1 **The Effect of Wedge and Tibial Slope Angles on Knee Contact**
2 **Pressure and Kinematics Following Medial Opening-Wedge High**
3 **Tibial Osteotomy**

4
5 Marianne S. Black^{a,b*}, Agnes G. d'Entremont^{a,b}, Robert G. McCormack^{c,d}, Gregory
6 Hansen.^{d,e}, Derek Carr^{d,f}, David R. Wilson^{b,c}

7
*^aUniversity of British Columbia
Department of Mechanical Engineering
2054-6250 Applied Science Lane
Vancouver, BC, Canada V6T 1Z4*

*^bCentre for Hip Health and Mobility
2635 Laurel Street
Vancouver, BC, Canada V5Z 1M9*

*^cUniversity of British Columbia
Department of Orthopaedics
3114 – 910 West 10th Avenue
Vancouver, BC, Canada V5Z 1M9*

*^dNew West Orthopaedic & Sports Medicine
Centre
65 Richmond St. Suite 102
New Westminster, BC, Canada V3L 5P5*

*^eBrockville General Hospital
Department of Orthopaedic Surgery
75 Charles Street
Brockville, ON, Canada K6V 1S8*

*^fCabrini Hospital Consulting Suites
243 New Street
Brighton, Australia VIC 3186*

***Corresponding author**

Marianne Black, MASc
Stanford University
Building 520, Room 227
452 Escondido Mall
Stanford, CA, USA 94305
Email: mblack32@stanford.edu

8 Abstract Word Count: 235

9 Manuscript Word Count: 3326

10

Abstract

Background: High tibial osteotomy is a surgical procedure to treat medial compartment osteoarthritis in varus knees. The reported success rates of the procedure are inconsistent, which may be due to sagittal plane alignment of the osteotomy. The objective of this study was to determine the effect of changing tibial slope, for a range of tibial wedge angles in high tibial osteotomy, on knee joint contact pressure location and kinematics during continuous loaded flexion/extension.

Methods: Seven cadaveric knee specimens were cycled through flexion and extension in an Oxford knee-loading rig. The osteotomy on each specimen was adjusted to seven clinically relevant wedge and slope combinations. We used pressure sensors to determine the position of the centre of pressure in each compartment of the tibial plateau and infrared motion capture markers to determine tibiofemoral and patellofemoral kinematics.

Findings: In early knee flexion, a 5 degree increase in tibial slope shifted the centre of pressure in the medial compartment anteriorly by 7mm for a 15 degree wedge ($p<0.001$), (from the neutral slope/wedge position). At all wedge angles, increasing the tibial slope resulted in the tibia translating anteriorly ($p<0.001$).

Interpretation: Changes to the tibial slope during high tibial osteotomy for all tested wedge angles shifted the centre of pressure in both the medial and lateral compartments substantially and altered knee kinematics. Tibial slope should be controlled during high tibial osteotomy to prevent unwanted changes in tibial plateau contact loads.

1 Introduction

Medial opening wedge high tibial osteotomy (HTO) is performed to treat medial compartment osteoarthritis in varus knees. The mechanical objective of HTO is to realign the knee in the coronal plane to decrease load in the diseased medial compartment and increase load through the healthier lateral compartment in an effort to reduce knee joint pain, delay progression of osteoarthritis, improve instability problems, or unload the medial compartment for resurfacing. HTO is an appealing surgical alternative to arthroplasty for many young, active patients¹.

HTO is not a universally successful procedure - there is a broad range of reported survival rates for closing wedge and opening wedge HTO procedures. Closing wedge HTO procedures were widely-used for a number of decades, and have 10 year survival rates ranging from 51-98%, where survival is generally defined as not having a revision HTO or conversion to a total knee arthroplasty¹⁻⁶. In contrast with closing-wedge HTO, opening-wedge HTO allows intraoperative adjustment of the tibial slope and wedge angle, and avoids complications involving the peroneal nerve and disruption of the tibiofibular joint^{2,7}. Five-year survival rates for opening wedge HTO range from 84% to 94%^{5,8,9} and Weale et al. reported a 10 year survival rate of 63%⁵. At 10 years post operation, Hernigou et al found that only 46% of patients reported being able to walk for 1-km without pain¹⁰.

