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Am. J. Sports Med. 2004; 32; 224

DOI: 10.1177/0363546503258908

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The Effect of Bracing on Patellofemoral Joint Stress During Free and Fast Walking

Christopher M. Powers,^{*†‡} PhD, PT, Samuel R. Ward,[†] PT, Yu-jen Chen,[†] MS, PT, Li-der Chan,[†] MS, PT, and Michael R. Terk,^{†‡} MD
From the [†]Department of Biokinesiology and Physical Therapy, University of Southern California, Los Angeles, California, and [‡]Department of Radiology, Keck School of Medicine University of Southern California, Los Angeles, California

Background: Although several studies have demonstrated decreases in patellofemoral pain (PFP) with the application of bracing, the mechanism by which bracing reduces symptoms has not been elucidated.

Hypothesis: Individuals who responded favorably to bracing will exhibit decreased patellofemoral stress during level walking.

Study Design: Repeated measures, cross-sectional.

Methods: Fifteen subjects with a diagnosis of PFP completed two phases of data collection: 1) MRI assessment of patellofemoral contact area and 2) gait analysis. Data were obtained under braced and nonbraced conditions. Variables obtained from both data collection sessions were used as input variables into a mathematical model to quantify patellofemoral stress.

Results: Subjects reported a 56% reduction in pain following bracing. Bracing significantly reduced peak stress during free and fast walking (17% and 27%, respectively). The decrease in stress was the result of increased contact area as patellofemoral joint reaction forces were increased following bracing.

Conclusion: Bracing resulted in a larger increase in patellofemoral contact area than the increase in joint reaction force, resulting in a decrease in joint stress.

Clinical Relevance: The results of this study suggest a possible mechanism by which bracing may be effective in reducing PFP and provides experimental support for the use of this treatment method.

Keywords: patella; patellofemoral; biomechanics; stress; bracing; gait

Patellofemoral pain (PFP) is a common disorder seen in orthopedic practice.^{3,4,9,21} Although the etiology of PFP is not entirely clear, the most commonly accepted hypothesis is related to abnormal patellar tracking, which increases patellofemoral stress and subsequent articular cartilage wear.¹⁵ As stress is defined as force per unit area, a reduction in patellofemoral joint reaction force and/or an increase in patellofemoral joint contact area (or a combination of both) would appear to be beneficial consequences of treatment.

Patellar bracing is commonly used in the management of PFP.^{10,12,20,22,25} The primary goal of bracing is to centralize the patella within the trochlear groove, thus improving alignment and tracking.^{7,12} Several studies have demon-

strated decreases in PFP with the application of bracing;^{1,16} however, the mechanism by which bracing reduces symptoms has not been elucidated. Although it is assumed that bracing improves patellar kinematics, imaging studies have reported that bracing has little or no effect on patellar alignment or tracking.^{8,11,14}

Apart from changing patellar kinematics, it has been suggested that bracing may have a more subtle effect on patellofemoral joint mechanics. For example, the compressive force applied to the patellofemoral joint as a result of bracing could seat the patella more firmly within the trochlear groove, thereby increasing contact area.¹⁵ Distributing the patellofemoral joint reaction force over a greater surface could theoretically decrease patellofemoral stress. To date, this hypothesis has not been explored.

Using a patient-specific, imaging-based model of the patellofemoral joint, the purpose of this study was to test the hypothesis that individuals who respond favorably to bracing would exhibit decreased patellofemoral joint stress during level walking. It was further hypothesized that decreased patellofemoral joint stress would be the result of an increase in patellofemoral joint contact area.

*Address correspondence and reprint requests to Christopher M. Powers, PhD, PT, Department of Biokinesiology and Physical Therapy, University of Southern California, 1540 E. Alcazar Street, CHP-155, Los Angeles, CA 90089-9006.

Information obtained from this study will provide a rationale by which bracing may be effective in reducing PFP and also provide experimental support for the use of this treatment method.

METHODS

Subjects

Fifteen females between the ages of 18 and 43 with a diagnosis of PFP consented to participate in this study. The average age, height, and weight of these subjects was 29.9 ± 8.0 years, 163.8 ± 4.6 cm, and 58.0 ± 8.0 kg, respectively. Subjects were recruited from orthopedic clinics in the Los Angeles area and were screened by physical exam to rule out ligamentous instability, internal derangement, and patellar tendinitis. Subjects were admitted to this study if 1) pain originated from the patellofemoral joint articulation, 2) pain was readily reproducible with activities commonly associated with PFP (for example, squatting, stair climbing, knee extension),^{18,19} and 3) pain was reduced following bracing. As the purpose of this study was to evaluate why patellar bracing reduces symptoms, only those subjects who reported decreased pain with bracing were included (see pain criterion below). Subjects were excluded from the study if they reported having previous knee surgery or a history of traumatic patellar dislocation.

