Published in final edited form as:

J Bone Joint Surg Am. 2007 November ; 89(11): 2398–2407. doi:10.2106/JBJS.F.01136.

A MECHANICAL HYPOTHESIS FOR THE EFFECTIVENESS OF KNEE BRACING FOR MEDIAL COMPARTMENT KNEE OSTEOARTHRITIS

Dan K Ramsey, PhD, Kristin Briem, PT, MHSc, Michael J Axe, MD, and Lynn Snyder-Mackler, ScD, PT, SCS

Department of Physical Therapy, Graduate Program in Biomechanics and Movement Sciences, and Center for Biomedical Engineering Research University of Delaware, Newark, DE 19716

Abstract

Background—Evidence that knee braces used for the treatment of osteoarthritis mediate pain relief and improve function by unloading the joint (increased joint separation) remains inconclusive. Alternatively, valgus braces may mediate pain relief by mechanically stabilizing the joint and reducing muscle co-contractions and joint compression. This study therefore sought to examine the degree to which unloader knee braces control knee instability and influence muscle co-contractions during gait.

Methods—Sixteen subjects with radiographic evidence of medial compartment knee osteoarthritis and malalignment were recruited and fitted with a custom Generation II Unloader Brace. Gait analysis was performed with the knee unbraced and with the brace in neutral alignment and 4° valgus. A two week washout period separated brace conditions. Muscle co-contraction indices were derived for agonist and antagonist muscle pairings. Pain, instability and functional status were assessed using self-report questionnaires. Repeated-measures ANOVA's, correlations and regression analysis were used for statistical analysis.

Results—The scores for pain, function and stability were worst when the knee was unsupported (baseline and washout). At baseline, 9 of 16 subjects reported knee instability, of which 5 complained it affected activities of daily living. Poor knee stability was significantly correlated with decreased activities of daily living, quality of life, global knee function and higher pain and symptoms. Knee function and stability scored highest with the neutral brace compared to the valgus brace. Vastus lateralis-lateral hamstring and vastus medialis-medial hamstring muscle co-contractions were significantly reduced as a result of bracing. Subjects with greater varus alignment exhibited greater decreases in vastus lateralis-lateral hamstrings co-contraction.

Conclusion—Neutral alignment performed as well or better than valgus alignment, in reducing pain, disability, muscle co-contraction, and knee adduction excursions. Pain relief may result from diminished muscle co-contractions rather than so called medial compartment unloading.

INTRODUCTION

Knee osteoarthritis (OA) is the most common cause of functional disability among Americans and the medial compartment is most often affected ^{1,2}. To correct varus alignment, so called unloader braces that provide an opposing valgus force are a common non-operative intervention. In theory, braces apply an external three-point bending force to the knee and attenuate load on the medial compartment ^{3–5}. Evidence for joint

unloading^{3,6-9} and effectiveness in decreasing pain and improved function^{3,7,10-15} have been reported.

Frontal plane joint laxity and mediolateral instability exacerbate functional decline and disease progression¹⁶⁻¹⁸. Varus-valgus knee laxity is exacerbated by meniscal and articular cartilage degeneration that decreases the distance between the tibiofemoral surfaces¹⁸⁻²¹. Frontal plane laxity appears to be localized to the medial compartment¹⁷. Greater laxity raises the likelihood of episodes of knee instability²². Many patients report functional instability^{17,22,23}, defined as the patient's perception of the knee "shifting, buckling and giving way during activities of daily living"²⁴.

Joint laxity and mediolateral instability necessitate increased muscle activity and co-activation of antagonistic muscles to stabilize the knee^{17,18,23,25}. Persons who are functionally unstable often stiffen their knee which involves a reduction in knee flexion excursion and increased muscular co-contraction²⁶⁻³⁰. Increased co-contraction, while stabilizing the knee, increases joint contact pressures that could exacerbate joint destruction^{17,23,25,31}.

The aim of this study was to examine the degree to which valgus unloader knee braces control instability and influence muscle co-contraction during gait. Our first hypothesis was that frontal plane joint laxity and functional instability would be controlled mechanically via the brace, whether set in the patient's normal varus alignment or at 4° of valgus (relative to normal). Secondly, pain relief may be mediated by decreased muscle co-contraction, rather than mechanically unloading (increased joint separation) from an opposing valgus force. Thirdly, improved self reported knee function and levels of pain would be similar for both brace conditions.