Sagittal plane alignment is generally not controlled as carefully as coronal plane alignment during opening wedge HTO¹¹, and it is not clear how sagittal plane alignment affects knee mechanics. There is consensus in the literature that an ideal coronal plane correction shifts the mechanical axis (from the centre of the hip to the centre of the ankle) to cross at 60% to 70% of the width of the tibial plateau (where 0% is the medial border and 100% is the lateral border)¹²⁻¹⁵. In the sagittal plane, studies using post-operative x-rays have shown that opening wedge HTO changes tibial slope by a mean of 3.5 degrees¹⁶, and that there is substantial variability in the tibial slope after the procedure, reported to be as much as ± 3.6 degrees¹⁷⁻²⁰.

It is not clear what effect the changes in tibial slope caused by opening-wedge HTO have on tibiofemoral contact mechanics because the results of biomechanical studies are inconsistent^{11,21,22}. One study of cadaver knees reported that an increase in tibial slope caused an anterior shift of contact pressure on the medial compartment of the tibial plateau¹¹, while another cadaver study found that an increase in slope caused no shift in peak contact pressure for knees with intact ligaments²². These inconsistencies highlight the importance of loading configurations and other testing parameters on the conclusions of biomechanical studies, as pointed out by both sets of authors in a subsequent discussion²³. It is unclear exactly which mechanical changes are associated with cartilage degeneration²⁴, so it is not clear how mechanical changes might be associated with survival or failure of HTO. However, there is evidence that changes in contact location and in relative velocity between the femoral and tibial cartilage at the joint surface are associated with degeneration^{25,26}, which have yet to be addressed by HTO studies.

The objective of this study was to determine the effect of changing tibial slope, for a range of tibial wedge angles in opening-wedge HTO, on knee joint contact pressure location, pressure distribution between the compartments, and kinematics during continuous loaded flexion/extension.

2 Methods

2.1 Specimens

Eleven cadaver knee specimens (mid-femur to mid-tibia) were included in this study. The specimens had no history or evidence of knee surgery, and the anterior cruciate ligament (ACL) and posterior cruciate ligament (PCL) were intact in each specimen. The specimens were stored in a -20°C freezer, and thawed for 48 hours before testing. The joint was dissected to the level of the capsule, and the quadriceps tendon was kept intact. We reamed the intramedullary canals of the tibia and femur and cemented in threaded steel rods with polymethyl methacrylate cement. Three specimens ultimately fractured during testing (likely suffering osteopenia and not HTO candidates), and one specimen's results strongly suggested incomplete release of the superficial MCL based on consistency with a study examining the effect of releasing the MCL in HTO²⁷. These specimens were excluded from the analysis, leaving 7 specimens (all male, mean age 62 (SD 14)).

2.1 Loading Rig

We flexed and extended each specimen under simulated vertical hip load resisted by simulated quadriceps force using an Oxford knee loading rig²⁸. The threaded rods in the intramedullary canals of the femur and tibia were connected to universal joints on the rig that simulated the hip and ankle joints. This system allowed 6 degrees of freedom between the femur and the tibia (Figure 1). A load of 118 N was applied at the hip joint, corresponding to approximately 15% body weight²⁹. This was the maximum load that could be applied without damaging the specimen. A motor and pulley system secured to the threaded rod fixed in the femur flexed and extended the knee by shortening and lengthening a cable attached to the quadriceps tendon with a tendon clamp. The quadriceps tendon was aligned with the femoral axis by adjusting the location of the pulley winding the cable in the motor system. The line of action of the cable relative to the femur did not change with flexion. Each complete cycle of flexion and extension (about 10° to 90° of flexion) lasted

approximately 70 seconds. We completed 3 sets of 3 continuous cycles of flexion-extension for each wedge-slope combination for each specimen.

