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Hamstrings Loading Contributes to Lateral Patellofemoral Malalignment and Elevated Cartilage Pressures: An In Vitro Study

John J. Elias, PhD¹, Marcus S. Kirkpatrick, MD¹, Archana Saranathan, MS^{1,2}, Saandeep Mani, MS^{1,2}, Laura G. Smith^{1,2}, and Miho J. Tanaka, MD³

¹Department of Orthopaedic Surgery, Akron General Medical Center, Akron, OH, USA

²Department of Biomedical Engineering, University of Akron, Akron, OH, USA

³Department of Orthopaedic Surgery, Johns Hopkins University, Baltimore, MD, USA

Abstract

Background—Hamstrings loading has previously been shown to increase tibiofemoral posterior translation and external rotation, which could contribute to patellofemoral malalignment and elevated patellofemoral pressures. The current study characterizes the influence of forces applied by the hamstrings on patellofemoral kinematics and the pressure applied to patellofemoral cartilage.

Methods—Ten knees were positioned at 40°, 60° and 80° of flexion in vitro, and loaded with 586 N applied through the quadriceps, with and without an additional 200 N applied through the hamstrings. Patellofemoral kinematics were characterized with magnetic sensors fixed to the patella and the femur, while the pressure applied to lateral and medial patellofemoral cartilage was measured with pressure sensors. A repeated measures ANOVA with three levels, combined with paired t-tests at each flexion angle, determined if loading the hamstrings significantly ($P < 0.05$) influenced the output.

Findings—Loading the hamstrings increased the average patellar flexion, lateral tilt and lateral shift by approximately 1°, 0.5° and 0.2 mm, respectively. Each increase was significant for at least two flexion angles. Loading the hamstrings increased the percentage of the total contact force applied to lateral cartilage by approximately 5%, which was significant at each flexion angle, and the maximum lateral pressure by approximately 0.3 MPa, which was significant at 40° and 60°.

Interpretation—The increased lateral shift and tilt of the patella caused by loading the hamstrings can contribute to lateral malalignment and shifts pressure toward the lateral facet of the patella, which could contribute to overloading of lateral cartilage.

Keywords

patellofemoral joint; hamstrings; kinematics; pressure; cartilage

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Corresponding Author: John J. Elias, PhD, Calhoun Research Laboratory, Akron General Medical Center, 400 Wabash Avenue, Akron, OH 44307, Phone: (330) 344-6176, Fax: (330) 344-2336, jelias@agmc.org.

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Introduction

Patellofemoral pain is commonly attributed to lateral malalignment. The forces applied to the patella by the quadriceps muscles and the patellar tendon have a lateral orientation and apply a moment acting to tilt the patella laterally. An anatomical abnormality, such as femoral anteversion or tibial torsion, can increase the lateral orientation of the patellar tendon and lead to malalignment. Excessive lateral shift and tilt can increase the pressure applied to cartilage on the lateral facet of the patella. Overloading the lateral cartilage can lead to cartilage degradation, and eventually arthrosis (Fulkerson, 2004). Pain can develop due to overloading of the subchondral bone (Fulkerson, 1990; Fulkerson, 2002).

In addition to anatomical abnormalities, variations in tibiofemoral kinematics influence the orientation of the patellar tendon. In particular, increased posterior translation and external rotation of the tibia can contribute to patellofemoral disorders (Kumagai et al., 2002; Li et al., 2002). Posterior translation of the tibia increases the posterior orientation of the patellar tendon, which has been related to increased patellar flexion in vivo (Siesler and Sheehan, 2007) and can increase patellofemoral compression. External rotation increases the lateral orientation of the patellar tendon, which has been related to lateral translation of the patella (Sheehan et al., 2009) and elevated patellofemoral pressures (Lee et al., 2001). In vitro studies have indicated that loading the hamstrings muscles causes tibial posterior translation and external rotation (Kwak et al, 2000; Li et al., 1999; MacWilliams et al., 1999; Yoo et al., 2005), increasing the flexion and lateral translation of the patella (Kwak et al, 2000). Loading the hamstrings has also been shown to increase the maximum patellofemoral pressure (Li et al., 2004), although the previous study did not indicate if the pressure increase was primarily due to an increase in compression or to lateral malalignment.