Procedures

All subjects completed two phases of data collection. Phase 1 consisted of MRI assessment to determine patellofemoral joint contact area, while phase 2 consisted of gait analysis. Data obtained from both data collection sessions were required as input variables into a biomechanical model to quantify patellofemoral joint stress. Prior to participation, all subjects were informed of the nature of the study and signed a consent form approved by the Institutional Review Board of the University of Southern California Health Sciences Campus.

Magnetic Resonance Imaging. All imaging was performed at the University of Southern California Imaging Sciences Center. Axial plane images of the patellofemoral joint were obtained with a 1.5T magnet (GE Medical Systems, Milwaukee, Wisconsin), using a fast-spoiled gradient echo pulse sequence with fat suppression (TE 1.5, TR 8.2, flip angle 10°). The image field of view was $10 \text{ cm} \times 10 \text{ cm}$ with a 256×256 matrix interpolated to 512×512 , giving a pixel size of $0.20 \text{ mm} \times 0.20 \text{ mm}$. Using this pulse sequence, the patellar and femoral cartilage was observed to be bright (white), and any separation between the cartilage surfaces appeared as a dark line.⁶

Resistance to the extensor mechanism was accomplished using a custom-built, nonferromagnetic loading apparatus that resembled a leg press machine (Captain Plastic, Seattle, Washington) (Fig. 1). This device allowed subjects to perform a unilateral leg press in the supine position. Loading was achieved by pushing against a foot-



Figure 1. Photograph shows the subject set up on the nonferromagnetic loading device used for imaging. This device allowed the subjects to do unilateral knee extension in the supine position. Resistance to knee extension was accomplished by pushing against a footplate that was connected (through a pulley system) to a moveable carriage containing epoxy weights. (Reprinted with permission from Salsich GB, et al: In vivo assessment of patellofemoral joint contact area in pain-free individuals. *Clin Orthop*, in press.)

plate that was connected (through a pulley system) to a moveable carriage containing epoxy weights.

Subjects were positioned supine on the loading device and Velcro straps were placed across hip and shoulders to stabilize the trunk and pelvis. Two 5-inch receive-only coils were placed on each side of the knee joint (with the patella centered between) and secured with tape. Starting with the knee fully extended, subjects were instructed to place the foot of the symptomatic side (or in the case of bilateral symptoms, the most painful side) on the footplate, and the device was moved into the MRI bore. The carriage was then loaded to 25% bodyweight and imaging commenced. A load of 25% of bodyweight was chosen because it provided quadriceps activation during imaging, could be tolerated by painful subjects, and could be supported by our loading device.

Following imaging at 0° degrees, the patient was removed from the MRI bore and repositioned on the loading device. MRI scans were obtained at 0° , 20° , 40° , and 60° of knee flexion (as measured by standard goniometer).

Images were obtained statically under braced (On-Track, Don Joy Inc., Vista, California) (Fig. 2) and non-braced conditions. The brace was composed of a 5-mm neoprene knee cuff with a patellar cutout. Self-adhesive Velcro patches placed directly over the patella were used to secure a 5-mm neoprene pull strap, which applied a constant medial pull on the patella.

Prior to and immediately following the application of the brace, subjects were asked to rate their perceived pain (visual analog scale) while performing an activity that reproduced their symptoms (that is, unilateral squat or deep knee bend). Application of the brace was deemed to be successful if at least a 50% reduction in symptoms was reported. Based on this pain criterion, a total of 16 subjects



Figure 2. The patellofemoral brace evaluated in the current study was On-Track Patellar Tracking System (Don Joy Inc., Vista, California).

were screened to enroll the 15 subjects reported in this study.

The sequence of braced and nonbraced imaging was randomized for each subject. Total imaging time was 60 seconds at each knee flexion angle.

Gait Analysis. Gait analysis was performed at the Musculoskeletal Biomechanics Research Laboratory at the University of Southern California. Three-dimensional motion was obtained using a six-camera motion analysis system (Vicon, Oxford Metrics Ltd., Oxford, England). Kinematic data were sampled at 60 Hz and recorded digi-

tally on a 1-GHz personal computer. Reflective markers (25-mm spheres) placed at specific anatomical landmarks were used to determine sagittal plane kinematics of the lower extremity. Ground reaction forces were collected at a rate of 600 Hz using four AMTI forceplates (Model #OR6-6-1, Newton, Massachusetts). The forceplates were situated within the middle of a 10-meter walkway with the pattern of tile flooring camouflaging their location.