2.2 Contact Mechanics

Knee joint contact pressure, area and centre of pressure were measured using capacitive pressure sensors (Pliance, Novel GmbH, Munich, Germany) designed for the tibiofemoral joint. Each sensor has an 8x16 sensor element matrix, with a sensing area of 21.5mm x 42mm. Each sensor element has a pressure resolution of 10kPa, which corresponds to a force resolution of 0.07N. Pressure sensors were calibrated before experimentation using a sensor-specific calibration device that allowed each sensor element to be calibrated independently using a 15-point calibration from 100kPa to 2400kPa. Immediately before experimentation, pressure sensors were zeroed with no applied load. Sensors were inserted sub-meniscally in both the medial and lateral tibiofemoral compartments by creating small incisions for sensor insertion anterior to the joint line (Figure 2). The joint was manually distracted during sensor insertion to allow complete insertion of the sensors. The sensors were screwed in place at 4 points to prevent any motion relative to the tibial plateau. In 5 trials comparing the measured load to the applied load, we found a maximum absolute error for the sensors on a simulated tibial plateau of 11.9% for an applied load of 22N and 1.4% for an applied load of 90N. We determined the resultant force on each compartment by adding the force on each sensing element (determined from the pressure on the sensing element and its area) in that compartment. We then calculated the proportion of joint load in each compartment by dividing the resultant force in the compartment by the resultant force in both compartments.

We used a custom written program (MATLAB, MathWorks, Natick, USA) to calculate total force and centre of pressure in each tibiofemoral compartment for the full range of flexion-extension. We determined the proportion of force transmitted through the medial and lateral compartments

and the location of the centre of pressure in each compartment. Contact pressure data were collected at 50Hz, and downsampled to 1Hz.

2.3 Kinematics

We measured tibiofemoral and patellofemoral joint kinematics by using an optical infrared motion capture system (Optotrak, Waterloo, Canada) to track motion sensors rigidly fixed to the femur, patella, proximal tibia (above osteotomy) and distal tibia (below osteotomy) using Steinman pins screwed into the bone. Landmarks on the tibia, patella and femur were digitized using the motion capture system's probing device to define coordinate systems in the tibia, patella and femur. Tibiofemoral kinematic parameters (flexion, internal rotation, abduction, medial translation, anterior translation and proximal translation) and patellofemoral kinematic parameters (flexion, tilt, spin, medial translation, anterior translation, and proximal translation) were calculated using a joint coordinate system convention³⁰. Kinematic data were collected at 50Hz, and downsampled to 1Hz.

2.4 Surgical Procedure

An orthopaedic surgeon performed a medial opening-wedge HTO on each specimen using a C-arm fluoroscope for guidance (Figure 3). The lateral cortex of the osteotomy was left intact. A bicortical external fixator (Sidekick Stealth Rearfoot Fixator, Wright Medical Technology, Memphis, USA) held the proximal and distal tibia segments securely in place during biomechanical testing, and allowed for incremental changes to be made to the wedge and slope. The tibial plateau remained intact so changes to slope were the same in the medial and lateral compartments. We tested a range of wedge and slope angles: wedge angles of 0° (closed osteotomy), 7.5°, and 15°, and slope angles of -5° (decreased tibial slope), 0° (no slope correction) and 5° (increased tibial slope). This resulted in the following wedge and slope combinations: 0° wedge with a 0° slope (neutral position), 7.5° wedge with a -5° slope, 7.5° wedge with a 0° slope, 7.5° wedge with a +5° slope, 15° wedge with a -5° slope, 15° wedge with a 0° slope, and 15° wedge with a +5° slope.

2.5 Statistics

We tested the null hypotheses that there is no difference in contact pressure parameters (anterior translation of medial compartment centre of pressure, lateral translation of medial compartment centre of pressure, anterior translation of lateral compartment centre of pressure, lateral translation of lateral compartment centre of pressure, and percent of total force in medial compartment), tibiofemoral kinematic parameters, and patellofemoral kinematic parameters between wedge-slope combinations over the range of tibiofemoral flexion tested using linear mixed models. The general model we used was:

$$y_i = b_0 + b_1 * TF_{angle} + b_2 * TF_{angle}^2 + b_3 * wedge_i + b_4 * TF_{angle} * wedge_i + b_5 * TF_{angle}^2 * wedge_i + b_6 * slope_j + b_7 * TF_{angle} * slope_j + b_8 * TF_{angle}^2 * slope_j$$

where y_i was the parameter being modelled in a particular condition, ' TF_{angle} ' was the tibiofemoral flexion angle, the wedge 'i' was (1) 0° wedge, (2) 7.5° wedge and (3) 15° wedge, and the slope 'j' was (1) 0° neutral slope, (2) -5° slope change and (3) 5° slope change. We evaluated multiple models for each parameter that included some or all of the general model terms, and then determined the best model for each parameter as the one with the minimum Bayesian information criteria. The Bayesian information criterion is used to determine the quality of the fit, while also penalizing the model for additional terms. The quadratic terms (b_2 , b_5 , and b_8) and linear interaction terms (b_4 and b_7) were only included in models where they reduced the Bayesian information criterion.