The existing biomechanical data suggests that hamstrings activation could exacerbate patellofemoral disorders. Further characterization of the influence of the hamstrings on patellofemoral function could help improve treatment methods for patients with patellofemoral pain related to malalignment. The current in vitro study was performed to characterize how hamstrings loading influences patellofemoral kinematics and the patellofemoral pressure distribution within a model representing a malaligned patellofemoral joint. The hypothesis of the study is that loading the hamstrings will increase the lateral shift and tilt of the patella, as well as shift pressure from the medial cartilage to the lateral cartilage of the patella.

Methods

In vitro experimental design

Ten unembalmed cadaveric knees from ten separate donors were tested in vitro to address the hypothesis. Previous in vitro studies provided variations in the lateral shift (Kwak et al., 2000) and peak patellofemoral pressure (Li et al., 2004) that could be expected due to loading the hamstrings. A power analysis for paired comparisons based on the previous data, performed at a power of 0.9 and a significance of 0.05, indicated that 10 specimens would be sufficient to identify significant differences related to loading the hamstrings on the order of 0.3 mm for the lateral shift and 0.2 MPa for the peak pressure, with standard deviations for the differences between the two loading conditions 15% smaller than the mean differences (Faul et al., 2007). The average age (standard deviation) was 66 (12) years, and four of the knees were from female donors. Each knee was stored at -20 °C prior to dissection. The knees were dissected to remove the skin, adipose tissue and the muscle tissue other than the tendon attachments for the quadriceps muscle group, the semimembranosus, and the biceps femoris. The lateral retinaculum was sectioned for insertion of the pressure sensors, and the patellofemoral cartilage was inspected to exclude

knees with extensive cartilage fibrillation or areas of exposed bone, although some softening was allowed due to the age of the specimens. The influence of the lateral release on joint function was considered to be minimal, since the lateral force applied to the patella was elevated to represent malalignment. Also, a previous in vitro study indicated that, for normal loading, a lateral release has no significant influence on patellar medial translation and increases medial tilt by approximately 1° over the flexion range used for the current study, with the change having no significant influence on the maximum pressure (Ostermeier et al., 2007). The medial retinaculum was left intact as a constraint against lateral patellar translation. The tendon attachments for the vastus medialis obliquus (VMO) and the vastus lateralis (VL) were separated from the combination of the vastus intermedius/vastus medialis longus/rectus femoris (VI/VML/RF). Lateral malalignment was simulated by osteotomizing the tibial tuberosity and shifting the tuberosity laterally (Kuroda et al., 2001; Mani et al., in press). The tuberosity was secured back on the tibia with two screws and nuts. The average tibial tuberosity-trochlear groove distance, which was measured with the knee in full extension as the lateral distance from the deepest point of the trochlear groove to the patellar tendon attachment, was 19 (1) mm, which is approximately 5 mm larger than the average value in asymptomatic knees (Alemparte et al., 2007; Schoettle et al., 2006). The alignment of the fibula with respect to the tibia was fixed with a cable tie.

Each knee was secured to a testing frame consisting of two acrylic plates connected by a hinge, fixtures for positioning the knee, and fixtures for loading the quadriceps and hamstrings muscles (Fig. 1). Smooth rods made of Garolite were inserted into the diaphysis of the femur and tibia. The femur was secured to the testing frame in a horizontal orientation, as described previously (Elias et al., 2009; Mani et al., in press). The tibial rod was passed through a nylon slotted fixture on the plate that controlled the flexion angle. Contact between the tibial rod and the fixture constrained extension, with only the relatively low friction between the two pieces of plastic constraining the other degrees of freedom. The orientation of the plate that determined the flexion angle was set to position the tibia at approximately 40° , 60° and 80° of flexion when the quadriceps were loaded. Over this flexion range, the patella was sufficiently constrained within the trochlear groove to simulate lateral malalignment without the risk of lateral dislocation, and the point of contact shifted from the distal to the proximal patella (Elias et al., 2009; Mani et al., in press). The knees were kept moist with 0.9% saline solution while on the testing frame.

