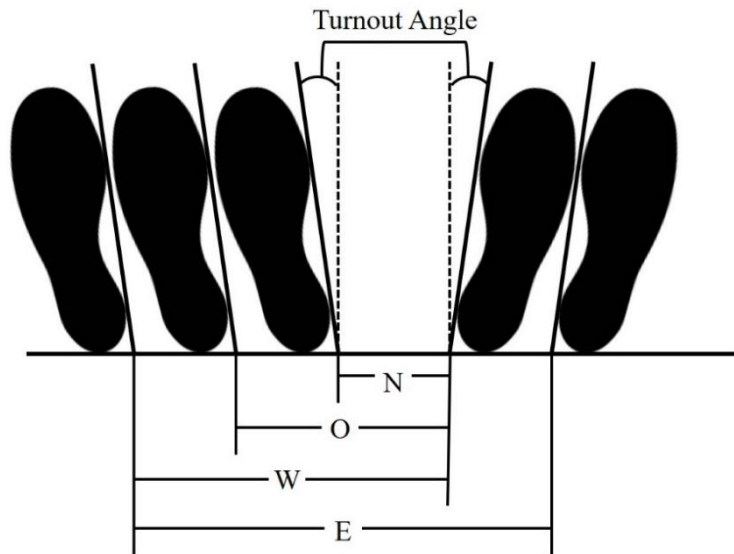


Figure 6. Four stance widths were used based on the participants natural stance width (O) and then 90% (N), 110% (W), and 120% (E) of that width. Foot turnout for right and left feet was held at a constant angle for each stance.

At least 48 hours after the 1RM session and no more than 10 days later, participants returned to the laboratory for the measurement visit. A 10-camera motion capture system (Motion Analysis, Santa Rosa, CA, USA) sampling at 200 Hz recorded kinematic data while a force plate (Optima, AMTI, Watertown, MA, USA) under each foot recorded ground reaction force at 1000 Hz. Stance widths and foot turnout were taped out as a guide based on the measurements from the 1RM session so that when the participant was in each position the tape lined the medial border of the foot (Figure 6). The turnout angle for each foot was kept the same for each stance width. The narrow (N) stance was 90% of original (O) stance measure, wide (W) was 110%, and extra wide (E) was 120%. The loads used were 35% and 85% of the 1RM. In total, eight conditions were assessed in a randomized order, with two consecutive squats performed per condition.

A torso and lower body reflective marker set was used, which included foot, shank, thigh, pelvis, and trunk segments. Markers were placed bilaterally on the heads of the 5th and 1st metatarsals, the posterior calcanei, medial and lateral malleoli, medial and lateral femoral epicondyles, anterior and posterior superior iliac spines, and the acromion processes. Additional tracking markers were placed on the iliac crests, the manubrium, a headband, and linearly along the barbell. Tracking clusters of four non-colinear markers were utilized on the lateral shanks and thighs.

Marker trajectories and ground reaction forces were exported to Visual 3D (C-Motion, Inc., Rockville, MD) where they were filtered using zero-lag Butterworth filters with cutoff frequencies of 6 and 30 Hz, respectively. Cutoff frequencies were determined

using residual analysis.¹⁸ Joint angles were calculated using a Cardan rotation sequence corresponding to flexion/extension, ab/adduction, and internal/external rotation. Knee extensor moments were calculated using standard inverse dynamics techniques and a 6-degree of freedom model. Knee flexion angles and KEMs were exported to a custom Matlab (Mathworks, Natick, MA) program to calculate JRF and PFJS using previously described methods.^{9,10,19}

For this approach, the quadriceps force (F) was first calculated:

$$F = \frac{KEM}{L}$$

where L is the effective moment arm of the quadriceps muscle from an equation by van Eijden et al.²⁰ that varies with knee flexion angle (θ) for angles 0°-120°:

$$L = 8.0E^{-5}\theta^3 - 0.013\theta^2 + 0.28\theta + 0.046$$

Next the JRF was calculated by multiplying F by a constant k, also described by van Eijden et al.²¹ in a different study, and also varying with knee flexion angle (θ) for angles 0°-120°:

$$k = \frac{4.62E^{-1} + 1.47E^{-3}\theta^2 - 3.84E^{-5}\theta^2}{1 - 1.63E^{-2}\theta + 1.55E^{-4}\theta^2 - 6.98E^{-7}\theta^3}$$

To obtain PFJS, JRF was divided by patellofemoral contact area (CA), which was determined by as a function of knee joint angle by fitting a third order polynomial ($R^2=0.94$) to cadaveric data from Matsuda et al.²² This particular study was used as they provide contact areas up to 135° of knee flexion. Finally, PFJS was determined:

$$PFJS = \frac{JRF}{CA}$$

A width-by-load (4x2) repeated measures analysis of variance (ANOVA) was used to assess differences in peak KEM, JRF, and PFJS across conditions. A one-way ANOVA for stance widths was used to evaluate differences between stance widths. All statistics were completed in SPSS using a significance level an alpha of $p < 0.05$.

