

## Effect of bracing on dynamic patellofemoral contact mechanics

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**Abstract**—Decreases in patellofemoral pain have been demonstrated with bracing; however, the mechanisms of pain reduction remain unclear. Our purpose was to evaluate the hypothesis that patellofemoral bracing decreases peak pressure on the retropatellar surface through an increase in patellofemoral contact area. Nine cadaveric knees were tested during simulated free-speed walking with no brace, a knee sleeve, two different patellar stabilization sleeves, and a wrap-style patellar stabilization brace. Contact area and pressure were measured using a dynamic pressure sensor located in the patellofemoral joint. For the unbraced knee, contact area and peak pressure varied with knee flexion angle, ranging from  $0.30 \pm 0.3 \text{ cm}^2$  and  $1.80 \pm 1.7 \text{ MPa}$  at full extension to  $2.28 \pm 0.5 \text{ cm}^2$  and  $4.19 \pm 1.7 \text{ MPa}$  at peak knee flexion. All braces increased contact area, while the wrap-style brace decreased peak pressure ( $p < 0.001$ ). Sleeve braces compress the quadriceps tendon causing the patella to engage the trochlear groove earlier during knee flexion. The wrap-style brace reduced peak pressure by shifting the location of highest pressure to a region with increased articular cartilage thickness. Sleeve braces may be useful for treatment of patellar subluxation disorders, while wrap-style braces may be effective for treatment of disorders associated with degenerative cartilage changes.

**Key words:** biomechanics, bracing, contact pressure, gait, in vitro simulation, knee, orthotics, patellofemoral mechanics, patellofemoral pain, pressure measurement.

## INTRODUCTION

Patellofemoral pain (PFP) syndrome is defined as pain originating from the patellofemoral articulation and associated structures that excludes other intra-articular and peripatellar pathology [1–2]. Because PFP syndrome is a diagnosis of exclusion, the current clinical definition may encompass superficially similar symptoms arising from a number of discrete causes [3]. PFP is a common knee disorder in sports-related injury medicine [4–8]; however, the pathophysiology of PFP is not clearly understood [4,9].

Current literature suggests that the etiology of PFP is multifactorial [9–11] and has been closely associated with patellofemoral malalignment and maltracking [12–14]. Abnormal patellar tracking changes, particularly lateral tracking, may lead to increased patellofemoral contact pressure and subsequent activation of nociceptive fibers in the subchondral bone, resulting in pain [4,9,15–16]. Abnormalities in other factors related to contact pressure (e.g., contact area, location of pressure [15], and

**Abbreviations:** PFP = patellofemoral pain, RF = rectus femoris, SD = standard deviation, VI = vastus intermedius, VL = vastus lateralis, VM = vastus medialis.

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joint stress [4,16–17]) may also contribute to the development of PFP.

Athletes and other patients with anterior knee pain are often persistent in pursuing treatment for PFP syndrome because participation in sports and daily activities may be substantially affected by the pain [9]. Effective treatment is crucial because chronic PFP limits mobility and may lead to arthritis and permanent disability [9,18]. Perhaps due to the heterogeneous nature of PFP syndrome, effective treatments that are successful in a majority of cases have remained elusive. In a retrospective study of 250 athletes, Blønd and Hansen found that many athletes continue to have problems even after a full nonoperative treatment program [19].

Conservative treatment of PFP syndrome often includes taping or bracing for patellar realignment/stabilization [9, 20]. While previous studies have reported decreases in lateral patellar translation with bracing under static conditions [21–23] and decreased contact pressure and proximal shift of the patella with the application of infrapatellar straps [24], some studies have shown no effect on patellar alignment with bracing [25]. One recent study reported that bracing decreased both lateral tilt and translation of the patella during dynamic loading [12], and subjective improvements in knee stability and pain have been reported with bracing [8, 20, 26]. Despite clinical decreases in PFP symptoms with bracing treatment, the specific mechanism by which bracing reduces pain remains unknown. Further complicating the matter is the fact that a wide range of patellofemoral bracing products exist and each brace may employ a different strategy to achieve symptom relief. For example, a previous study has shown increased efficacy of complex patellar stabilization braces compared with simpler modalities (i.e., knee sleeve designs, neutral taping) [12], while others have shown that application of either produces a similar effect [27–28].

The purpose of this study was to compare parameters associated with patellofemoral contact pressure (contact area, peak pressure, peak pressure location, and center of pressure) during dynamic simulated knee flexion-extension under a range of conditions: (1) no brace, (2) a knee sleeve, (3) two different patellar stabilization sleeves, and (4) a wrap-style patellar stabilization brace. The hypothesis of this study was that all patellofemoral braces would increase patellofemoral contact area while decreasing peak pressure compared with the unbraced knee.

## METHODS

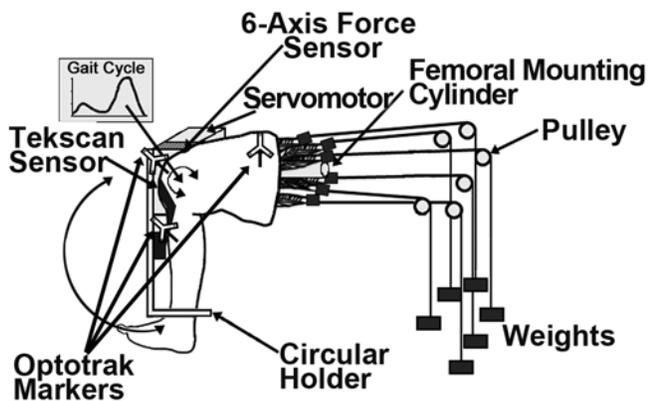
Nine fresh-frozen lower limbs (5 female, 4 male; mean age = 62.7 years, range 52 to 75 years; 3 left, 6 right) were used in the current study. Systemic or degenerative diseases were excluded by review of the donor history, and each knee was visually inspected to rule out macroscopic evidence of any previous knee surgery, substantial osteoarthritis, or apparent joint deformities. Each specimen was thawed for 24 hours at room temperature prior to testing and was regularly hydrated with normal saline. Each leg was transected just below the level of the greater trochanter. Care was taken to ensure that enough intact soft tissue was present above the knee to allow for proper brace application.