The knees were loaded with forces applied through only the quadriceps muscles, and with the quadriceps loaded in combination with the hamstrings. Straps made from cotton webbing with a nylon core were sutured into the isolated tendon attachments. The straps were secured to loading cables that passed over pulleys and were connected to weights. The cable representing the VI/VML/RF was aligned along the axis of the femur. The VMO cable was aligned at an angle of approximately 47° medial to the axis of the femur in the coronal plane, and the VL cable was aligned at an angle of approximately 19° lateral to the same axis (Farahmand et al., 1998), with the anatomical orientation in the sagittal plane also represented. The loading cables for the semimembranosus and the biceps femoris had proximal orientations from the attachment points on the tibia. As described previously (Elias et al., 2009), loads were applied to produce a physiologically realistic loading condition for patients with patellofemoral pain at each flexion angle, with the force applied by the VMO decreased by approximately 50% from a normal loading condition to represent a weak VMO that has been associated with patellofemoral pain. The loading cables representing the VI/VML/RF, the VL and the VMO were loaded to 432 N, 127 N and 27 N, respectively. The hamstrings forces were applied immediately after the measurements were recorded with the quadriceps loaded, with 200 N divided equally between the semimembranosus and the biceps femoris based on a previously measured ratio of quadriceps to hamstrings forces during in vitro simulation of weight-bearing knee extension (Elias et al., 2003).

Kinematic measurements

The position and orientation of the patella with respect to the femur was characterized using sensors from a pulsed DC magnetic tracking system (trakSTAR, Ascension Technology, Burlington, VT). Sensors were secured to the femur and patella of each knee with a set of nylon sensor holders, with the transmitter fixed near the distal end of the tibia. According to the manufacturer, the static resolutions for translations and rotations are 0.5 mm and 0.1°, respectively. A separate sensor was fixed to a digitizing probe (Sakai et al., 2000) to record the coordinates of previously described anatomical landmarks used to establish the femoral and patellar reference axes with the knee in full extension (Nha et al., 2008; Sakai et al., 2000). The transepicondylar axis (x-axis, positive to the right) was identified by digitizing the most medial and lateral points on the femoral epicondyles, with the knee center positioned midway between the two points (Fig. 2). The long axis of the femur was established by digitizing two points along the midline of the posterior surface of the femoral diaphysis. The mutual perpendicular to the two axes determined the anterior-posterior axis (y-axis, positive in anterior direction), with the proximal-distal axis (z-axis, positive in proximal direction) formed from the cross-product of the transepicondylar and anterior-posterior axes. The reference axes for the patella were similarly identified based on the axis connecting the most medial and lateral points on the patella and the axis from the midpoint of the medial-lateral axis to the most distal point on the patella. By characterizing the position and orientation of the patellar and femoral reference axes with respect to the sensors fixed to the respective bones, the position and orientation of the axes were quantified throughout testing.

Patellofemoral kinematics were determined by the translations and rotations of the patellar reference axes with respect to the femoral axes, with patellar flexion, rotation about the anterior-posterior axis resulting in lateral translation of the distal pole of the patella (lateral rotation), lateral tilt, and lateral translation (shift), quantified according to the floating axis coordinate system (Grood and Suntay, 1983). The analysis focused on variations in patellofemoral kinematics caused by applying the hamstrings forces to a knee already loaded through the quadriceps muscles. With the quadriceps loaded, the resolution for the kinematic measurements determined by the orientations of the reference axes, expressed as the standard deviation about the mean for continuous measurements, was less than 0.01° and 0.05 mm for the rotations and lateral shift, respectively. If the knee was instead unloaded and reloaded, the standard deviation about the mean would have been as large as 0.3° for rotations and 0.2 mm for lateral shift.