Results

The four stance widths were all significantly different from each other ($F_{3,23} = 9.272$, $p < .001$). The average narrow stance width was 29.6 ± 5.9 cm, normal was 32.8 ± 6.6 cm, wide was 36.1 ± 7.2 cm, and double-wide was 39.4 ± 7.9 cm. Average left foot turnout was $10.1 \pm 6.2^\circ$ and average right foot turnout was $12.8 \pm 6.4^\circ$.

There was no width-by-load interaction for peak KEM ($F_{3,75} = 1.06$, $p = .374$, $\eta^2 = 0.040$), nor a main effect of stance width ($F_{3,23} = 0.361$, $p = .782$, $\eta^2 = 0.045$). However, there was a main effect of load ($F_{1,25} = 75.76$, $p < .001$, $\eta^2 = 0.752$), where heavier loads resulted in higher peak KEM (Figure 7).

There was no width-by-load interaction for peak JRF ($F_{3,75} = 0.337$, $p = .799$, $\eta^2 = 0.013$), no effect of width ($F_{3,23} = 0.806$, $p = .504$, $\eta^2 = 0.095$). A main effect of load was

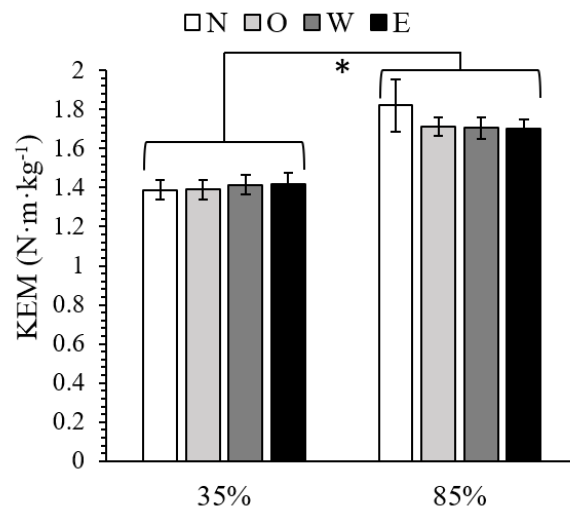


Figure 7. KEM grouped by 35% 1RM and 85% 1RM loads for widths of 90% (N), 100% (O), 110% (W), and 120% (E) of natural stance width. Significant differences for $p < 0.05$ are indicated by *.

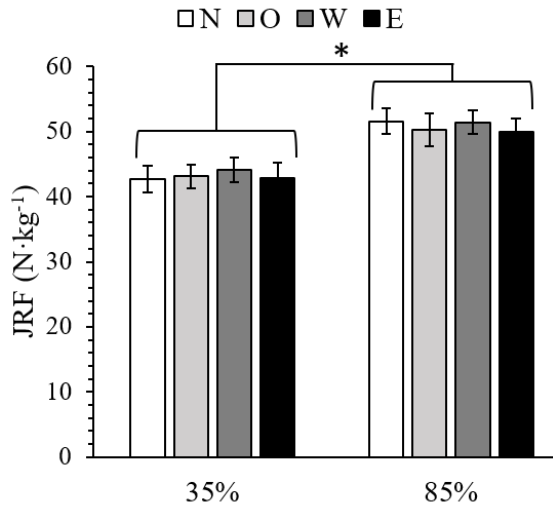


Figure 8. PFJS grouped by 35% 1RM and 85% 1RM loads for widths of 90% (N), 100% (O), 110% (W), and 120% (E) of natural stance width. Significant differences for $p < 0.05$ are indicated by *.