After minimal skin resection, the individual muscles crossing the knee joint (vastus medialis [VM], vastus intermedius [VI], rectus femoris [RF], vastus lateralis [VL], gracilis, sartorius, semitendinosus, semimembranosus, long and short heads of the biceps femoris, and iliotibial band) were separated from each other using fascial planes as a guide. Fiberglass mesh was sutured to the distal end of each muscle to prevent the muscle tissue from pulling apart during loading. Compliant steel cables were sutured to the mesh ends of the muscle components and were passed through adjustable pulleys to maintain the physiological line of action of each muscle [29]. Weights were hung from the steel cables to apply a load to the individual muscles. The maximum weight that could be suspended from an individual muscle was determined empirically. Based on this empirical limit, each component of the quadriceps was loaded according to the proportional physiological cross-sectional area of the muscle [30]. The total load on the extensor mechanism was 179.6 N, which was distributed such that 40, 36, and 24 percent of the load was suspended from the RF/VI, VL, and VM, respectively [29–30]. A pilot study with a single specimen was conducted to ensure proper fit of the braces during testing. A representative from the braces' manufacturer (DJO, Inc; Vista, California) was present during the pilot study to ensure proper application, tightening, and fit of the braces during pilot testing. Initially, the braces fit poorly (gapping of the posterior portion of the brace) when only the muscles of the extensor mechanism were loaded. The poor fit led to rotation of the brace about the knee during knee flexion-extension, likely due to the lack of normal muscle tension in the posterior leg. In vivo, even relaxed muscles are under tension between their origin and insertion. In

order to simulate this normal muscle tension, 0.05 kg weights were suspended from each of the individual flexor components (total flexor load = 1.5% extensor load). Simulation of normal muscle tension allowed for a more natural fit of the braces and eliminated brace slippage during testing.

The femur was secured within an aluminum cylinder using diaphyseal bolts and centered within the cylinder such that the long axis of the cylinder was representative of the long axis of the femur. In addition, the femur was positioned within the cylinder so that the physiological quadriceps-angle (Q-angle) in the frontal plane was maintained. The cylinder was then fixed rigidly to the frame of a custom knee-joint driving device such that when the knee was flexed to 90°, the tibia was perpendicular to the floor (**Figure 1**). The distal leg, just proximal to the ankle joint, was held with a circular holder that allowed small amplitude internal-external rotations and proximal-distal translations of the tibia relative to the femur. The circular holder was affixed to an aluminum plate that extended vertically from the circular holder to a servomotor attachment. The plate was affixed to the servomotor attachment via a rotating joint that allowed small amplitude abduction-adduction of the tibia relative to the femur. The entire tibial attachment mechanism was driven by a servomotor (Kollmorgen, Danaher Motion; Wood Dale, Illinois), and a 6-axis force sensor (JR3 Inc; Woodland, California) was used to measure the forces and moments exerted on the tibia throughout flexion-extension.

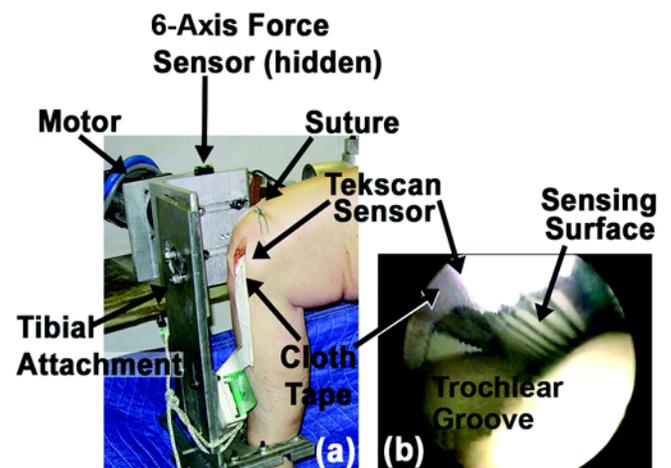
Contact area and pressure were measured using a 33 × 28 mm piezoresistive electronic pressure measuring film (K-Scan #4000, Tekscan Inc; Boston, Massachusetts)



**Figure 1.**  
Experimental setup.

[24,31]. Each sensor was individually calibrated on a custom materials-testing system. A sheet of 1/4 in. (6.4 mm) thick neoprene rubber (McMaster-Carr; Elmhurst, Illinois) was placed on either side of the sensor during calibration to simulate the compliance provided by patellofemoral cartilage [32–33]. The sensor and rubber sheets were placed under the testing platform between two steel plates to produce an area of nearly uniform pressure [32]. Following preconditioning with three loads to a minimum of 5,000 N applied over 10 seconds, a series of five loads ranging from 100 to 5,000 N were applied to the sensor, according to manufacturer guidelines. Software provided by the manufacturer (Tekscan Inc; Boston, Massachusetts) was used to determine and apply the calibration curve for each sensor.

An anteromedial parapatellar incision and removal of the infrapatellar fat pad were performed to gain access to the patellofemoral joint. The non-sensing edges of each sensor pad were trimmed and reinforced with flexible plastic and sealed with cloth tape. Sutures were passed through the reinforced areas of the sensor through the patellofemoral joint and out through the skin proximal to the knee joint (**Figure 2(a)**). The suture was then used to guide the sensor into the patellofemoral space and tied around the quadriceps tendons (**Figure 2(a)**). Suture was

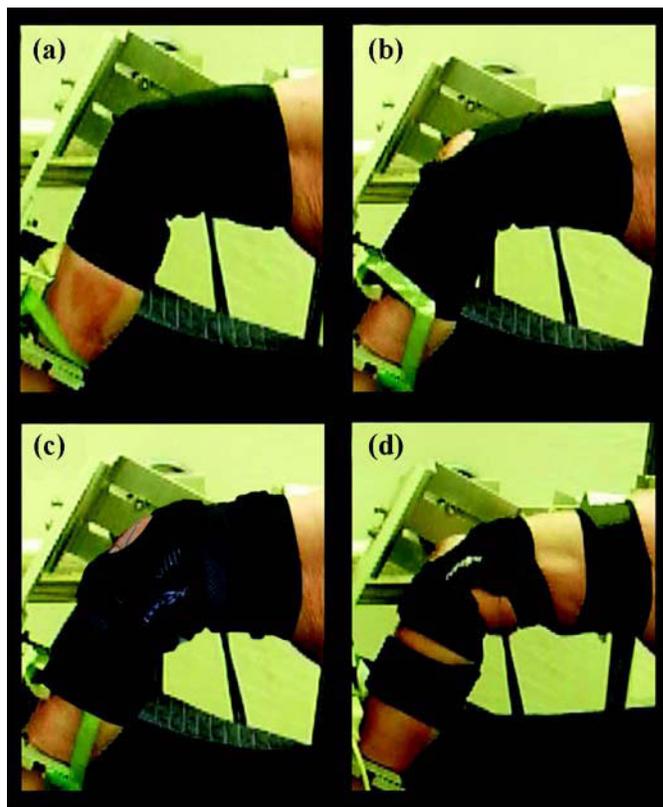


**Figure 2.**  
(a) Insertion of Tekscan surface through limited parapatellar incision. Suture was used to guide sensor onto retroapatellar surface and tied around quadriceps tendons. (b) Arthroscopy of patellofemoral joint space illustrating position of Tekscan sensor on retroapatellar surface. Arthroscopy was also used to ensure that sensor remained fixed with respect to patella during knee flexion-extension (not shown).