Pressure measurements

Patellofemoral forces and pressures were measured using thin film sensors (I-Scan 5051, Tekscan, Boston, MA). The sensors are 0.1 mm thick with 44 rows and columns of force-sensing elements, or sensels, every 1.27 mm. The sensors were lubricated with surgical jelly for calibration and the in vitro measurements to minimize shear loads acting on the sensor (Elias et al., 2009). Calibration was performed on a material testing machine, with each sensor sandwiched between two two steel plates and two sheets of neoprene rubber, as described previously (Elias et al., 2009). A second order polynomial related the raw output from each sensor to the applied force. Based on the calibration of the system, the resolution for pressure measurements was approximately 0.05 MPa. The reproducibility for patellofemoral pressure measurements has previously been measured at less than 0.1 MPa (Li et al., 2004). During testing, a sensor was positioned to cover the entire patellofemoral contact area. To identify the position of the patellar ridge on the sensor, the VMO and VL were loaded and the pressure pattern was recorded while palpating the portion of the patellar ridge that was accessible, with the sensor between the patella and the palpating finger. Force and pressure distributions were characterized in terms of the lateral force percentage and the

maximum lateral and medial pressure. The lateral force percentage was quantified as the percentage of the total contact force applied to cartilage lateral to the patellar ridge. For the maximum medial and lateral pressure, the maximum force applied to the medial and lateral cartilage, respectively, was divided by the sensel area. The maximum medial and lateral pressure measurements excluded a 5 mm wide band characterized as the patellar ridge. For each test, the sensor output was recorded at 10 Hz for 10 seconds following application of the muscle forces, with the data averaged to create a single pressure profile.

Statistical analysis

The kinematic parameters, the lateral force percentage and the maximum medial and lateral pressures were compared between the two loading cases. For each knee, the difference between the two loading conditions was calculated at each flexion angle for each output parameter to determine the standard error of the mean difference between the loading conditions. A repeated measures ANOVA with three levels, with repetition on the loading condition and the three flexion angles representing the three levels, was used to determine if any of the output varied significantly ($P < 0.05$) between the two loading conditions. When a significant difference between the two loading conditions was identified, two-tailed paired Student's t-tests were performed at each flexion to further identify the angles at which the changes were significant.

Results

Loading the hamstrings increased the patellar flexion, lateral tilt, lateral rotation and lateral shift of the patella with respect to the femur (Fig. 2). The average patellar flexion increased by a minimum of 1.0° , with the increase statistically significant at each flexion angle (Table 1). The significant increases in the average lateral rotation, at 80° , and tilt, at 40° and 60° , were approximately 0.5° . The increase in the average lateral shift was 0.2 mm at 60° and 80° , with the change significant at both flexion angles.

Loading the hamstrings shifted force and pressure toward the lateral facet of the patella (Fig. 3). With the quadriceps loaded, on average, at least two-thirds of the total compression was applied to the lateral cartilage at each flexion angle (Table 2). Loading the hamstrings increased the average lateral force percentage by at least 5% at each flexion angle, with each change statistically significant. The average maximum lateral pressure increased significantly by 0.3 MPa at 40° and 60° . Although the decrease in the maximum medial pressure was significant based on the repeated measures ANOVA including all three flexion angles, the decrease was not significant when the flexion angles were considered individually.

Discussion

The current data indicates that forces applied by the hamstrings could contribute to lateral malalignment of the patella. Previous in vitro studies have shown that loading the hamstrings shifts the tibia posteriorly and rotates the tibia externally (Kwak et al, 2000; Li et al., 1999; MacWilliams et al., 1999; Yoo et al., 2005), increasing the posterior and lateral components of the orientation of the patellar tendon. In vivo studies have shown a relationship between tibial posterior translation and increased patellar flexion (Siesler and Sheehan, 2007) and between tibial external rotation and lateral patellar shift (Sheehan et al., 2009), although relationships characterized in vivo are not as strong as those identified in vitro due to limited control of applied muscle forces. The current study showed the expected increased patellar flexion and lateral shift due to the influence of the hamstrings on tibiofemoral kinematics, but also showed increased lateral tilt and rotation of the patella, most likely due to external rotation of the tibia. Similar to the current study, a previous in

vitro study indicated that hamstrings loading increases patellar flexion, lateral shift, and lateral rotation by approximately 1° , 0.5 mm, and 0.8° , respectively (Kwak et al, 2000), but lateral tilt was not quantified. The previous study did not include anatomical conditions that contribute to patellofemoral malalignment. The changes in lateral shift and tilt are particularly important due to the influence on the distribution of force and pressure between the medial and lateral facets of the patella. Increased lateral shift within a malaligned patellofemoral joint can also increase the risk of lateral subluxation or dislocation.