3 Results

A 5 degree increased tibial slope shifted the centre of pressure in the medial compartment anteriorly by 4.5mm ($P<0.001$) (from the neutral slope/wedge position) in early knee flexion. This anterior shift due to an increased tibial slope decreased with knee flexion, and at 80 degrees of flexion the differences in anterior displacement in the medial compartment were insignificant (Figure 4 and Table 1).

A 5 degree increase in tibial slope shifted the centre of pressure in the lateral compartment posteriorly by up to 0.6mm (from the neutral slope/wedge position) in mid flexion ($P<0.001$), and a 5 degree decrease in tibial slope shifted the centre of pressure anteriorly by 1.4mm in mid flexion ($P<0.001$) (Figure 4 and Table 1).

A 15 degree wedge decreased the proportion of load in the medial compartment from a mean of 49% (for a zero degree wedge) to a mean of 22% at 10 degrees of flexion (Figure 6) ($P<0.001$). The difference in proportion of load in the medial compartment between a 15 degree wedge and 0 degree wedge decreased with increasing flexion. A 7.5 degree wedge decreased the proportion of load in the medial compartment from a mean of 50% (for zero degree wedge) to a mean of 36% at 10 degrees of flexion ($P<0.001$). The difference in proportion of load in the medial compartment between a 7.5 degree wedge and 0 degree wedge decreased with increasing flexion (Figure 4 and Table 1).

Increasing tibial slope internally rotated the tibia ($P<0.001$) in mid and late flexion. Increased wedge angle decreased tibiofemoral internal rotation in mid to late flexion ($P<0.001$) (Figure 5 and Table 2). Increasing tibial slope translated the tibia anteriorly over the entire range of flexion, including a 9.7mm anterior translation in early flexion ($P<0.001$), while increasing the wedge translated the tibia posteriorly over the entire range of flexion, including 3.6mm posterior translation in late flexion for a 7.5 degree wedge ($P<0.001$) (Figure 5 and Table 2).

187 Increased wedge angle increased patellofemoral internal spin over the entire range of flexion,
188 including a 3.5 degree increase in internal spin at late flexion for a 7.5 degree wedge ($P<0.001$)
189 (Figure 6). Increased wedge angle increased patellofemoral medial tilt over the entire range of
190 flexion ($P<0.001$) (Figure 6). Decreasing slope decreased patellofemoral anterior translation over
191 the entire range of flexion by a consistent 1.3mm ($P<0.001$).

4 Discussion

We measured contact pressures, centres of pressure and kinematics in cadaveric knee specimens before and after opening-wedge HTO to determine the effect of changing tibial slope for a range of wedge angles in opening-wedge HTO. A 5 degree increase in slope translated the centre of pressure in the lateral compartment posteriorly for mid flexion and translated the centre of pressure anteriorly in the medial compartment for early and middle stages of flexion. A 5 degree decrease in tibial slope translated the centre of pressure in the lateral compartment anteriorly in mid flexion and translated the centre of pressure in the medial compartment posteriorly in mid flexion. A 5 degree increase in tibial slope also produced significant changes to tibiofemoral internal rotation and tibiofemoral anterior translation.

The anterior/posterior shift of the centre of pressure in each compartment resulting from slope and wedge changes with HTO surgery could contribute to abnormal cartilage stresses. It is widely accepted that cartilage is adapted regionally for the forces that it must transmit³¹, and therefore a substantial shift in where force is transmitted may overload cartilage that is not adapted to the mechanical environment. In the lateral compartment, the substantial change in the anterior/posterior position of the center of pressure due to changes in wedge and slope may be large enough to cause abnormal stresses in the new location of the center of pressure, which could speed up progression of osteoarthritis in this compartment, particularly since significantly higher forces are going through the lateral compartment following the opening-wedge HTO.