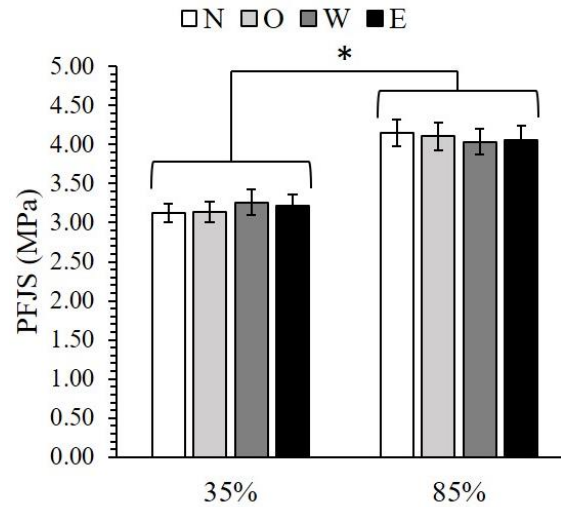


Figure 9. JRF grouped by 35% 1RM and 85% 1RM loads for widths of 90% (N), 100% (O), 110% (W), and 120% (E) of natural stance width. Significant differences for $p < 0.05$ are indicated by *.

found for JRF ($F_{1,25} = 41.896$, $p < .001$, $\eta^2 = 0.626$), where heavier loads resulted in higher peak JRF (Figure 8).

There was no width-by-load interaction for peak PFJS ($F_{3,75} = 2.813$, $p = .045$, $\eta^2 = 0.101$), nor an effect of width ($F_{3,23} = 0.231$, $p = .874$, $\eta^2 = 0.029$). A main effect of load was also found for PFJS ($F_{1,25} = 134.86$, $p < .001$, $\eta^2 = 0.844$), where heavier loads resulted in higher peak PFJS (Figure 9).

Discussion

The study goal was to determine how peak KEM, JRF, and PFJS change when females perform back squats using different load and stance width combinations. It was hypothesized that the greater KEM, JRF, and PFJS would be observed at the 85% 1RM load and the highest PFJS would occur at the most narrow and widest stances. The

hypothesis was partially supported in that KEM, JRF, and PFJS increased with greater load, but not with altered stance width. Previous research corroborates that greater loads produce greater PFJS, but little research has assessed PFJS with varying stance widths. This study not only confirmed previous research that joint loading increases with increasing weight load, but also assessed varying stance widths and found no corresponding differences in knee joint loading.

Several studies have previously reported that peak KEM increases as load increases during the back squat. In Wallace et al.⁹ a load of 35% 1RM produced greater KEM than unloaded bodyweight squats at multiple depths between full extension and 90° of knee flexion. Flores et al.¹¹, evaluating only females squatting to three different depths (90°, parallel, and full depth) and with three different loads (0%, 50%, and 85% of 1RM), also reported that within each depth, pKEM increased as load increased. In experience male lifters Cotter et al.²³ also observed that peak KEM increased with load. The present study further supports these previous results and provides additional evidence that increasing load during the back squat results in an increased KEM. Because JRF is directly related to KEM, it follows that JRF results reflected KEM results. This result supported Wallace et al.,⁹ who also found that JRF increases with load.

Although it has been reported that knee loading increases with added weight, few studies have investigated the effects of back squat stance width. In contrast to the current study, a recent study by Lorenzetti and colleagues¹⁵ evaluating the effects of stance width and turnouts during the back squat and reported greater KEM when squatting at a stance width of two times anterior superior iliac spine width with a foot turnout angle of 42°. ¹⁵

However, this extreme width was much greater than those of the present study and together with the extreme turnout raises questions about the applicability of the findings to most recreational athletes, especially since other turnout positions at that width did not produce significantly increased KEMs. Another study found increased KEMs were found for wider stances but because differences were slight, concluded a lack of clinical relevance.¹⁴ Considering knee and hip joints, one study found that for a wider stance there was an increase in the knee moments²⁴ while another found an increase in hip moments relative to knee moments.¹⁶ As discussed by Lahti et al.,¹⁶ changes to the ratio between hip and knee joint moments may have clinical and athletic relevance as altered stance positions may allow either the hip or knee muscles to create a greater moment. In a wider stance, the hip moment was relatively greater than the knee moment in comparison to narrower stances.¹⁶