Subjects were appropriately attired to permit marker placement directly on the skin. Anthropometric measures were obtained from each subject for use in calculating lower extremity kinetics. Reflective markers were then taped (bilaterally) to the following landmarks: anterior superior and posterior superior iliac spines, lateral thigh, lateral femoral epicondyle, lateral tibia, lateral malleolus, second metatarsal head, fifth metatarsal head, and posterior calcaneous. A small cutout on the lateral side of the brace allowed the lateral femoral epicondyle marker to be placed directly on the skin during the braced trials.

Subjects were instructed to walk along the 10-meter walkway with the middle 6 meters being used for data collection. Three trials of self-selected free and fast walking velocities were obtained. A trial was considered successful if the subject's instrumented foot landed within one of the forceplates (without targeting). Walking trials were repeated following the application of the patellar tracking system. The order of braced and nonbraced gait trials also was randomized.

To account for the potential influence of walking speed on kinematic and kinetic variables between braced and nonbraced conditions, only a 5% difference in gait velocity within a particular walking condition was allowed. The range of acceptable gait velocities for a particular condition was based on the speed of the first trial within a particular block of trials. For example, if the self-selected free walking velocity for a particular subject during trial 1 was 80 m/min, then all subsequent trials for free walking (including both braced and nonbraced conditions) had to fall between 76 m/min and 84 m/min. The same procedure was used for the fast walking condition. Using this criterion, the average self-selected free walking speed for all subjects was 79.2 ± 9.0 m/min, while the average self-selected fast walking speed was 107.4 ± 9.6 m/min.

Data Analysis

Patellofemoral Joint Contact Area. Contact area was measured from the sequential axial plane images of the patellofemoral joint (Fig. 3). Images were displayed for analysis using Scion Medical Imaging Software (Scion Corp., Frederick, Maryland). The section of the image containing the patella and surrounding portion of the femur was enlarged to 1.5 times the normal view to enhance visualization of the articular cartilage. Contact was defined as areas of patella and femur approximation in which no distinct separation could be found between the cartilage borders of the two joint surfaces. Since cartilage is relatively bright on fat-suppressed, fast-spoiled gradient echo images, the definition of contact area was operatively defined as "white on white."⁶

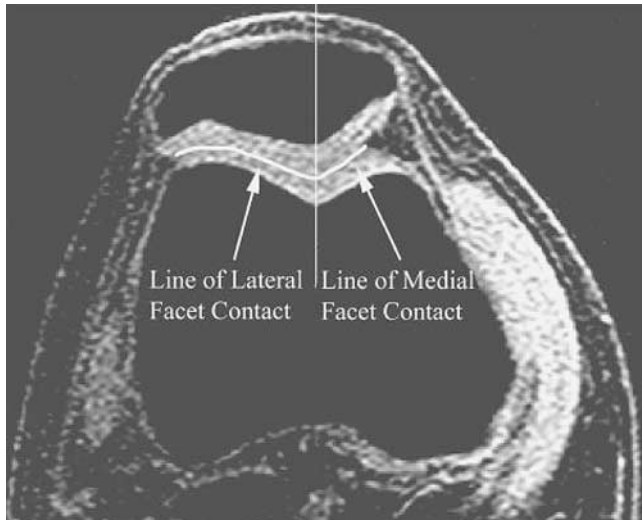


Figure 3. The method used to measure patellofemoral contact area is shown. The contact area was measured from the sequential axial plane images of the patellofemoral joint. Contact was defined as areas of patella and femur approximation in which no distinct separation could be found between the cartilage borders of the two joint surfaces (curvilinear lines). The median ridge of the patella served as the point of separation between the medial and lateral facets (vertical line).

The line of contact (curvilinear) between the patella and femur was measured and recorded using the “electronic calipers” feature within the Scion software. To obtain contact area for each slice, the length of each respective line of contact was multiplied by the 1-mm slice thickness. The areas of contact from each sequential image were summed to obtain the total patellofemoral joint contact area (reported in mm²). This method has been shown to be reliable and comparable to contact area measurements obtained using Fuji pressure-sensitive film in cadaver specimens.⁶

MRI procedures were repeated for each knee flexion angle. Contact area measurements were made twice by the same investigator and averaged for final analysis. Contact area values at 0°, 20°, 40°, and 60° of knee flexion were connected with linear segments and interpolated at each knee flexion angle between 0° and 60°. This process allowed the contact area to be approximated for every angle experienced during the gait cycle.