Our finding that both slope and wedge substantially altered location of the centre of pressure in the medial compartment is potentially critical in furthering our understanding of cartilage changes that occur in the medial compartment following an opening-wedge HTO since cartilage has been found to regenerate in the medial compartment following opening-wedge HTO in some cases, primarily when there is a larger wedge correction³². Further investigation is needed to understand what

changes in contact pressure location in the medial compartment could result in regeneration versus further degeneration of cartilage.

Our findings regarding significant differences in patellofemoral kinematics with changes to wedge are consistent with previous work showing an increased in medial patella tilt with an increase in wedge size, as well as the medial tilt decreasing in higher flexion angles³³. Although patellofemoral kinematics are not a primary focus of this procedure, it is important to be aware of potentially negative patellofemoral outcomes that result from altering the osteotomy. Abnormal patellofemoral joint kinematics have been related to patellofemoral pain³⁴. Specifically, female subjects with less medial tilt in early flexion were found to be more likely to suffer from patellofemoral pain³⁴. Although we saw an increase in medial tilt following an increase in HTO wedge, the magnitude of the change in tilt we found was similar to the difference between subjects with and without patellofemoral pain.

Our findings suggest that the effect of slope on anterior translation is also affected by the wedge angle, and that both angles should be considered when optimizing anterior translation. Our finding that increased tibial slope results in increased tibial anterior translation is consistent with previous studies^{11,35,36}. An opening-wedge HTO which increased tibial slope led to increased tibial anterior translation in an *in vivo* kinematic study³⁷. To our knowledge our study is the first to assess the effect of wedge angle on anterior translation, and we found that increasing the wedge angle decreased anterior translation. An increase in tibial slope is known to increase stress on the ACL³⁸, therefore understanding the effect that both wedge and slope have on anterior translation may be beneficial in mitigating large stresses on the ACL.

Our study describes the effect of tibial slope on anterior/posterior translation of contact in the tibiofemoral joint comprehensively and provides insight into why there is inconsistency in the literature. Our finding that increased tibial slope translated contact anteriorly in the medial

compartment for most of the range of flexion is qualitatively consistent with a previous study's finding that increased tibial slope with an anterior opening wedge HTO increased pressure in the anterior half of the medial compartment¹¹. These authors also reported anterior translation of the tibia with an increase in slope, which is consistent with our findings. However, they did not assess pressure distribution in the lateral compartment. Neither our findings, nor Agneskirchner's, are consistent with another study which found that increased tibial slope shifted the location of peak pressure on the entire tibial plateau posteriorly (although the shift was not statistically significant)²². While we did observe posterior translation of the centre of pressure in the lateral compartment, this was only in later stages of flexion, which were not tested in Rodner's study. These inconsistencies between Rodner's study, Agneskirchner's study and our study are likely due to the very different loading methods used. While muscle loading was simulated in our current study and in Agneskirchner's, the flexion angle of the knee was fixed in Rodner's study and muscle load was not simulated. Since there is a considerable component of quadriceps force in the anterior/posterior direction through most of flexion, this would account for differences in anterior/posterior position of the tibia and of contact.

One strength of our study is that the design allowed us to assess the effect of different slopes for a range of wedge angles. Our finding that changes in wedge angle significantly affected the impact of changes in slope angle on contact pressure and kinematics support the importance of this comprehensive assessment. This approach is in contrast with a study in which varying slopes were created indirectly through the positioning of the osteotomy plate, affecting the opening of the osteotomy²². While this approach was clinically relevant, it did not yield consistent differences in tibial slope. Our approach is also distinct from a study where only tibial slope was varied (wedge angle was held constant) by performing an anterior opening wedge osteotomy¹¹. A further strength is that we used validated, capacitive pressure sensors designed for tibiofemoral pressure

measurements, which have about one-quarter the measurement error of the Tekscan pressure sensors³⁹ used in previous studies of opening wedge HTO^{11,22}.