MATERIALS AND METHODS

Subjects

Sixteen subjects (54.9 ± 8.8 yrs, body mass index (BMI) 31.1 ± 4.2 kg/m²) with genu varum and medial compartment knee OA were referred from a local orthopedic practice. Diagnosis was based on clinical history, a physical examination, and joint space narrowing as observed from standing posteroanterior radiographs with the knee flexed 30°³²⁻³⁴. Personal and radiographic data of the study subjects are presented in Table 1. Joint space width, the weight-bearing line (center of the femoral head to the center of the ankle mortise) and joint laxity from stress radiographs were measured by a single examiner.^{17,35-38}

Physical activity had been curtailed because of knee pain in all patients. No one received physical therapy prior to the study. Persons with a history of ligament deficiency or reconstruction, cardiovascular disease, diabetes, neurological impairment, impaired balance, rheumatoid arthritis, total knee replacement in either knee, orthopedic problems in the hips, ankles or spine, or a body mass index (BMI) ≥ 40.0 were excluded. Intra-articular corticosteroid and hyaluronic acid injections were not administered within three months of the study. We did not control for the use of oral anti-inflammatory medications. The study was approved by the Human Subjects Review Board and all subjects provided informed consent to participate in the study.

Motion Analysis

Subjects underwent 3-dimensional lower extremity gait analysis with simultaneous surface electromyographic (EMG) measurement on three separate occasions, (knee unbraced, neutral brace alignment, and 4° valgus correction). Kinematic data were collected at 120Hz using a passive 6-camera system (VICON 512, Oxford Metrics, UK) and ground reaction

force data recorded at 1800 Hz from a Bertec force platform (Bertec Corp, Worthington, OH). Motion and kinetic recordings were synchronized for simultaneous collection.

Joint centers were defined and rigid thermoplastic shells affixed with four orthogonal markers were attached to the thigh and shank with an elastic wrap to minimize movement artifacts. A marker triad placed on the sacrum and two additional markers on the subject's heel counter along with the marker on the 5th metatarsal head were used to track pelvis and foot movement.

EMG activity was recorded concurrently at 1800 Hz using a 16-channel system (Motion Lab Systems, Baton Rouge, LA) and bandpass filtered between 20–1000 Hz prior to sampling. Pre-amplified surface electrodes (20mm inter-electrode distance, 12mm disk diameter) were placed over the medial and lateral hamstrings, vastus medialis and lateralis, and medial and lateral heads of the gastrocnemius muscles³⁹. Maximal voluntary isometric contractions (MVIC) were performed to ensure correct electrode placement. An MVIC and a resting baseline were recorded for each muscle for normalization.

Brace

Patients performed the first of three gait analyses (Test 1). Custom knee braces (Generation II Unloader Select, Generation II USA, Inc., Bothell, Washington) were then manufactured based on measurements taken at the initial assessment. Braces were factory-set in 4° of valgus, relative to the varus alignment measured at the time of fitting. To set braces in neutral, the proximal and distal hinges were loosened ½ turn each to remove the valgus load. The same physical therapist confirmed proper brace fit and instructed subjects on brace application. Persons wore the brace throughout the day for two weeks before returning for the second gait analysis (Test 2). Following test 2, no brace was worn for two weeks (washout period). After the washout period braces were reset to the original 4° of valgus setting, relative to the varus alignment measured at the time of fitting. Patients then wore the brace for an additional two weeks before the final gait analysis (Test 3). Tension in the dynamic force strap was standardized using a compact digital triple scale, accurate to within ±0.05 kg, to ensure consistent strap tension between the neutral and valgus brace test sessions.

Pain and Functional Status Measurement

Pain and functional status were assessed during each of the brace conditions and washout period using the Knee injury and Osteoarthritis Outcome Score (KOOS)^{40–43}. Instability was assessed using the question: “To what degree does giving way, buckling or shifting of the knee affect your level of daily activity?” taken from the Knee Outcome Survey-Activities of Daily Living Scale. Reliability and responsiveness of the questionnaire and this particular question for assessing instability in individuals with osteoarthritis (OA) has been assessed and reported by others^{22,24}.

Data Management and Processing

Marker trajectories were low-pass filtered (Butterworth 4th order, phase lag) at 6 Hz using custom-written software (LabView 7, National Instruments Corporation, Austin, TX). Three-dimensional joint kinematics were calculated using the Euler angle sequence and referenced to the coordinate system from a standing calibration taken prior to motion recordings (Visual 3D, C-Motion, Rockville, MD). Stance was normalized to 100 data points and averaged across 10 trials for each subject and brace condition.

Raw EMG were low pass filtered at 350 Hz, full wave rectified and filtered a second time with a phase corrected 8th order, 20Hz-low pass Butterworth filter to generate the linear

envelope (LabView 7, National Instruments, Austin, TX). Linear envelopes were normalized to peak EMG recorded during MVIC's. Co-contraction indices (simultaneous antagonist muscle activation) were derived for the following muscle pairs: vastus medialis-medial hamstring, vastus medialis-medial gastrocnemius, vastus lateralis-lateral hamstring, and vastus lateralis-lateral gastrocnemius muscles. Muscle responses were analyzed from 100msec prior to initial contact (to account for electromechanical delay⁴⁴) to the first peak knee adduction moment. This interval was normalized to 100 data points. Co-contraction indices for each pair were derived using the procedure of Rudolph et al.⁴⁵.