Most studies on the back squat and stance width focus on angles and moments, so there is little research to compare to for JRF. The same is true for PFJS, but the method used to find PFJS provides some insight to why PFJS did not change with stance width. First, the contact area data was determined based on cadaver data which assumed no foot turnout or tibiofemoral rotation.²² Hefzy et al.²⁵ addressed this concern by finding patellar contact area at different tibial rotation angles and discovered that with lateral tibial rotation, the patella was displaced and tilted more laterally when extending from 90° to 0°. However, though patella position differed, the total contact area was not significantly changed.²⁵ Thus, in the current study, even though participants' patellar displacement or tilt might change, the overall contact area throughout the squat remains relatively

consistent with the cadaver data used to estimate CA.²² Thus, with their natural turnout held constant for each stance width, participant's patella displacement and tilt during the back squats was assumed to still reasonably fit the contact area data used.²²

Second, the PFJS equation accounts for the force of the quadriceps as a group. However, when looking at the individual quadriceps by surface electromyography, a change in quadriceps activity with stance width has not been observed.^{26,27} Because varying stance width is sometimes referenced as a way to target different quadricep muscles, two studies used surface electromyography on the quadricep group and found no differences in the activation of vastus medialis, rectus femoris, or vastus lateralis with altered squat stance width.^{26,27} Instead, the only changes were found in increased adductor and gluteus maximus activation for wide stances.^{26,27} With no reason to expect a change in the relative activation of the quadriceps muscles or total quadriceps muscle activation at different stance widths, the total quadricep force used to calculate PFJS may not change with width. Together with no change in total patella contact area, the result that PFJS does not change with stance width is reasonable.

The knowledge that PFJS does not change with stance width by the calculations provides a crucial foundation for understanding how to use the benefits of squatting as a strength exercise while not exacerbating patellofemoral pain syndrome symptoms. Although the overall PFJS may not change with stance width, where the stress is concentrated may change. For example, although total contact area does not change, during knee flexion there is an increase in lateral patellar articular surface contact with lateral tibial rotation and vice versa for medial rotation.²⁵ Elias et al.²⁸ also looked at Q-

angle and found that for three of four cadaver knees tested, increased Q-angle put more pressure on the lateral cartilage whereas decrease Q-angle put more on the medial cartilage. In another study, Elias et al.²⁹ found that decreased vastus medialis activity shifted greater pressure to the lateral patellar articular surface. Though these three examples do not directly address stance width, they indicate that there is some relationship between where maximum stress is located and how the lower extremity is positioned, whether intentionally or because of structural anatomy. Stance width may change some of these factors, but a next step in understanding would be to assess PFJS at different foot turnouts and to determine if electromyography is providing a true assessment of how the quadriceps pull on the patella as the limb is positioned differently. Depending on where a cartilage injury or pain from patellofemoral pain syndrome is originating from, fine-tuning a patient's position may allow a decrease of stress at the sight of inflammation while still allowing strengthening exercise.

Several factors should be considered when interpreting the results of this study. First, participants squatted at a self-selected pace, which may influence forces and moments. Participants were verbally told to be "steady" and a timer was watched by the researcher so that the participant used about two seconds on descent and two seconds on ascent. The researcher told participants to ascend or descend slower or faster based on visual assessment of the participant relative to the timer. Second, all participants were experienced with the back squat, but some were not accustomed to squatting to parallel depth and instead use a depth of 90° of knee flexion in their training. Thus, squatting to parallel depth would have been a novel motor skill for these participants. Third,

minimalist running shoes were provided to all participants in order to standardize footwear; however, some participants usually lifted in weightlifting shoes, so their starting position was less plantarflexed than in their normal lifting routine. Because of warmup squats and 1RM testing, participants had time to adjust to these variables, but their practiced movement patterns did not necessarily match the study's control of the movement. Finally, as mentioned earlier, the contact area equations are general to male and female populations and were acquired from cadaver knees and together with the moment arm data do not exactly represent the individual participants. A more exact representation of PFJS under these conditions could be calculated with individualized contact area data.

Conclusion

Active females experienced with the back squat performed squats at two weight loads and four stance widths. KEM, JRF, and PFJS were evaluated for all conditions and there was a main effect of load, but not width. The results of this study support previous research that also found a main effect of load on these variables. Little research has assessed the influence of width on these variables, especially on PFJS. However, knowing that there is no apparent influence of stance width on PFJS with the present model, other factors should be assessed such as foot turnout angle. Moreover, a clinically relevant consideration is where stress is concentrated on the patella when these variables are altered and how that understanding could be used to minimize aggravation to patellofemoral pain syndrome while still strengthening the knee musculature.