One limitation of this study was that the cadaver specimens were not initially in varus malalignment, as would be the case in living patients undergoing HTO. This is because it is not reasonably possible to obtain a sufficient number of specimens in varus malalignment. We believe that our report of relative changes to wedge and slope on contact pressure and kinematics still provides value to understanding the effect of HTO. Another limitation is that we included only the extensor mechanism in our loading configuration, and we did not simulate the hamstrings tendons. Active hamstrings muscles would have led to more posterior translation of the tibia. While this did not fully represent physiological loading, it was necessary to simplify the loading to the primary muscle group in the testing situation due to the indeterminacy that would be introduced by including other muscle groups. Another limitation is that we could not simulate the effects of slope only (ie a configuration with 0° wedge and +/- 5° slope) because of the restrictions imposed by our osteotomy model. However, the isolated effects of slope have been studied in the literature. A final limitation of the study is that the sample size was small. Although it is not possible to predict power in linear mixed models, it is possible that the power was insufficient and therefore the study did not detect all kinematic and load/pressure distribution changes caused by varying load and slope.

5 Conclusions

Changes to tibial slope during HTO on the order of the reported error for current procedures shifted joint contact pressure location substantially and changed tibiofemoral and patellofemoral kinematics. Changes were observed consistently for a range of clinically relevant wedge angles. Changes in contact pressure location and kinematics have the potential to affect patient outcomes. These findings make it clear that tibial slope should be controlled more accurately during high tibial osteotomy to prevent unwanted changes in tibial plateau contact loads.

Source of Funding

Funding was provided by: Canadian Institutes of Health Research (Operating Grant MOP-106680), Natural Sciences and Engineering Research Council of Canada (Discovery Grant RGPIN 227629-09), and the Canada Foundation for Innovation.

References

1. Akizuki S, Shibakawa a, Takizawa T, Yamazaki I, Horiuchi H. The long-term outcome of high tibial osteotomy: a ten- to 20-year follow-up. *J Bone Joint Surg Br.* 2008;90(5):592-596. doi:10.1302/0301-620X.90B5.20386.
2. Naudie D, Bourne R. Survivorship of the high tibial valgus osteotomy A 10-to 22-year followup study. ... *Relat Res.* 1999. http://journals.lww.com/corr/abstract/1999/10000/survivorship_of_the_high_tibial_valgus_osteotomy_a.3.aspx. Accessed June 3, 2014.
3. Koshino T, Yoshida T, Ara Y, Saito I, Saito T. Fifteen to twenty-eight years' follow-up results of high tibial valgus osteotomy for osteoarthritic knee. *Knee.* 2004;11(6):439-444. doi:10.1016/j.knee.2004.03.005.
4. Hui C, Salmon LJ, Kok A, et al. Long-term survival of high tibial osteotomy for medial compartment osteoarthritis of the knee. *Am J Sports Med.* 2011;39(1):64-70. doi:10.1177/0363546510377445.
5. Weale AE, Lee AS, MacEachern AG. High tibial osteotomy using a dynamic axial external fixator. *Clin Orthop Relat Res.* 2001;(382):154-167. <http://www.ncbi.nlm.nih.gov/pubmed/11153983>.
6. Billings A, Scott DF, Camargo MP, Hofmann AA. High Tibial Osteotomy with a Calibrated Osteotomy Guide , Rigid Internal Fixation , and Early Motion . Long-Term Follow-up H igh Tibial O steotomy with a Calibrated O steotomy G uide , R igid Internal Fixation , and E arly Motion. 2011.
7. Amendola A, Bonasia DE. Results of high tibial osteotomy: review of the literature. *Int Orthop.* 2010;34(2):155-160. doi:10.1007/s00264-009-0889-8.
8. Hernigou P, Ma W. Open wedge tibial osteotomy with acrylic bone cement as bone substitute. *Knee.* 2001;8(2):103-110. <http://www.ncbi.nlm.nih.gov/pubmed/11337236>.
9. Sterett WI, Steadman JR. Chondral resurfacing and high tibial osteotomy in the varus knee. *Am J Sports Med.* 2004;32(5):1243-1249. doi:10.1177/0363546503259301.
10. Hernigou P, Medevielle D, Debeyre J, Goutallier D. Proximal tibial osteotomy for osteoarthritis with varus deformity. A ten to thirteen-year follow-up study. *J Bone Jt Surg.* 1987;69(3):332.

324 [http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Proximal+Tibial](http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Proximal+Tibial+Osteotomy+for+Osteoarthritis+with+Varus+Deformity#0)
325 [+Osteotomy+for+Osteoarthritis+with+Varus+Deformity#0](http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Proximal+Tibial+Osteotomy+for+Osteoarthritis+with+Varus+Deformity#0). Accessed June 30,
326 2011.