Statistical Methods

Repeated-measures analysis of variance (ANOVA) was performed with *post hoc* pairwise comparisons (Least Significant Difference) for pain, function, instability, kinematic variables, and muscle co-contraction indices. Pearson product moment correlations were used to assess salient relationships among parametric variables. Spearman rank correlations were performed to assess the relationship between instability with KOOS subscores, for each period. Linear regression analysis was used to test the effect of knee alignment on muscle co-contraction for each brace condition. Statistical significance was set at $p < 0.05$ except for muscle co-contraction indices. Significance was set at $p < 0.1$ in an effort to avoid a type I error given the highly variable nature of EMG data⁴⁶. Using a general linear model for repeated measures for within-subjects effects, we obtained an observed power greater than 0.8, indicating good statistical level. All statistical analyses were performed using SPSS 14 (SPSS inc., Chicago, IL).

RESULTS

Instability

Data from all 16 subjects are presented. During the baseline assessment (Test 1), nine of 16 subjects reported the presence of knee instability, 5 of which indicated that it affected their ability to perform activities of daily living (Table 2). After 2 weeks of wearing the brace in neutral (Test 2), 1 of 16 subjects reported instability affected daily activity. Eight subjects complained that instability affected daily activity during the washout period and 6 with the valgus brace setting.

Self Report Questionnaires

Differences were found between conditions for all five subscales of the Knee Osteoarthritis Outcome Scores (KOOS). Pain, symptoms and activities of daily living were significantly lower (worse) during the baseline and washout periods compared with the neutral brace setting (Figure 1). Based on the numbers, no significant differences were evident between the washout and valgus condition or between the two braced conditions for pain and activities of daily living scores, but scores for symptoms were worse in the valgus than in the neutral condition ($p=0.049$). Based on the numbers, there were no differences in pain, symptoms and activities of daily living scores between the baseline and washout conditions. Sport and recreation, and quality of life scores significantly improved from baseline as a result of both bracing conditions. With the numbers available, scores were no different between bracing conditions and between the unbraced and washout period except for sport and recreation where it remained significantly higher during the washout period. Knee instability was significantly correlated to self-report ratings of pain, symptoms, activities of daily living and quality of life (Table 3). Those complaining of instability had increased pain and symptoms with lower activities of daily living knee function and quality of life.

Muscle Co-Contraction

The level of vastus medialis-medial hamstring (VMMH) muscle co-contraction was significantly reduced with the 4° valgus setting ($p=0.068$) (Figure 2). Vastus lateralis-lateral hamstrings (VLLH) co-contraction was significantly reduced from baseline in both neutral and valgus conditions ($p=0.014$ and $p=0.023$, respectively). At baseline measurement, frontal plane knee angle strongly predicted VLLH co-contraction ($p=0.005$; $R^2=.438$) and VMMH co-contraction ($p=0.066$; $R^2=.221$), where greater co-contraction was seen in subjects with more varus angulation. The magnitude of change in VLLH co-contraction seen in both of the braced conditions was observed to be related to degree of baseline varus angulation. Subjects in more varus alignment at baseline showed a greater decrease in VLLH co-contraction, both in the neutral brace ($p<0.001$; $r=.801$, $R^2=.642$) and the valgus setting ($p<0.001$; $r=.772$; $R^2=.596$) (Figure 3). A similar relationship was seen between degree of varus alignment and the decrease in VMMH co-contraction measures from baseline to both neutral brace and valgus brace conditions ($p=0.07$; $r=.464$; $R^2=.215$ and $p=0.06$; $r=.464$; $R^2=.23$, respectively).

Knee adduction excursions were significantly reduced as a result of bracing (Figure 4), with excursions (from heel-strike to first peak adduction moment) were lowest at 4° valgus correction. The magnitude of knee flexion excursion and medial joint space narrowing were strongly correlated, those with substantial narrowing exhibited greater knee stiffening, demonstrated by lower knee flexion excursions during weight acceptance ($p<0.001$, $r=-0.776$). Peak knee flexion angle and flexion excursions remained unchanged from the unbraced conditions.

DISCUSSION

Self reported knee pain and functional disability in people with medial knee osteoarthritis (OA) were significantly reduced in both the neutral and unloading brace conditions. Muscle co-contraction and knee adduction excursions were also lower when the knees were braced. Our hypothesis that bracing in neutral would afford the same benefits to patients with medial knee OA and varus malalignment as a brace with a 4° valgus correction was supported by the results of this study.