also passed through the distal reinforced portion of the sensor and used to anchor the sensor distally to the patellar tendon. The sensor was positioned in the joint such that it covered the posterior surface of the patella. Prior to testing, the patellar ridge was manually palpated and the position of the ridge with respect to the sensor was recorded. Small adjustments to sensor position were then made to ensure that the patellar ridge was located above the middle third of the sensor. Once the final sensor position was determined, the suture anchors were tightened; the sensor was not removed from the joint between trials. Arthroscopy was used to ensure that the sensor remained fixed with respect to the patella during knee flexion-extension (**Figure 2(b)**).

Average knee flexion angles for a gait cycle were obtained from 30 nondisabled subjects during free-speed walking [34]. The initial stance phase of the gait cycle involves knee flexion from almost full extension to approximately 15°, followed by extension again to near full extension. In the swing phase, the knee flexes to approximately 60° of flexion and then extends to the starting position of stance phase. For each dynamic trial, a servomotor was used to drive the knee through three strides. The speed of motion (3 strides in 12 seconds) corresponded to approximately one-quarter the average self-selected stride rate [35]. Prior to testing, each knee was moved through three complete range-of-motion cycles (0°–120°) for preconditioning. After preconditioning, three trials—a total of nine strides—were performed with each knee without the application of a patellofemoral brace. Nonbraced testing was performed prior to bracing the knees to minimize the effects of soft-tissue changes due to application and removal of the braces.

Each knee was then tested in each of four patellofemoral braces: a knee sleeve, two different patellar stabilization sleeves, and a wrap-style patellar stabilization brace. The knee sleeve (DonJoy Knee Support, DJO, Inc) was constructed of neoprene with no hole in the sleeve over the patella (**Figure 3(a)**). The first patellar stabilization sleeve (sleeve 1) (DonJoy Lateral “J” with 1/4 in. buttress, DJO, Inc) was constructed of a neoprene sleeve with a J-shaped buttress pad positioned inferior-lateral to the patella, a cutout over the patella, and a lateral-to-medial external stabilization strap (**Figure 3(b)**). The second patellar stabilization sleeve (sleeve 2) (DonJoy Tru-Pull Advanced with 1/4 in. buttress, DJO, Inc) was constructed of a neoprene sleeve with a C-shaped buttress pad positioned lateral to the patella, a cutout over



**Figure 3.**

Patellofemoral braces used. (a) Knee sleeve, (b) patellar stabilization sleeve 1, and (c) patellar stabilization sleeve 2 are sleeve-type braces that cover entire distal portion of quadriceps muscle. (d) Wrap-style patellar stabilization brace has continuous strap that is wrapped around knee and extends both proximal and distal to knee.

the patella, and a lateral-to-medial external stabilization strap (**Figure 3(c)**). The wrap-style patellar stabilization brace (DonJoy Tru-Pull Wraparound with 1/4 in. buttress, DJO, Inc) consisted of a bifurcated strap with a C-shaped buttress pad positioned lateral to the patella (**Figure 3(d)**). Individual braces were tested in random order to eliminate effects from previous bracing conditions. Preconditioning cycles were performed prior to testing with each brace, and then three trials were performed with each knee in each brace. Finally, to facilitate comparison of the results of the current study to published results, each knee was also tested at static knee flexion angles of 0°, 30°, 60°, 90°, and 120° for the unbraced and each braced condition.

Average values for each contact parameter (contact area, peak pressure, peak pressure location, and center of pressure) for the nine strides were obtained for each knee.

Contact parameters during unbraced trials were compared with the respective parameter for each braced trial at 5° increments using analysis of variance with repeated measures (each specimen had three paired conditions: unbraced vs knee sleeve, unbraced vs patellar stabilization sleeve, and unbraced vs wrap-style patellar stabilization brace). An alpha of 0.05 was used to test for significance. If significance was detected, Tukey's honestly significant difference test was used to further test for differences among individual groups. The flexion versus extension portions of the gait cycle were compared within conditions using a paired *t*-test. Previous studies have shown that average patellofemoral contact area are approximately 4 cm<sup>2</sup> and 5.2 cm<sup>2</sup> in unloaded and loaded knees, respectively [36]. Pilot data from the current study suggested a minimum difference in contact area between an unbraced knee and a braced knee of 0.1 cm<sup>2</sup>, or 1.9 to 2.5 percent of the average patellofemoral contact area. Assuming a standard deviation [SD] of the difference in the response of matched pairs of 0.08 cm<sup>2</sup>, a power analysis showed that nine specimens would be needed to yield a power of 90 percent. Therefore, the pilot data suggested that an effect size of 1.25 could be detected with an experimental group of nine specimens.

## RESULTS

Patellofemoral contact area moved from the distal articular surface of the patella proximally with increasing knee flexion. Testing at static knee flexion angles demonstrated no significant differences in contact area, peak

pressure, or center of pressure between the unbraced condition and any of the braced conditions.

The **Table** provides a summary of all results for each brace. For the unbraced condition, mean ± SD contact area varied with knee flexion angle and ranged from 0.30 ± 0.3 cm<sup>2</sup> at full extension to 2.28 ± 0.5 cm<sup>2</sup> at peak knee flexion (59°). Contact area was greater during knee flexion than knee extension for the unbraced knee ( $p < 0.01$ , **Figure 4(a)**) and for all braced conditions ( $p < 0.001$ ). All bracing conditions significantly increased contact area compared with the unbraced condition ( $p < 0.001$ , **Figure 5(a)**). Both patellar stabilization sleeves and the knee sleeve significantly increased contact area compared with the wrap-style patellar stabilization brace ( $p < 0.001$ ). For all braced conditions, contact area increases were most pronounced during knee extension and prior to the swing phase of the gait cycle.