Knee Joint Kinematics and Kinetics. Reflective marker coordinate and force data were stored in a motion file generated by the Vicon 370 software. Data processing software (Workstation Version 3.5, Oxford Metrics, Oxford, United Kingdom) was used to reconstruct the three-dimensional motion data, identify the gait cycle events, and filter the raw coordinate data. A second data processing step (Plug-in-Gait Model, Version 1.7, Oxford Metrics, Oxford, United Kingdom) was used to compute segment kinematics and inertial properties for the foot, shank, and thigh. The principal moment of inertia of each segment was determined from the subject’s total body weight, segment geometry, and anthropometric data using standard

regression equations.² The net sagittal plane knee extensor (internal) moment was calculated from the inertial properties, segment kinematics, and forceplate data using standard inverse dynamic equations.

All moment data were normalized by body mass and reported in units of Nm/kg. Only kinematic and kinetic data corresponding to the forceplate step were used. Data obtained from the three trials were averaged for statistical analysis.

Patellofemoral Joint Kinetics. As described previously, patellofemoral joint reaction force and stress were calculated using a biomechanical model.^{17,24} Input variables for the model algorithm included knee joint angle, knee extensor moment, and patellofemoral joint contact area.

The effective lever arm (L_{eff}) for the quadriceps was calculated using a nonlinear equation ($L_{eff} = 8.0e^{-5}x^3 - 0.013x^2 + 0.28x + 0.046$, where x = knee joint angle) fit to the data ($R^2 = 0.98$) of Van Eijden et al.²³ Quadriceps force (F_q) was then calculated by dividing the knee extensor moment by the effective moment arm (Equation 1):

$$F_q = M_k / L_{eff} \quad (1)$$

Patellofemoral joint reaction force (JRF_{pf}) was calculated as the product of the quadriceps force and a constant k (Equation 2). The constant k was determined for each knee flexion angle by using a nonlinear equation ($k = [-3.8e^{-5}x^2 + 1.5e^{-3}x + 0.462]/[-7.0e^{-7}x^3 + 1.6e^{-4}x^2 + 0.016x + 1]$) fit to the data ($R^2 = 0.99$) of Van Eijden et al.²³

$$JRF_{pf} = k \cdot F_q \quad (2)$$

Patellofemoral joint stress (PFJS) was then calculated as the patellofemoral joint reaction force divided by the patellofemoral contact area (CA_{pf}) (Equation 3):

$$PFJS = JRF_{pf} / CA_{pf} \quad (3)$$

The model output was patellofemoral joint reaction force, patellofemoral joint stress, and used contact area (which represents contact area as a function of knee flexion angle during gait), all normalized to the gait cycle.

Statistical Analysis. Comparison of contact area between the braced and nonbraced conditions across flexion angles was made using a 2×4 (Brace Condition \times Knee Flexion Angle) analysis of variance (ANOVA) with repeated measures. To determine if bracing influenced kinetic and kinematic variables across walking speeds, 2×2 (Brace Condition \times Gait Speed) ANOVAs with repeated measures were performed. This analysis was repeated for each dependent variable (peak patellofemoral stress, peak patellofemoral joint reaction force, mean used contact area, peak knee extensor moment, and peak knee flexion during stance).

Significant main effects were reported if there were no significant interactions. If a significant interaction was identified, main effects were analyzed separately. All sta-