Key Points

Findings: For females back-squatting, higher knee moments, patellofemoral joint reaction forces, and patellofemoral joint stresses are seen when weight load is increased. There is no apparent effect of stance width on these variables.

Implications: can be a good exercise for strengthening the quadriceps, but clinicians should be thoughtful about the weight load used.

Caution: The findings of this study are primarily focused on the patellofemoral joint, not the knee altogether. The focus of the study is on weight and stance width during the squat and does not discuss appropriate knee flexion angles.

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CHAPTER FIVE

CONCLUSIONS AND FUTURE DIRECTION

The back squat is a useful exercise in clinical and athletic populations for strengthening the quadriceps, as well as other hip and knee muscles. However, as a loaded and repetitive movement, it poses a risk to patellofemoral joint health because of the potential for high PFJS. For females especially, PFPS is a common knee diagnosis and is associated with high PFJS. However, exercises like the back squat can help strengthen the quadriceps which can help manage and improve symptoms. Consequently,

understanding how variations on back squat technique may decrease PFJS is beneficial to individuals developing or recovering from PFPS.

In the first study (Chapter Three), the research question built upon the research of Wallace et al.¹ and Salem et al.² to assess patellofemoral joint loading, focusing on PFJS, in females back squatting with three different loads and three different depths. One key change in the study methodology in comparison to previous research was that loads were based off 1RM measured for each depth specifically. The weights were 0%, 50%, and 85% of 1RM for each depth and the depths were below parallel, parallel, and above parallel. For KEM, there was a depth-by-load interaction so that as load increased within each depth, KEM also increased. For JRF, there was a main effect of both load and depth. For PFJS, there was a depth-by-load interaction so that as load increased within each depth, PFJS also increased. Through the results of the study, in order perform squats for strength with the least PFJS, unloaded full range of motion squats or loaded squats to less than 90° are recommended.

To follow-up the findings on back squat depth and load, another simple modification is stance width. Detailed in Chapter Four, females back squatted to parallel depth with two weight loads and four stance widths. A heavy and light load (85% and 35% 1RM) were determined based on 1RM testing to parallel squat depth. Stance widths were based on 90%, 100%, 110%, and 120% of the natural stance measured when squatting to parallel. Foot turnout was held constant for each stance width. There was a main effect of load for KEM, JRF, and PFJS, but no effect of stance width. Although no

main effect of stance width was observed, the result provides a baseline for further studies.

Altogether, this research suggests that lightening the weight load is the primary way to decrease PFJS and other knee loading when back squatting. In both studies there was a main effect of load for KEM, JRF, and PFJS. For depth, there was an interaction between load and depth so that within a depth, greater loads resulted in greater PFJS. However, there was no influence of width on any of the knee loading investigated. Given these overall results, it is recommended that clinicians and coaches consider weight load when using the squat exercise with individuals showing signs of or recovering from PFPS. The individual's stance width and turnout should be unaltered from what is most natural and comfortable. Finally, based on the present findings and previous studies, full range of motion squats are best unloaded, and squats to less than 90° are best for adding load.

The next step to understanding how PFJS changes with modifications to back squat technique is to assess PFJS during the back squat when altering stance width and turnout. Most simply, because there is little research on stance width, replication is necessary. Second, turnout naturally changes as individuals change their stance, but to control variables foot turnout was held constant for this research. Finally, some research has suggested that contact region and potentially area may change with tibial rotation.³ With further understanding of the relationship between foot turnout position and tibial rotation, there is potential that foot turnout may effect PFJS.

From a methodological perspective, there are several issues with current assessments of PFJS. To truly understand patellofemoral joint loading, an individualized and improved model is needed. The method used in this research relied on cadaveric data for moment arm⁴ and patellofemoral contact areas, and on inverse dynamics to calculate an overall quadriceps force. Although other methods use musculoskeletal modeling with inverse dynamics or static optimization to get more specific muscle forces, for slow movements like the squat, the results differ little.⁵ Beyond muscle force, the second major component of PFJS calculations is patellofemoral contact area; however, an understanding of how the patella articulates and tracks throughout knee flexion must be individualized to gain a true understanding of what occurs. At present, the resources necessary to gain this information are inaccessible for most laboratories.^{4,6} Thus, until individualized methods can become more readily available, we must continue to gain insights through generic models that will provide the basis for how to proceed when the opportunity to create individualized models arrives.

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