All patients had medial joint laxity, the majority complained of knee instability and 30% said it affected their activities of daily living. Poor knee stability was significantly correlated with decreased activities of daily living, quality of life, global knee function and higher pain and symptoms. Ultimately, functional stability was accomplished by compensatory neuromuscular adaptations, demonstrated by the higher levels of vastus medialis-medial hamstrings (VMMH) and vastus lateralis-lateral hamstrings (VLLH) muscle co-contractions. As expected functional knee stability improved with the neutral brace setting, with only 1 reporting that instability affected daily activity. Functional knee instability worsened during the washout period with 8 patients saying instability affected their activities of daily living. The fact that more individuals complained of functional instability during the washout period after having worn the brace in neutral suggests that they may have been unstable at the outset, without realizing it. The neutral brace setting also resulted in the highest overall improvements in pain and knee function score. The equivalent baseline and washout scores clearly illustrate that the 2 week washout period was sufficient, a duration often reported in the literature⁴⁷⁻⁵⁰.

At baseline when the knee was unsupported, subjects demonstrated significantly greater VMMH ($p=0.068$) and VLLH ($p=0.014$) co-contraction during weight-acceptance, which may be an attempt to stiffen the knee via increased joint compression. Work in our lab has shown that greater VMMH co-contraction in varus aligned knees, coupled with the larger

medial load (adduction moment) appears to be a response to stabilize the medial compartment through increased compression¹⁷. This strategy is contra-intuitive because increased co-contraction, while stabilizing the knee, increases joint contact pressures that could exacerbate joint destruction and pain^{17,23,25,31}. The findings that VLLH co-contractions were greater in magnitude than VMMH confirm earlier studies, and may represent an attempt to redistribute the load laterally as others have speculated^{51,52}. Both bracing conditions led to a significant overall lowering of antagonist muscle co-contractions on both the medial and lateral sides of the joint. This may result in decreased joint compression.

Valgus unloader braces apply an external valgus (abduction) moment to the knee³⁻⁵. Radiographic evaluations have shown a 1.4° lateral shift of the femoral-tibial angle with bracing⁷, as well as a 2.2° change in condylar separation angle and a 1.2 mm increase in condylar separation at heel strike⁸. One study however found no significant changes in femoral-tibial angle or joint space, based on the numbers⁹. Intuitively, unloader braces should reduce the knee varus angle and attenuate loads transmitted to the medial compartment. For knees in genu varum, the external varus (adduction) moment depends on mechanical alignment of the knee and the frontal plane location of the ground reaction force vector relative to the knee when the foot contacts the ground during stance. Thus, the ground reaction force vector would be expected to shift laterally and the overall external varus moments reduced. Using instrumented unloader braces to measure the valgus moment exerted by the brace, net varus moments have shown to be significantly reduced at 20% and 25% during the stance phase of gait⁵³ and by an average of 13%³.

The data suggest that pain relief from OA bracing may be result of reduced muscle co-contractions, mediated by the brace mechanically stabilizing the knee. This study included just 16 subjects. While small, the relatively consistent findings in the sample across the wide range of BMI's and severity of medial compartment knee OA increase the generalizability of these results to those for whom bracing is typically prescribed. The observed power of this study is more than 80%, thus increasing the sample size may actually result in a study that is overpowered for the variables of interest. With more subjects, however, perhaps other relationships with secondary variables would emerge in the regression analysis to help determine how changes in pain and function are predicted by muscle co-contraction. Quantifying the explained variance of these relationships will produce a better understanding of these mechanisms.

Brace order was not randomized. This was intentional because the basis for our protocol was to examine the subtle influences of bracing on symptomatic pain relief and neuromuscular function between the neutral and valgus brace settings. Conventional wisdom suggests the 4° valgus setting would produce the greater decrease in symptoms. Going from valgus to a neutral setting might have masked benefits of wearing the brace in the patient's normal alignment. Subjects served as their own controls with analysis focusing on the differences between brace conditions. As the data suggest, the two week washout period between the neutral and valgus force conditions was sufficient, therefore it is unlikely that order affected the clinical interpretations of the data.

The benefits of this study lie with the potential that the positive effects of the neutrally aligned brace may influence increased use of osteoarthritic braces as a method to reduce pain and improve function. Bracing is a cost-effective treatment intervention,⁵⁴ although greater access in response to clinical need appears appropriate. Among a group of patients with OA who were questioned about their health status, use of medications, various non surgical treatment modalities and use of health care resources, only 11% were informed of bracing and only 12% of those informed tried them⁵⁵. Their efficacy in maintaining higher

levels of activities has been shown⁵⁶ and compliance for long term use are encouraging^{4,15,56}.

Our results could impact the treatment of patients with symptomatic medial knee. With annual sales of OA knee braces in the United States numbering well over 125,000 (Frost & Sullivan: US Orthopedic Braces and Support Market, 2004), absent the need to induce the valgus correction, a wider range of individual body types could be braced. Reductions of patient morbidity for this widespread chronic condition could have positive impact on healthcare costs and economic productivity of the affected individuals.