For the unbraced condition, peak pressure varied with knee flexion angle, like contact area, and ranged from 1.80 ± 1.7 MPa at full extension to 4.19 ± 1.7 MPa at peak knee flexion. Peak pressure was greater during knee flexion than knee extension for the unbraced knee ( $p < 0.01$ , **Figure 4(b)**) and for all braced conditions ( $p < 0.001$ ). The wrap-style patellar stabilization brace significantly decreased peak pressure compared with the unbraced condition and all other braced conditions ( $p < 0.001$ ) (**Figure 5(b)**), particularly prior to the swing phase of the gait cycle. However, the first patellar stabilization sleeve and the knee sleeve did not significantly alter peak pressure compared with the unbraced condition. The second patellar stabilization sleeve significantly

### Table.

Summary of results for statistical tests. Each brace was primarily compared with unbraced condition. Dashes indicate no significant difference from unbraced condition. If significant difference ( $p < 0.01$ ) was found, direction of change with respect to unbraced condition is indicated. Superscript symbols indicate additional significant differences identified between bracing conditions.

Condition	Brace	Construction	Brand Name	Contact Area	Peak Pressure	M/L Center of Pressure	P/D Center of Pressure
2	Knee Sleeve	Sleeve	Knee Support	Increase*	—	Medial†	Proximal*†‡
3	Stabilization Sleeve 1	Sleeve	Lateral J	Increase**	—	Medial*§	Proximal*‡§
4	Stabilization Sleeve 2	Sleeve	Tru-Pull Advanced	Increase*†	Increase*†§	Medial*	—
5	Stabilization Brace	Wrap	Tru-Pull	Increase†‡§	Decrease†‡§	Medial†‡	Proximal†‡§

\*Significant difference from stabilization brace ( $p < 0.05$ ).

†Significant difference from stabilization sleeve 1 ( $p < 0.05$ ).

‡Significant difference from stabilization sleeve 2 ( $p < 0.05$ ).

§Significant difference from knee sleeve ( $p < 0.05$ ).

M/L = medial/lateral, P/D = proximal/distal.

increased peak patellofemoral pressure compared with the unbraced condition and all other braced conditions ( $p < 0.001$ ). In addition, the wrap-style patellar stabilization brace shifted the location of the peak pressure point proximally on the patella compared with the unbraced condition ( $p < 0.01$ ) and all other braced conditions ( $p < 0.001$ ). All other braced conditions had no significant effect on the location of the peak pressure point.

For the unbraced condition (Figure 4(c)) and all braced conditions, the center of pressure shifted medially on the patella with increasing knee flexion angle, beginning on the lateral facet of the patella and shifting to the medial facet at approximately  $30^\circ$  of knee flexion. All braced conditions significantly shifted the center of pressure medially compared with the unbraced condition ( $p < 0.001$ , Figure 5(c)). In addition, all braced conditions, except the second patellar stabilization sleeve, shifted the center of pressure proximally on the patella compared with the unbraced condition ( $p < 0.001$ ). The knee sleeve shifted the center of pressure further proximally than all other braced conditions, particularly prior to swing phase of the gait cycle (Figure 5(c)).

## DISCUSSION

The patellofemoral joint is thought to transmit some of the highest loads in the human musculoskeletal system [37]. Loads during activities such as stair climbing and squatting have been estimated to be from 3.3 to 7.6 times body weight, respectively [38]. High loads from activities such as these may exceed the tolerance of patellofemoral tissues, particularly if applied repetitively over long periods of time, resulting in pain [4]. Uninjured joints have been shown to accept from  $<1$  to approximately 8 times body weight without sustaining clinical injury [38]. However, symptomatic patellofemoral joints likely have a reduced capacity to tolerate loading [4], and loads that would not have caused injury in an uninjured joint may cause further injury to a symptomatic patellofemoral joint, creating a vicious cycle of loading and injury over time. Treatments such as bracing, infrapatellar straps, and taping are primarily aimed at correcting patellofemoral maltracking [12–13,24] or improving control of the joint through proprioceptive feedback [28]. However, the implied hypothesis is that correcting maltracking and improving joint control have the additional benefit of decreasing contact pressure in the patellofemoral joint [24,39].