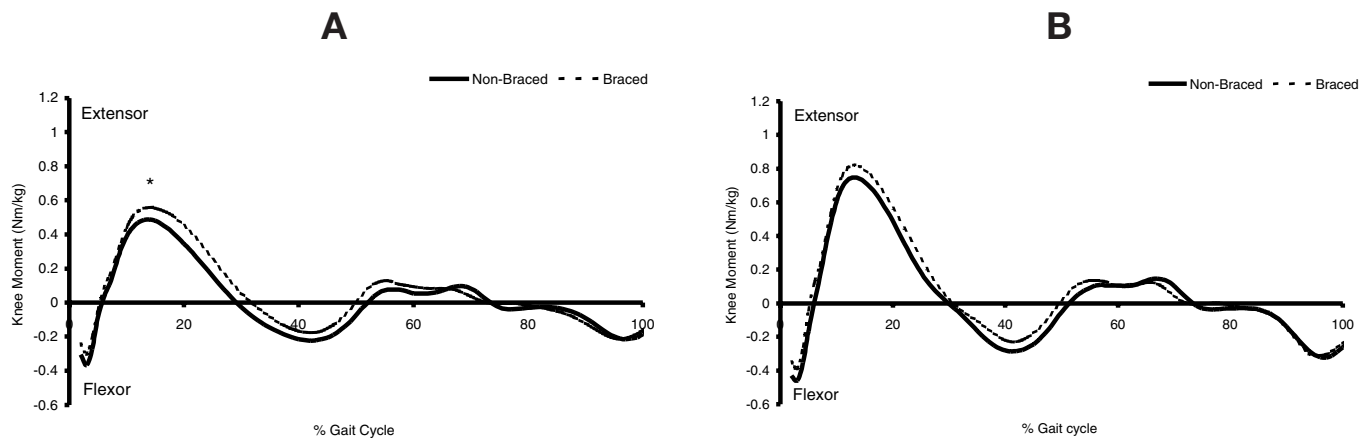


Figure 4. Knee angle plotted as a function of the gait cycle for both nonbraced (solid line) and braced (dash line) conditions during (A) self-selected free walking and (B) fast walking. There was no significant difference in knee kinematics between brace conditions.

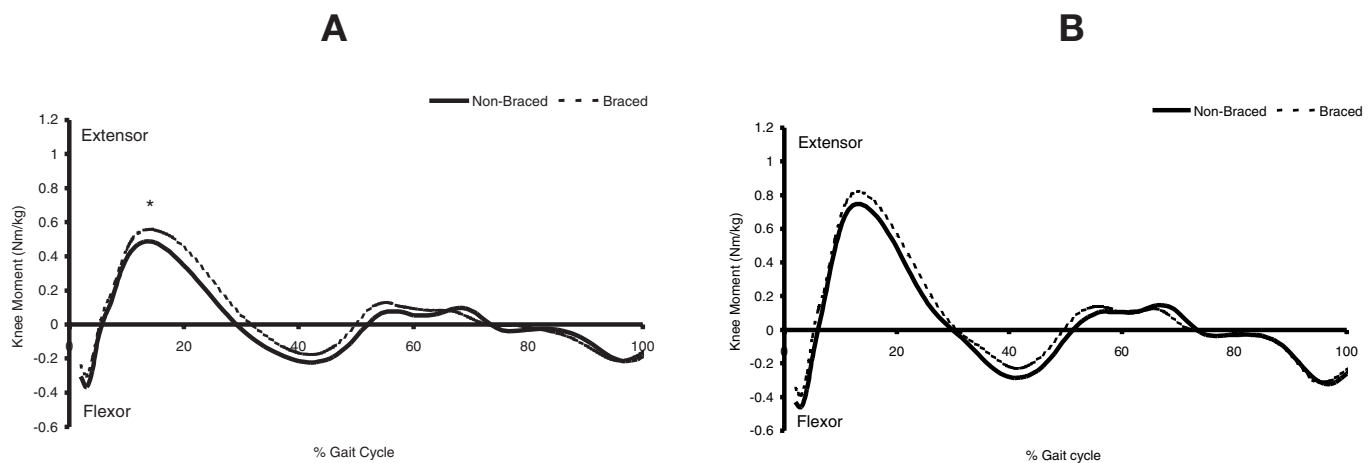


Figure 5. Net knee joint moment plotted as a function of the gait cycle for both nonbraced (solid line) and braced (dash line) conditions during (A) self-selected free walking and (B) fast walking. *Indicates that peak knee extensor moment was significantly greater during braced conditions when compared to nonbraced conditions during free walking. No significant differences were found during fast walking.

tistical analyses were performed using SPSS statistical software (SPSS Inc., Chicago, Illinois) with a significance level of $P < 0.05$.

RESULTS

Pain Response

Based on the 10-point visual analog scale, the average pre-brace pain level was 4.8 ± 1.9 , and the post-brace pain level was 2.1 ± 1.8 . This corresponded to a 56% reduction in pain.

Knee Kinematics

For both free and fast walking, there were no significant differences in knee kinematics between the braced and nonbraced conditions (Fig. 4).

Net Knee Joint Moments

During free walking, the peak knee extensor moment was significantly greater in the braced condition when compared to the nonbraced condition (0.60 ± 0.25 versus 0.50 ± 0.22 Nm/kg; $P = 0.005$) (Fig. 5A). The same trend was observed during fast walking; however, this difference was not statistically significant (0.83 ± 0.32 versus 0.75 ± 0.20 Nm/kg; $P = 0.186$) (Fig. 5B).