Acknowledgments

This publication was made possible by Grant Number P20-RR16458 from the National Center for Research Resources (NCRR), a component of the National Institutes of Health (NIH). Its contents are the sole responsibility of the authors and do not necessarily represent the official views of the NCRR or NIH. Funding was also provided by the NIH T32HD007490 and R01AR048212. No benefits were received or will be received from a commercial party related directly or indirectly to the subject of this article. Braces ordered from the manufacturer by the Physical Therapy Clinic were paid with the grants that funded this study.

Funding provided by the National Institute of Health (P20RR016458, T32HD007490, R01HD037985, R01AR048212)

References

1. Felson DT, Lawrence RC, Dieppe PA, Hirsch R, Helmick CG, Jordan JM, Kington RS, Lane NE, Nevitt MC, Zhang Y, Sowers M, McAlindon T, Spector TD, Poole AR, Yanovski SZ, Ateshian G, Sharma L, Buckwalter JA, Brandt KD, Fries JF. Osteoarthritis: new insights. Part 1: the disease and its risk factors. *Ann Intern Med.* 2000; 133:635–646. [PubMed: 11033593]
2. Teichtahl A, Wluka A, Cicuttini FM. Abnormal biomechanics: a precursor or result of knee osteoarthritis? *Br J Sports Med.* 2003; 37:289–290. [PubMed: 12893709]
3. Pollo FE, Otis JC, Backus SI, Warren RF, Wickiewicz TL. Reduction of medial compartment loads with valgus bracing of the osteoarthritic knee. *Am J Sports Med.* 2002; 30:414–421. [PubMed: 12016084]
4. Giori NJ. Load-shifting brace treatment for osteoarthritis of the knee: A minimum 2 1/2-year follow-up study. *J Rehabil Res Dev.* 2004; 41:187–194. [PubMed: 15558372]
5. Cole BJ, Harner CD. Degenerative arthritis of the knee in active patients: evaluation and management. *J Am Acad Orthop Surg.* 1999; 7:389–402. [PubMed: 11505927]
6. Dennis DA, Komistek RD, Nadaud MC, Mahfouz M. Evaluation of offloading braces for treatment of unicompartmental knee arthrosis. *J Arthroplasty.* 2006; 21:2–8. [PubMed: 16781418]
7. Matsuno H, Kadowaki KM, Tsuji H. Generation II knee bracing for severe medial compartment osteoarthritis of the knee. *Arch Phys Med Rehabil.* 1997; 78:745–749. [PubMed: 9228878]
8. Komistek RD, Dennis DA, Northcut EJ, Wood A, Parker AW, Traina SM. An in vivo analysis of the effectiveness of the osteoarthritic knee brace during heel-strike of gait. *J Arthroplasty.* 1999; 14:738–742. [PubMed: 10512447]
9. Horlick SG, Loomer RL. Valgus knee bracing for medial gonarthrosis. *Clin J Sport Med.* 1993; 3:251–255.
10. Finger S, Paulos LE. Clinical and biomechanical evaluation of the unloading brace. *J Knee Surg.* 2002; 15:155–158. [PubMed: 12152976]
11. Lindenfeld TN, Hewett TE, Andriacchi TP. Joint loading with valgus bracing in patients with varus gonarthrosis. *Clin Orthop Rel Res.* 1997:290–297.
12. Kirkley A, Webster-Bogaert S, Litchfield R, Amendola A, MacDonald S, McCalden R, Fowler P. The effect of bracing on varus gonarthrosis. *J Bone Joint Surg Am.* 1999; 81:539–548. [PubMed: 10225800]