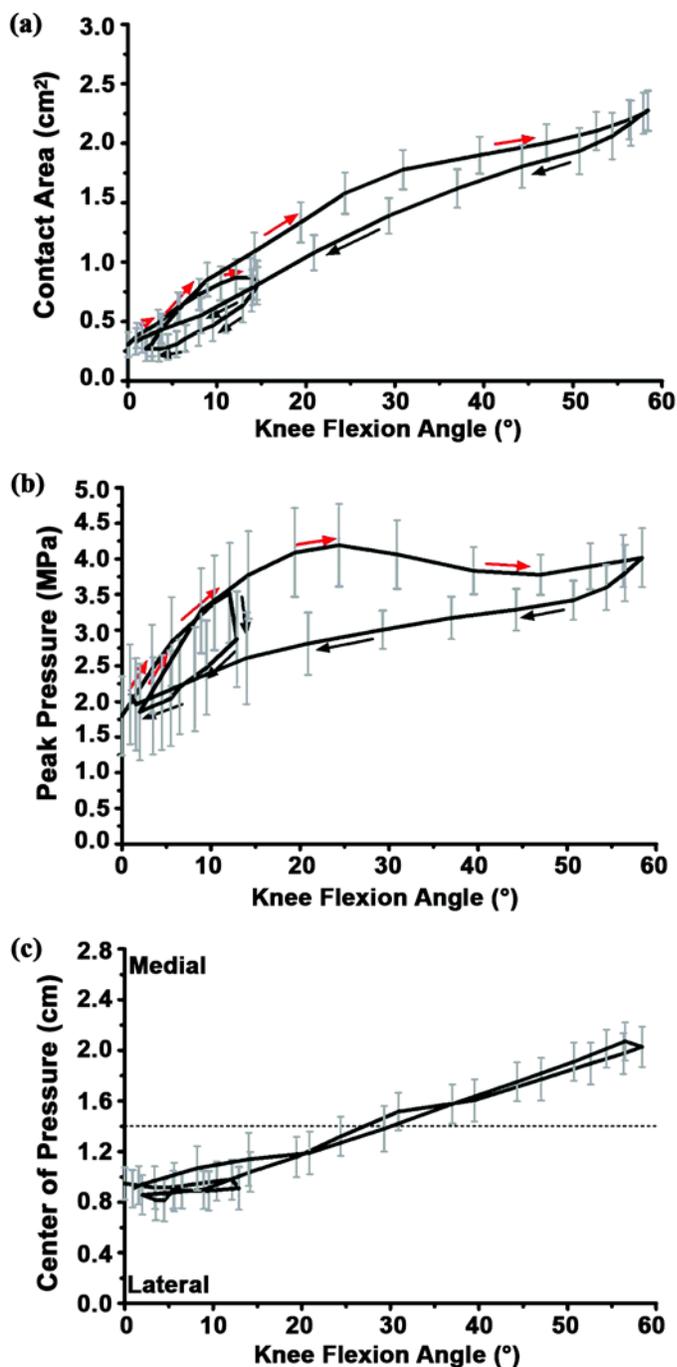
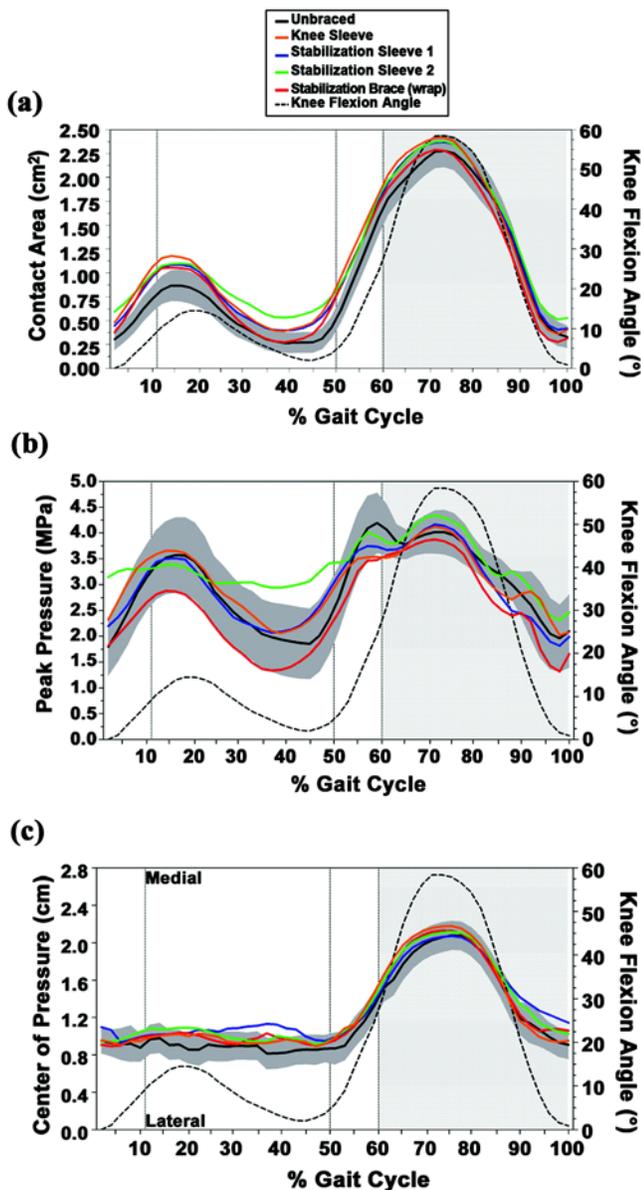


Figure 4.

(a) Mean contact area vs knee flexion angle for unbraced condition. (b) Mean peak pressure vs knee flexion angle for unbraced condition. Red arrows above line indicate knee flexion, while black arrows below line indicate knee extension. Two loops flexion/extension are shown, which represent peaks of knee flexion during stance and swing phases of gait, respectively. (c) Medial/lateral location of center of pressure for unbraced condition. Dotted line represents approximate location of patellar ridge and error bars standard error of the mean.



**Figure 5.**

(a) Dynamic results for patellofemoral contact area over stride. All bracing conditions significantly increased patellofemoral contact area when compared with unbraced condition ( $p < 0.001$ ). (b) Peak patellofemoral pressure over stride. Wrap-style patellar stabilization brace significantly decreased peak pressure compared with unbraced condition and all other braced conditions ( $p < 0.001$ ). (c) Medial/lateral shift of center of pressure over stride. All braces shifted center of pressure significantly in medial direction compared with unbraced condition ( $p < 0.01$ ). Dashed line indicates knee flexion angle plotted on right y-axis, and dark grey shading indicates standard error of the mean for unbraced condition. Vertical dotted lines indicate standard markers of gait cycle: contralateral toe-off, foot strike, and toe-off, respectively. Light grey shading indicates swing phase of gait cycle.

Knee sleeves are commonly considered the simplest form of a knee brace, as they simply provide a compressive force to the entire knee joint. Previous studies have suggested that therapeutic effects seen with these braces are due to enhanced sensory feedback rather than effects on patellar movement [27]. Proprioceptive effects have also been proposed as one mechanism for pain reduction with patellar stabilization braces [27–28]. However, in addition to joint compression, patellar stabilization braces are designed to apply a medially directed force to the patella. Therefore, another proposed mechanism for pain reduction is through reduction of joint stress due to patellar medial shift [21,39]. Joint stress (or pressure) depends on the magnitude of patellofemoral contact force and the area over which that force is distributed. Therefore, patellofemoral pressure can be reduced by decreasing the force or by increasing patellofemoral contact area. In the current study, all bracing conditions increased patellofemoral contact area. However, for the knee sleeve and the patellar stabilization sleeves, the increases in contact area were not accompanied by decreases in contact pressure. These findings suggest that while the compression applied by sleeve-type braces increases contact area, it also increases contact force, leading to no decrease in patellofemoral contact pressure. This effect may be due to the generalized compression on the quadriceps tendon complex from the sleeve design of the brace.