327 11. Agneskirchner JD, Hurschler C, Stukenborg-Colsman C, Imhoff AB, Lobenhoffer
328 P. Effect of high tibial flexion osteotomy on cartilage pressure and joint
329 kinematics: a biomechanical study in human cadaveric knees. *Arch Orthop*
330 *Trauma Surg.* 2004;124(9):575-584. doi:10.1007/s00402-004-0728-8.

331 12. Fujisawa Y, Masuhara K, Shiomi S. The effect of high tibial osteotomy on
332 osteoarthritis of the knee. An arthroscopic study of 54 knee joints. *Orthop Clin*
333 *North Am.* 1979;10(3):585. <http://www.ncbi.nlm.nih.gov/pubmed/460834>.
334 Accessed June 30, 2011.

335 13. Sgaglione N a., Moynihan DP, Uggen C. The Use of Allografts in High Tibial
336 Osteotomy: Opening Wedge Technique. *Oper Tech Sports Med.* 2007;15(2):72-80.
337 doi:10.1053/j.otsm.2006.07.004.

338 14. Briem K, Ramsey DK, Newcomb W, Rudolph KS, Snyder-mackler L. Effects of
339 the Amount of Valgus Correction for Medial Compartment Knee Osteoarthritis on
340 Clinical Outcome , Knee Kinetics and Muscle Co-Contraction after Opening
341 Wedge High Tibial Osteotomy. *J Orthop Res.* 2007;(March):311-318.
342 doi:10.1002/jor.

343 15. Dugdale TW, Noyes FR, Styer D. Preoperative planning for high tibial osteotomy.
344 The effect of lateral tibiofemoral separation and tibiofemoral length. *Clin Orthop*
345 *Relat Res.* 1992;(274):248-264. <http://www.ncbi.nlm.nih.gov/pubmed/1729010>.

346 16. Bombaci H, Canbora K, Onur G, Görgeç M. The effect of open wedge osteotomy
347 on the posterior tibial slope. *Acta Orthop Traumatol Turc.* 2005;39(5):404-410.
348 <http://www.ncbi.nlm.nih.gov/pubmed/19684296>.

349 17. Cullu E, Aydoğdu S, Alparslan B, Sur H. Tibial slope changes following dome-
350 type high tibial osteotomy. *Knee Surg Sports Traumatol Arthrosc.* 2005;13(1):38-
351 43. doi:10.1007/s00167-004-0501-0.

352 18. Hohmann E, Bryant A, Imhoff AB. The effect of closed wedge high tibial
353 osteotomy on tibial slope: a radiographic study. *Knee Surg Sports Traumatol*
354 *Arthrosc.* 2006;14(5):454-459. doi:10.1007/s00167-005-0700-3.

355 19. Marti CB, Gautier E, Wachtl SW, Jakob RP. Accuracy of frontal and sagittal plane
356 correction in open-wedge high tibial osteotomy. *Arthroscopy.* 2004;20(4):366-372.
357 doi:10.1016/j.arthro.2004.01.024.

358 20. El-Azab H, Glabgly P, Paul J, Imhoff AB, Hinterwimmer S. Patellar height and
359 posterior tibial slope after open- and closed-wedge high tibial osteotomy: a
360 radiological study on 100 patients. *Am J Sports Med.* 2010;38(2):323-329.
361 doi:10.1177/0363546509348050.

362 21. Giffin JR, Vogrin TM, Zantop T, Woo SL, Harner CD. Effects of increasing tibial
363 slope on the biomechanics of the knee. *Am J Sport Med.* 2004;32(2):376-382.
364 <http://www.ncbi.nlm.nih.gov/entrez/query.fcgi?cmd=Retrieve&db=PubMed&dopt>

=Citation&list_uids=14977661.