13. Draper ER, Cable JM, Sanchez-Ballester J, Hunt N, Robinson JR, Strachan RK. Improvement in function after valgus bracing of the knee. An analysis of gait symmetry. *J Bone Joint Surg Br.* 2000; 82:1001–1005. [PubMed: 11041589]
14. Hewett TE, Noyes FR, Barber-Westin SD, Heckmann TP. Decrease in knee joint pain increase in function in patients with medial compartment arthrosis: A prospective analysis of valgus bracing. *Orthopedics.* 1998; 21:131–138. [PubMed: 9507265]
15. Barnes CL, Cawley PW, Hederman B. Effect of CounterForce brace on symptomatic relief in a group of patients with symptomatic unicompartmental osteoarthritis: a prospective 2-year investigation. *Am J Sports Med.* 2002; 31:396–401.
16. Fitzgerald GK. Therapeutic exercise for knee osteoarthritis: considering factors that may influence outcome. *Eura Medicophys.* 2005; 41:163–171. [PubMed: 16200033]
17. Lewek MD, Rudolph KS, Snyder-Mackler L. Control of frontal plane knee laxity during gait in patients with medial compartment knee osteoarthritis. *Osteoarthritis Cartilage.* 2004; 12:745–751. [PubMed: 15325641]
18. Sharma L, Lou C, Felson DT, Dunlop DD, Kirwan-Mellis G, Hayes KW, Weinrach D, Buchanan TS. Laxity in healthy and osteoarthritic knees. *Arthritis Rheum.* 1999; 42:861–870. [PubMed: 10323441]
19. van der EM, Steultjens M, Wieringa H, Dinant H, Dekker J. Structural joint changes, malalignment, and laxity in osteoarthritis of the knee. *Scand J Rheumatol.* 2005; 34:298–301. [PubMed: 16195163]
20. Sharma L, Hayes KW, Felson DT, Buchanan TS, Kirwan-Mellis G, Lou C, Pai YC, Dunlop DD. Does laxity alter the relationship between strength and physical function in knee osteoarthritis? *Arthritis Rheum.* 1999; 42:25–32.
21. Noyes FR, Grood ES, Torzilli PA. The Definitions of Terms for Motion and Position of the Knee and Injuries of the Ligaments. *J Bone Joint Surg Am.* 1989; 71A:465–472. [PubMed: 2647751]
22. Fitzgerald GK, Piva SR, Irrgang JJ. Reports of joint instability in knee osteoarthritis: its prevalence and relationship to physical function. *Arthritis Rheum.* 2004; 51:941–946. [PubMed: 15593258]
23. Lewek MD, Ramsey DK, Snyder-Mackler L, Rudolph KS. Knee stabilization in patients with medial compartment knee osteoarthritis. *Arthritis Rheum.* 2005; 52:2845–2853. [PubMed: 16142714]
24. Irrgang JJ, Snyder-Mackler L, Wainner RS, Fu FH, Harner CD. Development of a patient-reported measure of function of the knee. *J Bone Joint Surg Am.* 1998; 80A:1132–1145. [PubMed: 9730122]
25. Childs JD, Sparto PJ, Fitzgerald GK, Bizzini M, Irrgang JJ. Alterations in lower extremity movement and muscle activation patterns in individuals with knee osteoarthritis. *Clin Biomech.* 2004; 19:44–49.
26. Chmielewski TL, Rudolph KS, Fitzgerald GK, Axe MJ, Snyder-Mackler L. Biomechanical evidence supporting a differential response to acute ACL injury. *Clin Biomech.* 2001; 16:586–591.
27. Rudolph KS, Eastlack ME, Axe MJ, Snyder-Mackler L. 1998 Basmajian Student Award Paper: Movement patterns after anterior cruciate ligament injury: a comparison of patients who compensate well for the injury and those who require operative stabilization. *J Electromyogr Kinesiol.* 1998; 8:349–362. [PubMed: 9840891]
28. Rudolph KS, Axe MJ, Buchanan TS, Scholz JP, Snyder-Mackler L. Dynamic stability in the anterior cruciate ligament deficient knee. *Knee Surg Sports Traumatol Arthrosc.* 2001; 9:62–71. [PubMed: 11354855]
29. Williams GN, Barrance PJ, Snyder-Mackler L, Axe MJ, Buchanan TS. Specificity of muscle action after anterior cruciate ligament injury. *J Orthop Res.* 2003; 21:1131–1137. [PubMed: 14554229]
30. Chmielewski TL, Hurd WJ, Snyder-Mackler L. Elucidation of a potentially destabilizing control strategy in ACL deficient non-copers. *J Electromyogr Kinesiol.* 2005; 15:83–92. [PubMed: 15642656]
31. Hodge WA, Fijan RS, Carlson KL, Burgess RG, Harris WH, Mann RW. Contact Pressures in the Human Hip-Joint Measured In vivo. *Proceedings of the National Academy of Sciences of the United States of America.* 1986; 83:2879–2883. [PubMed: 3458248]