Compression of the quadriceps tendon complex may cause a posterior shift in the line of action of the quadriceps tendons that causes the patella to “float” less freely above the trochlear groove, thereby engaging with the groove at smaller knee flexion angles. As the lateral surface of the trochlear groove is more prominent, normal engagement of the patella with the groove first involves pressure on the lateral facet of the patella. However, premature engagement of the patella with the groove causes the medial surface to be engaged earlier, producing a medial shift in the center of pressure compared with an unbraced knee at the same knee flexion angle. Braces that provide generalized compression may be clinically useful in treating patellar subluxation and dislocation disorders, as they cause the patella to engage the trochlear groove at more extended knee positions, thereby not allowing the patella to “escape” the confines of the trochlear groove as easily as in an unbraced knee.

The contact area between the patella and the femur begins on the distal patella and migrates proximally during knee flexion [32,40]. Draper et al. found that if the articular surface of the patella is divided into three

regions—proximal, middle, and distal—the middle region is the area with the thickest articular cartilage [12]. Li et al. showed that thinner cartilage results in higher stress for the same applied load [15]. In the current study, both a decrease in magnitude and a proximal shift in location of the peak patellofemoral pressure with the wrap-style patellar stabilization brace suggest that during knee flexion, the wrap brace shifted the location of the highest pressures to a region of the patella with increased articular cartilage thickness. Furthermore, Li et al. showed that a 10 percent reduction in cartilage thickness leads to a 10 percent increase in peak hydrostatic pressure [15]. Therefore, small changes in the location of the areas of highest pressure, like those seen with the wrap-style brace, could likely lead to clinical decreases in PFP symptoms. The shift in location and magnitude of peak pressure with application of the wrap-style patellar stabilization brace suggests wrap-style braces may be effective for treatment of disorders associated with degenerative cartilage changes.

Quadriceps muscle force has been reported to be 647 N during walking and 1,923 N during stair climbing [41]. The quadriceps load of 179.6 N used in the present study is similar to those used in previous studies [31,42] and is similar to those applied in non-weight-bearing exercise. However, it remains uncertain whether increasing the applied quadriceps muscle load would have resulted in increased contact pressures in the patellofemoral joint [43], as Eilerman et al. found no difference in patellofemoral contact pressures with quadriceps muscle forces at either 647 N or 1,923 N [41]. Finally, the most important information obtained in this study is the relative change in pressure distribution between the unbraced and braced conditions. Relative pressure distribution has been shown to remain consistent with increasing load [42].

A limitation of this study is that some patients with PFP present with altered patellofemoral kinematics and architecture, which are not represented in this study. In addition, the ground reaction forces due to axial limb loading were not included in the current study. However, results from this study for a range of static knee flexion angles were similar to those of previous studies, both in vitro and in vivo [16,44–45]. Braces and taping may be effective at correcting abnormal patellofemoral kinematics only in the subset of patients with PFP who exhibit maltracking. Therefore, it is reasonable to assume that simulating the effects of bracing on a normal knee would only tend to underestimate the effect size when compared to patients with PFP and maltracking. Finally, the introduction of the pressure sensor into the patellofemoral

joint may have altered patellofemoral kinematics. However, the patterns of patellofemoral contact demonstrated in the unbraced knee in this study were similar to those reported by Huberti and Hayes [46–47] and Marder et al. [48], who used pressure-sensitive film that had an effective thickness approximately 3 times greater than that of the sensor used in the current study [46–49]. For all the comparisons in the current study, the pressure sensor was inserted into the joint prior to testing and its placement was not altered during the experiment. Therefore, differences in contact characteristics with and without bracing represent relative measurements for which the effects of the pressure sensor on joint kinematics were constant.

## CONCLUSIONS

Conservative management of PFP often includes bracing treatment. Clinical improvements in pain have been reported with bracing [8–9,20,27,50–51]; however, the specific mechanism by which bracing reduces pain is not well understood. The purpose of this study was to evaluate the hypothesis that patellofemoral braces decrease peak pressure on the retropatellar surface through an increase in patellofemoral contact area. All braces increased contact area; however, only the wrap-style patellar stabilization brace decreased peak pressure in the patellofemoral joint.

These findings suggest that while the compression applied by sleeve-type braces increases contact area, it also increases contact force, leading to no decrease in patellofemoral contact pressure. This effect may be due to the generalized compression on the quadriceps tendon complex from the sleeve design of the brace. Braces that provide generalized compression may be clinically useful in treating patellar subluxation and dislocation disorders because they cause the patella to engage the trochlear groove at more extended knee positions, thereby not allowing the patella to “escape” the confines of the trochlear groove as easily as in an unbraced knee.

Both a decrease in magnitude and a proximal shift in location of the peak patellofemoral pressure with the wrap-style patellar stabilization brace suggest that during knee flexion, the wrap brace shifted the location of the highest pressures to a region of the patella with increased articular cartilage thickness. These results suggest that wrap-style braces may be effective for treatment of disorders associated with degenerative cartilage changes.

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*Study concept and design:* N. A. Wilson, B. T. Mazahery, J. L. Koh, L-Q. Zhang.

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*Critical revision of manuscript for important intellectual content:* N. A. Wilson, L-Q. Zhang.

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**Additional Contributions:** Dr. Wilson is now with Rush Medical College, Rush University, Chicago, Illinois.