The current data also indicates that forces applied by the hamstrings could contribute to overloading of lateral cartilage for patients with lateral malalignment. The increases in the lateral force percentage and maximum lateral pressure related to loading the hamstrings logically follow from the increased lateral shift and tilt of the patella. The maximum medial pressure did not decrease consistently when the hamstrings were loaded, likely due to the increased posterior orientation of the patellar tendon increasing patellofemoral compression. Similar to the current study, loading the hamstrings has previously been shown to increase the maximum patellofemoral pressure by approximately 0.2 MPa in vitro (Li et al., 2004). The previous study did not distinguish between medial and lateral contact forces and pressures to show that the primary change is related to contact shifting from medial to lateral cartilage, rather than a uniform increase due to elevated compression. The increase in the pressure applied to lateral cartilage could accelerate cartilage degradation and arthrosis (Fulkerson, 2004). Supporting the concern related to hamstrings loading, recent in vivo studies have shown a relationship between hamstrings tightness and increased patellofemoral pressures (Whyte et al., 2010) and pain (White et al., 2009) and between elevated hamstrings forces and patellofemoral pain (Besier et al., 2009).

In order to determine if the hamstrings could contribute to cartilage overloading in knees with lateral malalignment, anatomic conditions related to malalignment had to be simulated. The simulated VMO weakness is representative of patients with patellofemoral pain and has been shown to increase the pressure applied to lateral cartilage (Elias et al., 2009). The lateral shift of the tibial tuberosity provided an elevated TT-TG distance, which is a primary clinical parameter related to lateral malalignment (Alemparte et al., 2007; Schoettle et al., 2006). The in vitro model did not include other anatomical conditions that could contribute to lateral malalignment, such as trochlear dysplasia. Agreement between the current results and previous studies on the influence of hamstrings loading on patellofemoral flexion, lateral shift and lateral rotation (Kwak et al., 2000) and the peak patellofemoral pressure (Li et al., 2004) without representation of malalignment indicates that the trends noted for the current study may also occur for knees with normal patellofemoral alignment.

Due to the relatively small variations in the output parameters caused by loading the hamstrings, knee function was represented at individual flexion angles instead of dynamically. The hamstrings force was added at each flexion angle without unloading the quadriceps or disturbing the magnetic sensors, allowing identification of significant variations in patellofemoral rotations and shift on the order of 0.5° and 0.2 mm, respectively. The accuracy of the variation in patellar shift is limited by the quoted translational resolution of the sensors, 0.5 mm. This resolution does not directly correspond to the resolution for patellar shift, since the position and orientation of each sensor combine to determine both the position and orientation of the reference axes fixed to the bone. For the force and pressure measurements, varying the loading condition at each flexion angle minimized artifacts between loading conditions related to wrapping the sensor around the patella and shear applied to the sensor (Elias et al, 2010). The accuracy of the pressure magnitudes are further influenced by compliance differences between the set-up used for calibration and the in vitro testing environment (Elias et al, 2010). Although the order of testing was not randomized for the loading conditions, the order should have little influence on the primary