Patellofemoral Joint Reaction Force

During free walking, the peak patellofemoral joint reaction force was significantly greater in the braced condition when compared to the nonbraced condition (8.7 ± 4.7 versus 6.9 ± 3.7 N/kg; $P = 0.005$) (Fig. 6A). During fast walking, the peak patellofemoral joint reaction force also was greater in the braced condition compared to the nonbraced condition (12.6 ± 6.1 versus 10.9 ± 4.0 N/kg);

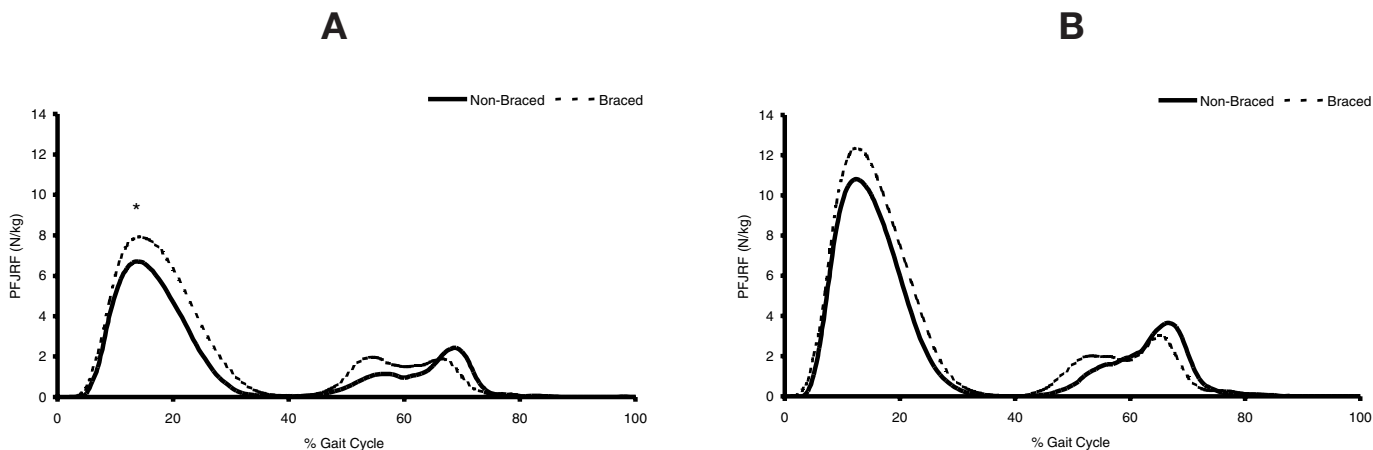


Figure 6. Patellofemoral joint reaction force (PFJRF) plotted as a function of the gait cycle for both nonbraced (solid line) and braced (dash line) conditions during (A) self-selected free walking and (B) fast walking. *Indicates that PFJRF was significantly greater during braced conditions when compared to nonbraced conditions during free walking. No significant differences were found during fast walking.

however, this difference was not statistically significant ($P = 0.112$) (Fig. 6b).

Patellofemoral Joint Contact Area

When compared to the nonbraced condition, application of the patellar brace resulted in significant increases in contact area at 0° (103.9 versus 140.6 mm²; $P = 0.012$), 20° (160.5 ± versus 259 ± mm²; $P < 0.001$), 40° (323.5 versus 396.1 mm²; $P < 0.001$), and 60° (398.9 versus 450.1 mm²; $P < 0.001$)(Fig. 7).

During free walking, the mean used contact area was significantly greater in the braced condition compared to the nonbraced condition (266.8 ± 68.1 versus 188.8 ± 31.1 mm²; $P < 0.001$)(Fig. 8A). Similarly, during fast walking, the mean used contact area was significantly greater in the braced condition when compared to the nonbraced condition (269.9 ± 64.4 versus 193.7 ± 31.5 mm²; $P < 0.001$)(Fig. 8B).

Patellofemoral Joint Stress

During free walking, the peak patellofemoral joint stress was significantly less in the braced condition compared to the nonbraced condition (2.0 ± 0.8 versus 2.4 ± 1.0 MPa; $P = 0.039$)(Fig. 9A). Similarly, the peak patellofemoral joint stress during fast walking was significantly less in the braced condition when compared to the nonbraced condition (3.7 ± 1.0 versus 2.7 ± 1.0 MPa; $P = 0.004$)(Fig. 9B).