## REFERENCES

- Dixit S, DiFiori JP, Burton M, Mines B. Management of patellofemoral pain syndrome. *Am Fam Physician*. 2007; 75(2):194–202. [PMID: 17263214]
- Fulkerson JP, Arndt EA. Anterior knee pain in females. *Clin Orthop Relat Res*. 2000;372:69–73. [PMID: 10738416] DOI:10.1097/00003086-200003000-00009
- Holmes SW Jr, Clancy WG Jr. Clinical classification of patellofemoral pain and dysfunction. *J Orthop Sports Phys Ther*. 1998;28(5):299–306. [PMID: 9809278]
- Dye SF. The pathophysiology of patellofemoral pain: A tissue homeostasis perspective. *Clin Orthop Relat Res*. 2005; 436:100–110. [PMID: 15995427] DOI:10.1097/01.blo.0000172303.74414.7d
- Ireland ML, Willson JD, Ballantyne BT, Davis IM. Hip strength in females with and without patellofemoral pain. *J Orthop Sports Phys Ther*. 2003;33(11):671–76. [PMID: 14669962]
- Lieb FJ, Perry J. Quadriceps function. An anatomical and mechanical study using amputated limbs. *J Bone Joint Surg Am*. 1968;50(8):1535–48. [PMID: 5722849]
- Lin F, Wang G, Koh JL, Hendrix RW, Zhang LQ. In vivo and noninvasive three-dimensional patellar tracking induced by individual heads of quadriceps. *Med Sci Sports Exerc*. 2004;36(1):93–101. [PMID: 14707774] DOI:10.1249/01.MSS.0000106260.45656.CC
- Powers CM, Doubleday KL, Escudero C. Influence of patellofemoral bracing on pain, knee extensor torque, and gait function in females with patellofemoral pain. *Physiother Theory Pract*. 2008;24(3):143–50. [PMID: 18569852] DOI:10.1080/09593980701665793
- Fulkerson JP. Diagnosis and treatment of patients with patellofemoral pain. *Am J Sports Med*. 2002;30(3):447–56. [PMID: 12016090]
- Brunet ME, Brinker MR, Cook SD, Christakis P, Fong B, Patron L, O'Connor DP. Patellar tracking during simulated quadriceps contraction. *Clin Orthop Relat Res*. 2003;414: 266–75. [PMID: 12966302] DOI:10.1097/01.blo.0000079266.91782.11
- Devereaux MD, Lachmann SM. Patellofemoral arthralgia in athletes attending a Sports Injury Clinic. *Br J Sports Med*. 1984;18(1):18–21. [PMID: 6722419] DOI:10.1136/bjism.18.1.18
- Draper CE, Besier TF, Santos JM, Jennings F, Fredericson M, Gold GE, Beaupre GS, Delp SL. Using real-time MRI to quantify altered joint kinematics in subjects with patellofemoral pain and to evaluate the effects of a patellar brace or sleeve on joint motion. *J Orthop Res*. 2009;27(5): 571–77. [PMID: 18985690] DOI:10.1002/jor.20790
- Sheehan FT, Derasari A, Brindle TJ, Alter KE. Understanding patellofemoral pain with maltracking in the presence of joint laxity: Complete 3-D in vivo patellofemoral and tibiofemoral kinematics. *J Orthop Res*. 2009;27(5):561–70. [PMID: 19009601] DOI:10.1002/jor.20783
- Wilson NA, Press JM, Koh JL, Hendrix RW, Zhang LQ. In vivo noninvasive evaluation of abnormal patellar tracking during squatting in patients with patellofemoral pain. *J Bone Joint Surg Am*. 2009;91(3):558–66. [PMID: 19255215] DOI:10.2106/JBJS.G.00572
- Li G, Lopez O, Rubash H. Variability of a three-dimensional finite element model constructed using magnetic resonance images of a knee for joint contact stress analysis. *J Biomech Eng*. 2001;123(4):341–46. [PMID: 11563759] DOI:10.1115/1.1385841
- Powers CM, Ward SR, Chen YJ, Chan LD, Terk MR. The effect of bracing on patellofemoral joint stress during free and fast walking. *Am J Sports Med*. 2004;32(1):224–31. [PMID: 14754748] DOI:10.1177/0363546503258908
- Powers CM, Ward SR, Chen YJ, Chan LD, Terk MR. Effect of bracing on patellofemoral joint stress while ascending and descending stairs. *Clin J Sport Med*. 2004; 14(4):206–14. [PMID: 15273526] DOI:10.1097/00042752-200407000-00003
- MacIntyre NJ, Hill NA, Fellows RA, Ellis RE, Wilson DR. Patellofemoral joint kinematics in individuals with and without patellofemoral pain syndrome. *J Bone Joint Surg Am*. 2006;88(12):2596–2605. [PMID: 17142409] DOI:10.2106/JBJS.E.00674