results related to the shift in contact from medial to lateral cartilage with application of hamstrings forces. Lateral shift of the patella with respect to the sensor, and the designated position of the patellar ridge on the sensor, could have contributed to the increase in the lateral force percentage attributed to hamstrings loading, although the shift due to the hamstrings at 60° and 80° was only approximately 15% of the width of a sensel. Testing at individual flexion angles allowed application of quadriceps forces that are physiologically realistic in magnitude and distribution among the muscles of the quadriceps group for subjects with patellofemoral pain (Elias et al., 2009), along with hamstrings co-contraction representative of a weight-bearing activity (Elias et al., 2003). Only three flexion angles were tested, although the range was large enough for the pressure to shift from the distal to the proximal patella as the flexion angle increased (Elias et al., 2009). Because of the simulated lateral malalignment and VMO weakness and the large quadriceps forces, flexion angles less than 40° were not tested to avoid patellar instability. Previous studies focused on normally aligned knees showed that hamstrings loading shifts the patella laterally at full extension (Kwak et al., 2000) and increases the peak pressure at 30° of flexion (Li et al., 2004), indicating that the influence of the hamstrings is a concern at lower flexion angles.

Conclusions

The current study indicates that hamstrings contraction in a knee with lateral patellofemoral malalignment and VMO weakness contributes to the malalignment and elevated lateral pressures. The current data should be considered in assessment of appropriate rehabilitation exercises and activities for patients with patellofemoral disorders. Quadriceps strengthening is a primary component of rehabilitation, but can be performed through a variety of exercises. Hamstrings activation has been shown to vary greatly between exercises performed for quadriceps strengthening, even between various closed chain exercises (Escamilla et al., 1998; Wilk et al., 1996). Focusing on exercises and activities that minimize hamstrings activation could reduce the risk of exacerbating patellofemoral disorders related to lateral malalignment.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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Figure 1.

A schematic diagram of the testing frame. The cables applying the forces representing the quadriceps and hamstrings muscles were secured to straps sutured into the tendons. The total force applied by the quadriceps was 586 N, with 200 N applied through the hamstrings for the quadriceps plus hamstrings loading condition. The tibial tuberosity was lateralized from the normal attachment position on the tibia.

Figure 2.

Loading the hamstrings increased the flexion, lateral shift, lateral rotation and lateral tilt of the patella with respect to the femur. The transepicondylar axis is shown, along with the medial, lateral and distal points digitized on the patella. The patellofemoral kinematic changes are related to increased posterior translation and external rotation of the tibia caused by loading the hamstrings (Kwak et al, 2000; Li et al., 1999; MacWilliams et al., 1999; Yoo et al., 2005).

Figure 3.

Patellofemoral pressure distributions for two knees at all three flexion angles with and without hamstrings loading. The dashed lines represent the position of the patellar ridge for each pressure pattern. The with hamstrings condition generally shows higher pressure (darker colors) on the lateral facet and lower pressure on the medial facet than the no hamstrings conditions.

Table 1

Average patellofemoral kinematics for loading with and without hamstrings (hams).

	Flexion (deg)			Lateral Rotation (deg)			Lateral Tilt (deg)			Lateral Shift (mm)		
	No Hams	With Hams	SE of Diff	P-value	No Hams	With Hams	SE of Diff	P-value	No Hams	With Hams	SE of Diff	P-value
40°	30.1	31.1	0.2	0.002	8.4	8.4	0.3	0.8	5.3	5.8	2.4	0.3
60°	44.5	46.1	0.2	0.001	8.6	8.9	0.2	0.1	7.6	8.1	5.0	0.006
80°	59.7	61.2	0.1	0.003	8.2	8.8	0.1	0.003	10.0	10.2	7.6	0.003

SE of diff: Standard error of the mean difference between loading conditions

Bold font indicates $P < 0.05$ for a comparison.

Table 2

Average force and pressure output for loading with and without hamstrings (hams).

	Lateral Force Percentage (%)			Peak Lateral Pressure (MPa)			Peak Medial Pressure (MPa)		
	No Hams	With Hams	SE of Diff	P-value	No Hams	With Hams	SE of Diff	No Hams	With Hams
40°	67	72	1	0.001	2.1	2.4	0.04	1.8	1.7
60°	71	78	1	0.001	2.6	2.9	0.1	1.8	1.6
80°	76	81	1	0.003	2.8	3.2	0.2	1.5	1.2

SE of diff: Standard error of the mean difference between loading conditions

Bold font indicates *P* < 0.05 for a comparison.