32. Mason RB, Horne JG. The posteroanterior 45 degrees flexion weight-bearing radiograph of the knee. *J Arthroplasty*. 1995; 10:790–792. [PubMed: 8749762]
33. Messieh SS, Fowler PJ, Munro T. Anteroposterior Radiographs of the Osteoarthritic Knee. *J Bone Joint Surg Br*. 1990; 72:639–640. [PubMed: 2380220]
34. Piperno M, Le Graverand MPH, Conrozier T, Bochu M, Mathieu P, Vignon E. Quantitative evaluation of joint space width in femorotibial osteoarthritis: comparison of three radiographic views. *Osteoarthritis Cartilage*. 1998; 6:252–259. [PubMed: 9876394]
35. Swanson KE, Stocks GW, Warren PD, Hazel MR, Janssen HF. Does axial limb rotation affect the alignment measurements in deformed limbs? *Clin Orthop Rel Res*. 2000:246–252.
36. Dugdale TW, Noyes FR, Styer D. Preoperative Planning for High Tibial Osteotomy - the Effect of Lateral Tibiofemoral Separation and Tibiofemoral Length. *Clin Orthop Rel Res*. 1992:248–264.
37. Tallroth K, Lindholm TS. Stress radiographs in the evaluation of degenerative femorotibial joint disease. *Skeletal Radiol*. 1987; 16:617–620. [PubMed: 3423831]
38. Moore TM, Meyers MH, Harvey JP Jr. Collateral ligament laxity of the knee. Long-term comparison between plateau fractures normal. *J Bone Joint Surg Am*. 1976; 58:594–598. [PubMed: 932058]
39. Perroto, A. *Anatomical Guide for the Electromyographer: The Limbs and Trunk*. 3. Springfield, IL: 1994.
40. Roos EM, Roos HP, Lohmander LS, Ekdahl C, Beynnon BD. Knee Injury and Osteoarthritis Outcome Score (KOOS)--development of a self-administered outcome measure. *J Orthop Sports Phys Ther*. 1998; 28:88–96. [PubMed: 9699158]
41. Roos EM, Klassbo M, Lohmander LS. WOMAC osteoarthritis index. Reliability, validity, and responsiveness in patients with arthroscopically assessed osteoarthritis. Western Ontario and MacMaster Universities. *Scand. J Rheumatol*. 1999; 28:210–215.
42. Roos EM, Roos HP, Lohmander LS. WOMAC Osteoarthritis Index--additional dimensions for use in subjects with post-traumatic osteoarthritis of the knee. Western Ontario and MacMaster Universities. *Osteoarthritis Cartilage*. 1999; 7:216–221. [PubMed: 10222220]
43. Roos EM, Lohmander LS. The Knee injury and Osteoarthritis Outcome Score (KOOS): from joint injury to osteoarthritis. *Health Qual Life Outcomes*. 2003; 1:64. [PubMed: 14613558]
44. Vos EJ, Mullender MG, Schenau GJ. Electromechanical Delay in the Vastus Lateralis Muscle During Dynamic Isometric Contractions. *Eur J Appl Physiol*. 1990; 60:467–471.
45. Rudolph KS, Axe MJ, Snyder-Mackler L. Dynamic stability after ACL injury: who can hop? *Knee Surg Sports Traumatol Arthrosc*. 2000; 8:262–269.
46. Chmielewski TL, Hurd WJ, Rudolph KS, Axe MJ, Snyder-Mackler L. Perturbation training improves knee kinematics and reduces muscle co-contraction after complete unilateral anterior cruciate ligament rupture. *Phys Ther*. 2005; 85:740–749. [PubMed: 16048422]
47. Andriacchi TP, Lang PL, Alexander EJ, Hurwitz DE. Methods for evaluating the progression of osteoarthritis. *J Rehabil Res Dev*. 2000; 37:163–170. [PubMed: 10850822]
48. Hurwitz DE, Sharma L, Andriacchi TP. Effect of knee pain on joint loading in patients with osteoarthritis. *Curr Opin Rheumatol*. 1999; 11:422–426. [PubMed: 10503665]
49. Hurwitz DE, Ryals AR, Block JA, Sharma L, Schnitzer TJ, Andriacchi TP. Knee pain and joint loading in subjects with osteoarthritis of the knee. *J Orthop Res*. 2000; 18:572–579. [PubMed: 11052493]
50. Karlsson J, Sjogren LS, Lohmander LS. Comparison of two hyaluronan drugs and placebo in patients with knee osteoarthritis. A controlled, randomized, double-blind, parallel-design multicentre study. *Rheumatology (Oxford)*. 2002; 41:1240–1248. [PubMed: 12421996]
51. Andriacchi TP. Dynamics of knee malalignment [Review]. *Orthop Clin North Am*. 1994; 25:395–403. [PubMed: 8028883]
52. Schipplein OD, Andriacchi TP. Interaction between active and passive knee stabilizers during level walking. *J Orthop Res*. 1991; 9:113–119. [PubMed: 1984041]
53. Self BP, Greenwald RM, Pflaster DS. A biomechanical analysis of a medial unloading brace for osteoarthritis in the knee. *Arthritis Care Res*. 2000; 13:191–197. [PubMed: 14635273]

54. Segal L, Day SE, Chapman AB, Osborne RH. Can we reduce disease burden from osteoarthritis? *Med J Aust.* 2004; 180:S11–S17.
55. Li LC, Maetzel A, Pencharz JN, Maguire L, Bombardier C. Use of mainstream nonpharmacologic treatment by patients with arthritis. *Arthritis Rheum.* 2004; 51:203–209. [PubMed: 15077260]
56. Horlick, SG.; Kwon, BK.; Berkowitz, J.; Glick, N. Functional Knee Bracing for the Treatment of Unicompartement Gonarthrosis. Presented at the University of British Columbia - Orthopedic Update Meeting; Vancouver, British Columbia. June 1996;

Figure 1.
Change in Knee injury and Osteoarthritis Outcome Scores (KOOS) induced by brace setting.