19. Blønd L, Hansen L. Patellofemoral pain syndrome in athletes: A 5.7-year retrospective follow-up study of 250 athletes. *Acta Orthop Belg.* 1998;64(4):393–400. [\[PMID: 9922542\]](#)
20. Crossley K, Bennell K, Green S, McConnell J. A systematic review of physical interventions for patellofemoral pain syndrome. *Clin J Sport Med.* 2001;11(2):103–10. [\[PMID: 11403109\]](#)  
[DOI:10.1097/00042752-200104000-00007](#)
21. Powers CM, Ward SR, Chan LD, Chen YJ, Turk MR. The effect of bracing on patella alignment and patellofemoral joint contact area. *Med Sci Sports Exerc.* 2004;36(7):1226–32. [\[PMID: 15235330\]](#)  
[DOI:10.1249/01.MSS.0000132376.50984.27](#)
22. Shellock FG. Effect of a patella-stabilizing brace on lateral subluxation of the patella: Assessment using kinematic MRI. *Am J Knee Surg.* 2000;13(3):137–42. [\[PMID: 11277241\]](#)
23. Worrell T, Ingersoll CD, Bockrath-Pugliese K, Minis P. Effect of patellar taping and bracing on patellar position as determined by MRI in patients with patellofemoral pain. *J Athl Train.* 1998;33(1):16–20. [\[PMID: 16558478\]](#)
24. Bohnsack M, Halcour A, Klages P, Wilharm A, Ostermeier S, Rühmann O, Hurschler C. The influence of patellar bracing on patellar and knee load-distribution and kinematics: An experimental cadaver study. *Knee Surg Sports Traumatol Arthrosc.* 2008;16(2):135–41. [\[PMID: 18000652\]](#)  
[DOI:10.1007/s00167-007-0428-3](#)
25. Muhle C, Brinkmann G, Skaf A, Heller M, Resnick D. Effect of a patellar realignment brace on patients with patellar subluxation and dislocation. Evaluation with kinematic magnetic resonance imaging. *Am J Sports Med.* 1999;27(3):350–53. [\[PMID: 10352772\]](#)
26. Greenwald AE, Bagley AM, France EP, Paulos LE, Greenwald RM. A biomechanical and clinical evaluation of a patellofemoral knee brace. *Clin Orthop Relat Res.* 1996;324:187–95. [\[PMID: 8595755\]](#)  
[DOI:10.1097/00003086-199603000-00022](#)
27. Lun VM, Wiley JP, Meeuwisse WH, Yanagawa TL. Effectiveness of patellar bracing for treatment of patellofemoral pain syndrome. *Clin J Sport Med.* 2005;15(4):235–40. [\[PMID: 16003037\]](#)  
[DOI:10.1097/01.jsm.0000171258.16941.13](#)
28. Selfe J, Richards J, Thewlis D, Kilmurray S. The biomechanics of step descent under different treatment modalities used in patellofemoral pain. *Gait Posture.* 2008;27(2):258–63. [\[PMID: 17532637\]](#)  
[DOI:10.1016/j.gaitpost.2007.03.017](#)
29. Powers CM, Lilley JC, Lee TQ. The effects of axial and multi-plane loading of the extensor mechanism on the patellofemoral joint. *Clin Biomech (Bristol, Avon).* 1998;13(8):616–24. [\[PMID: 11415841\]](#)  
[DOI:10.1016/S0268-0033\(98\)00013-8](#)
30. Winters JM, Woo SL. Multiple muscle systems: Biomechanics and movement organization. New York (NY): Springer-Verlag; 1990.
31. Beck PR, Thomas AL, Farr J, Lewis PB, Cole BJ. Trochlear contact pressures after anteromedialization of the tibial tubercle. *Am J Sports Med.* 2005;33(11):1710–15. [\[PMID: 16093531\]](#)  
[DOI:10.1177/0363546505278300](#)
32. Elias JJ, Kilambi S, Goerke DR, Cosgarea AJ. Improving vastus medialis obliquus function reduces pressure applied to lateral patellofemoral cartilage. *J Orthop Res.* 2009;27(5):578–83. [\[PMID: 18985700\]](#)  
[DOI:10.1002/jor.20791](#)
33. Wilson DR, Apreleva MV, Eichler MJ, Harrold FR. Accuracy and repeatability of a pressure measurement system in the patellofemoral joint. *J Biomech.* 2003;36(12):1909–15. [\[PMID: 14614944\]](#)  
[DOI:10.1016/S0021-9290\(03\)00105-2](#)
34. Zhang LQ, Wang G, Nuber GW, Press JM, Koh JL. In vivo load sharing among the quadriceps components. *J Orthop Res.* 2003;21(3):565–71. [\[PMID: 12706033\]](#)  
[DOI:10.1016/S0736-0266\(02\)00196-1](#)
35. Umberger BR, Martin PE. Mechanical power and efficiency of level walking with different stride rates. *J Exp Biol.* 2007;210(Pt 18):3255–65. [\[PMID: 17766303\]](#)  
[DOI:10.1242/jeb.000950](#)
36. Gold GE, Besier TF, Draper CE, Asakawa DS, Delp SL, Beaupre GS. Weight-bearing MRI of patellofemoral joint cartilage contact area. *J Magn Reson Imaging.* 2004;20(3):526–30. [\[PMID: 15332263\]](#)  
[DOI:10.1002/jmri.20146](#)
37. Dye SF. Functional anatomy and biomechanics of the patellofemoral joint. In: Scott WN, editor. *The knee.* St. Louis (MO): Mosby; 1994. p. 381–89.
38. Reilly DT, Martens M. Experimental analysis of the quadriceps muscle force and patello-femoral joint reaction force for various activities. *Acta Orthop Scand.* 1972;43(2):126–37. [\[PMID: 5079747\]](#)
39. Yonclas PP, Nadler RR, Moran ME, Kepler KL, Napolitano E. Orthotics and assistive devices in the treatment of upper and lower limb osteoarthritis: An update. *Am J Phys Med Rehabil.* 2006;85(11 Suppl):S82–97. [\[PMID: 17079983\]](#)  
[DOI:10.1097/01.phm.0000247790.71487.80](#)
40. Heegaard J, Leyvraz PF, Curnier A, Rakotomanana L, Huiskes R. The biomechanics of the human patella during passive knee flexion. *J Biomech.* 1995;28(11):1265–79. [\[PMID: 8522541\]](#)  
[DOI:10.1016/0021-9290\(95\)00059-Q](#)
41. Eilerman M, Thomas J, Marsalka D. The effect of harvesting the central one-third of the patellar tendon on patellofemoral contact pressure. *Am J Sports Med.* 1992;20(6):

- 738–41. [\[PMID: 1456369\]](#)  
[DOI:10.1177/036354659202000616](#)
42. Garretson RB 3rd, Kato lik LI, Verma N, Beck PR, Bach BR, Cole BJ. Contact pressure at osteochondral donor sites in the patellofemoral joint. *Am J Sports Med.* 2004;32(4):967–74. [\[PMID: 15150045\]](#)  
[DOI:10.1177/0363546503261706](#)
43. Simonian PT, Sussmann PS, Wickiewicz TL, Pa letta GA, Warren RF. Contact pressures at osteochondral donor sites in the knee. *Am J Sports Med.* 1998;26(4):491–94. [\[PMID: 9689365\]](#)
44. Brechter JH, Powers CM. Patellofemoral joint stress during stair ascent and descent in persons with and without patellofemoral pain. *Gait Posture.* 2002;16(2):115–23. [\[PMID: 12297253\]](#)  
[DOI:10.1016/S0966-6362\(02\)00090-5](#)
45. Frankel VH. Biomechanics of the knee. *Orthop Clin North Am.* 1971;2(1):175–90. [\[PMID: 5171112\]](#)
46. Huberti HH, Hayes WC. Patellofemoral contact pressures. The influence of q-angle and tendofemoral contact. *J Bone Joint Surg Am.* 1984;66(5):715–24. [\[PMID: 6725318\]](#)
47. Huberti HH, Hayes WC. Contact pressures in chondromalacia patellae and the effects of capsular reconstructive procedures. *J Orthop Res.* 1988;6(4):499–508. [\[PMID: 3379503\]](#)  
[DOI:10.1002/jor.1100060405](#)
48. Marder RA, Swanson TV, Sharkey NA, Duwelius P J. Effects of partial pat ellectomy and reattachment of the patellar tendon on pat ellofemoral contact areas and pressures. *J Bone Joint Surg Am.* 1993;75(1):35–45. [\[PMID: 8419389\]](#)
49. Harris ML, Morberg P, Bruce WJ, Walsh WR. An improved method for measuring tibiofemoral contact areas in total knee arthroplasty: A comparison of K-scan sensor and Fuji film. *J Biomech.* 1999;32(9):951–58. [\[PMID: 10460132\]](#)  
[DOI:10.1016/S0021-9290\(99\)00072-X](#)
50. Levine J, Splain S. Use of the infrapatella strap in the treatment of pat ellofemoral pain. *Clin Orthop Relat Res.* 1979;139:179–81. [\[PMID: 455839\]](#)
51. Palumbo PM Jr. Dynamic patellar brace: A new orthosis in the management of patellofemoral disorders. A preliminary report. *Am J Sports Med.* 1981;9(1):45–49. [\[PMID: 7468897\]](#)  
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