DISCUSSION

The purpose of this study was to test the premise that individuals who respond favorably to bracing would exhibit decreased patellofemoral joint stress during level walking. This hypothesis was supported by the finding of sig-

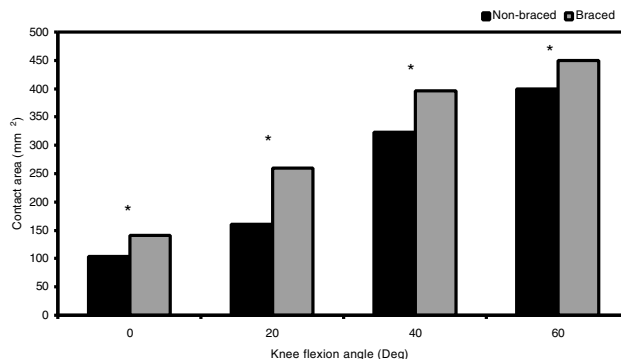


Figure 7. Patellofemoral joint contact area across knee flexion angles for braced and nonbraced conditions. *Indicates brace condition greater than nonbraced condition ($P < 0.05$).

nificant decreases in peak stress during both free and fast gait speeds (reductions of 17% and 27%, respectively).

As elevated patellofemoral joint stress is believed to be a causative factor with respect to the development of PFP, it is conceivable that the observed pain reduction following bracing was the result of diminished stress. Although articular cartilage is aneural and cannot be a cause of symptoms, it has been proposed that pain receptors in the subchondral bone plate are susceptible to elevated joint stress and can be a source of pain.⁵ However, care must be made in suggesting a cause and effect relationship between pain and stress, as stress was not quantified during the provocative maneuver used to reproduce symptoms. Although it is possible that the reduction in patellofemoral stress following bracing would be evident in more pain-producing tasks such as squatting, further research is necessary to explore the relationship between stress and pain.

The observed decreases in peak stress were a function of increased contact area as the patellofemoral joint reaction forces were significantly elevated following bracing

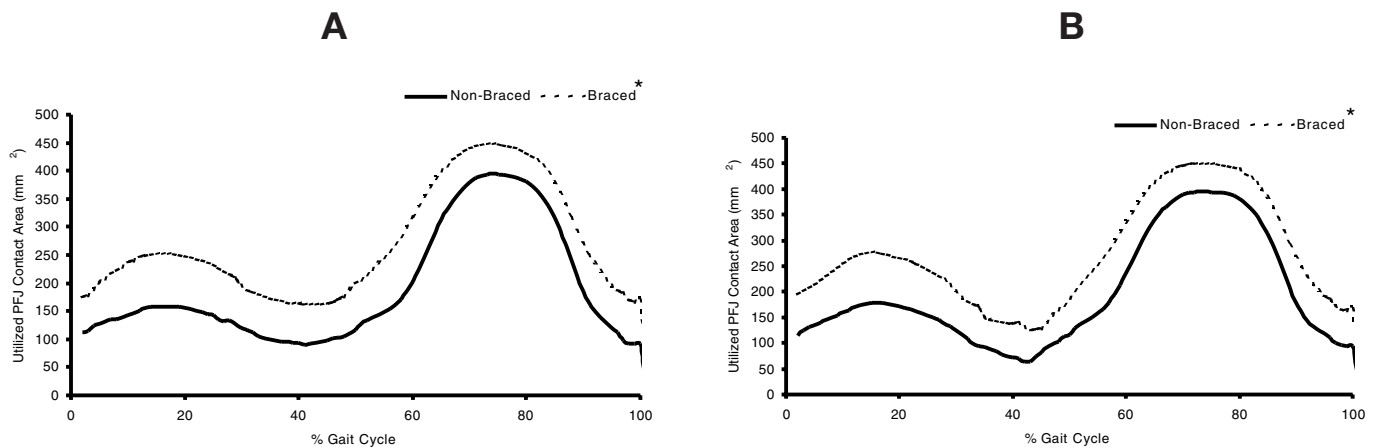


Figure 8. Used patellofemoral joint (PFJ) contact area plotted as a function of the gait cycle for both nonbraced (solid line) and braced (dash line) conditions during (A) self-selected free walking and (B) fast walking. *Indicates that used PFJ contact area was significantly greater during braced conditions when compared to nonbraced conditions during both free and fast walking.