Figure 2a

Figure 2b

Figure 2.

Muscle co-contraction during gait. Co-contraction values calculated from 100 ms prior to initial contact through peak knee adduction moment for **a)** VMMH (vastus medialis–medial hamstrings), VMMG (vastus medialis–medial gastrocnemius), **b)** VLLH (vastus lateralis–lateral hamstrings), and VLLG (vastus lateralis–lateral gastrocnemius). Values represent mean and standard deviation.

Figure 3a

Figure 3b

Figure 3.

Scatter plots depicting the association between the change in **a)** VLLH (vastus lateralis–lateral hamstrings) and **b)** VMMH (vastus medialis–medial hamstrings) muscle co-contractions for the neutral and valgus brace settings relative to the degree of baseline varus alignment. Best-fit linear regression lines are superimposed on the data.

Figure 4a

Figure 4b

Figure 4.

Knee flexion **a)** and adduction excursions **b)** during stance phase of gait. Bracing reduced knee flexion and adduction excursions during weight acceptance, from initial contact to peak knee flexion.

Table 1

Subjects' personal and radiographic data depicting joint alignment, joint space and laxity.

Subjects	Age (Yrs)	BMI (kg/m ²)	Knee alignment		Joint space		Joint laxity	
			WBL (%)	Mech axis (°)	Medial (mm)	Lateral (mm)	Medial (mm)	Lateral (mm)
1	57	27.2	0.084	170	3.3	4.9	5.4	4.8
2	61	37.3	0.012	170	1.8	7.1	4.7	2.8
3	70	28.8	0.309	177	1.1	5.7	4.4	2.9
4	47	32.0	0.198	177	0.4	6.4	3.8	1.8
5	61	30.4	0.257	175	0.5	8.8	7.4	6.4
6	55	28.7	0.068	170	0.5	7.9	7.1	5.4
7	73	28.9	0.536	178	1.1	5.8	3.3	1.8
8	53	26.0	0.139	172	0.6	8.0	7.5	1.1
9	57	25.2	0.242	175	2.2	4.5	6.5	3.9
10	58	35.2	0.148	174	0.5	7.6	6.1	2.2
11	47	38.2	-0.043	156	0.0	7.3	6.1	1.5
12	51	37.5	0.173	174	5.5	7.9	4.2	3.7
13	40	29.6	0.053	170	4.0	9.6	2.7	3.7
14	51	32.8	0.088	171	0.9	7.5	5.4	2.8
15	55	32.4	0.255	175	3.3	7.4	3.5	4.4
16	43	26.9	0.091	171	0.3	5.8	7.7	5.1
n = 16	54.9 (8.8)	31.1 (4.2)	0.163 (0.139)	172.2 (5.1)	1.6 (1.6)	7.0 (1.4)	5.4 (1.6)	3.4 (1.5)
Significance					p < 0.001			
p = 0.001								

BMI: Body mass index

WBL: Weight bearing line

Mech axis: Mechanical Axis

Table 2

Response to the knee outcome survey-activities of daily living scale (KOS-ADLS) question of giving way, buckling, or shifting of the knee

	Subjects			
	<i>Baseline</i>	<i>Neutral</i>	<i>Washout</i>	<i>Valgus</i>
I do not have giving way, buckling, or shifting of the knee	7	7	6	8
I have the symptom but it does not affect my activity	4	8	1	2
The symptom affects my activity slightly	2	1	7	5
The symptom affects my activity moderately	2		1	1
The symptom affects my activity severely	1			
The symptom prevents me from all daily activity				

Table 3

Correlation between knee instability and pain, symptom, activity of daily living (ADL), and quality of life (QOL) for each bracing condition.

Instability		Pain	Symptom	ADL	QOL
Baseline	Correlation Coefficient	.506(*)	.593(**)	.470(*)	.716(**)
	Sig. (1-tailed)	.023	.008	.033	.001
Neutral	Correlation Coefficient	.557(*)	.264	.517(*)	.444(*)
	Sig. (1-tailed)	.012	.162	.020	.043
Washout	Correlation Coefficient	.395	.463(*)	.472(*)	.452(*)
	Sig. (1-tailed)	.073	.041	.038	.045
Valgus	Correlation Coefficient	.461(*)	.304	.474(*)	.690(**)
	Sig. (1-tailed)	.036	.126	.032	.002

* Significant at the 0.05 level (1-tailed).

** Significant at the 0.01 level (1-tailed).