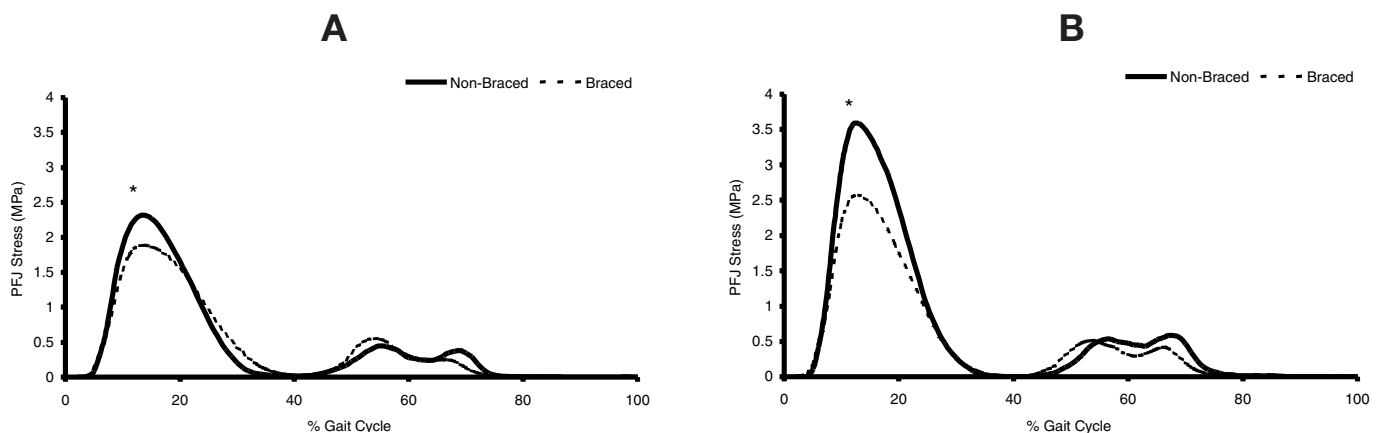


Figure 9. Patellofemoral joint (PFJ) stress plotted as a function of the gait cycle for both nonbraced (solid line) and braced (dash line) conditions during (A) self-selected free walking and (B) fast walking. *Indicates that peak PFJ stress was significantly lower during braced conditions when compared to nonbraced conditions during both free and fast walking.

(increases of 21% and 13% for free and fast walking speeds, respectively). When averaged across all knee flexion angles, contact area following bracing increased 33%. In addition, used contact area increased 41% during free walking and 39% during fast walking. In general, the larger increase in contact area offset the increase in joint reaction force resulting in an overall decrease in joint stress.

The largest improvement in contact area occurred at 20° of knee flexion (61%). We consider this finding to be relevant as this position corresponds to the peak knee flexion angle during weight acceptance (Fig. 1). Incidentally, this is also the point in the gait cycle where peak stress occurred (Fig. 6). Twenty degrees of knee flexion also has been identified as the angle at which patellar subluxation begins to occur¹³; therefore, the ability of a brace to increase contact area at this knee flexion angle would appear to be important.

The observed increases in patellofemoral joint reaction force following bracing were the result of significantly larger knee extensor moments as the knee kinematics were nearly identical between conditions. The larger knee

extensor moments following bracing could not, however, be explained by walking speed as this variable was controlled between braced and nonbraced trials. Salsich et al.¹⁹ reported reduced knee extensor moments in subjects with PFP compared to healthy controls and concluded that this may be a compensatory strategy to reduce patellofemoral joint forces (that is, “quadriceps avoidance”). It is possible that prior to bracing, the PFP subjects were adopting quadriceps avoidance behavior and that following application of the brace resumed a more “normal” knee extensor moment pattern. Without a nonpainful (control group), this cannot be stated with great certainty; however, similar increases in knee extensor moments have been observed in subjects with PFP following patellar taping.¹⁸

Under nonbraced conditions, increases in joint reaction forces would likely translate into greater joint stress. This may explain why ascending and descending stairs is particularly challenging for individuals with PFP. However, the increases in joint reaction forces observed following bracing were offset by relatively larger increases in contact area, thereby reducing stress. Such findings suggest

that interventions aimed at improving contact area may be beneficial in this population and offer insight as to how bracing may influence PFP.

Care must be taken in extrapolating the results of this study to all patellofemoral braces in general as only one brace was evaluated. However, it is reasonable to assume that similar results would be expected with other braces that move the patella. Further research is necessary to test this assumption.

CONCLUSIONS

Patellofemoral bracing significantly reduced peak stress during free and fast walking. The observed decrease in stress was the result of increased contact area as the patellofemoral joint reaction forces also were increased following bracing. The finding of reduced stress with bracing may explain why bracing is effective in reducing symptoms in the PFP population.

ACKNOWLEDGMENT

This work was funded in part by a grant from Don Joy Inc.

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