22. Rodner CM, Adams DJ, Diaz V, et al. Medial Opening Wedge Tibial Osteotomy and the Sagittal Plane: The Effect of Increasing Tibial Slope on Tibiofemoral Contact Pressure. *Am J Sports Med.* 2006;34(9):1431-1441. doi:10.1177/0363546506287297.
23. Agneskirchner JD, Lobenhoffer P. Letter to the editor re: Meidal opening wedge tibial osteotomy and the sagittal plane: the effect of increasing tibial slope on tibiofemoral contact pressure. *Am J Sports Med.* 2007;35(3):494-495-496. doi:10.1177/0363546506298111.
24. Wilson DR, McWalter EJ, Johnston JD. The measurement of joint mechanics and their role in osteoarthritis genesis and progression. *Rheum Dis Clin North Am.* 2008;34(3):605-622. doi:10.1016/j.rdc.2008.05.002.
25. Anderst WJ, Tashman S. The association between velocity of the center of closest proximity on subchondral bones and osteoarthritis progression. *J Orthop Res.* 2009;27(1):71-77. doi:10.1002/jor.20702.
26. Andriacchi TP, Mündermann A, Smith RL, Alexander EJ, Dyrby CO, Koo S. A framework for the in vivo pathomechanics of osteoarthritis at the knee. *Ann Biomed Eng.* 2004;32(3):447-457. <http://www.ncbi.nlm.nih.gov/pubmed/15095819>.
27. Agneskirchner JD, Hurschler C, Wrann CD, Lobenhoffer P. The effects of valgus medial opening wedge high tibial osteotomy on articular cartilage pressure of the knee: a biomechanical study. *Arthrosc J Arthrosc Relat Surg Off Publ Arthrosc Assoc North Am Int Arthrosc Assoc.* 2007;23(8):852-861. doi:10.1016/j.arthro.2007.05.018.
28. Zavatsky AB. A Kinematic-Freedom Analysis of a Flexed-Knee-Stance Testing Rig. *J Biomech.* 1997;30(3):277-280. <http://www.ncbi.nlm.nih.gov/pubmed/21899235>.
29. Walpole SC, Prieto-Merino D, Edwards P, Cleland J, Stevens G, Roberts I. The weight of nations: an estimation of adult human biomass. *BMC Public Health.* 2012;12(1):439. doi:10.1186/1471-2458-12-439.
30. Cole G, Nigg B, Ronsky J, Yeadon M. Application of the joint coordinate system to three-dimensional joint attitude and movement representation: a standardization proposal. *J Biomech Eng.* 1993;115:344. <http://link.aip.org/link/?JBENDY/115/344/1>. Accessed July 4, 2011.
31. Koo S, Rylander JH, Andriacchi TP. Knee joint kinematics during walking influences the spatial cartilage thickness distribution in the knee. *J Biomech.* 2011;44(7):1405-1409. doi:10.1016/j.jbiomech.2010.11.020.
32. Koshino T, Wada S, Ara Y, Saito T. Regeneration of degenerated articular cartilage after high tibial valgus osteotomy for medial compartmental osteoarthritis of the knee. *Knee.* 2003;10(3):229-236. <http://www.ncbi.nlm.nih.gov/pubmed/12893144>.

33. Gaasbeek R, Welsing R, Barink M, Verdonshot N, van Kampen A. The influence of open and closed high tibial osteotomy on dynamic patellar tracking: a biomechanical study. *Knee Surg Sports Traumatol Arthrosc.* 2007;15(8):978-984. doi:10.1007/s00167-007-0305-0.
34. Draper CE, Besier TF, Santos JM, et al. 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):571-577. doi:10.1002/jor.20790.
35. Shelburne KB, Kim HJ, Sterett WI, Pandy MG. Effect of posterior tibial slope on knee biomechanics during functional activity. *J Orthop Res.* 2011;29(2):223-231. doi:10.1002/jor.21242.
36. Dejour H, Bonnin M. Tibial translation after anterior cruciate ligament rupture. Two radiological tests compared. *J Bone Jt Surgery-British Vol.* 1994;76(5):745. <http://web.jbjs.org.uk/cgi/content/abstract/76-B/5/745>. Accessed June 30, 2011.
37. d'Entremont AG, McCormack RG, Horlick SG, Stone TB, Manzary MG, Wilson DR. Effect of opening-wedge high tibial osteotomy on the three-dimensional kinematics of the knee. *Bone Jt J.* 2014;In Press:1214-1221. doi:10.1302/0301-620X.96B9.32522\$2.00.
38. Amis A a. Biomechanics of high tibial osteotomy. *Knee Surgery, Sport Traumatol Arthrosc.* 2012:197-205. doi:10.1007/s00167-012-2122-3.
39. Martinelli L, Hurschler C, Rosenbaum D. Comparison of capacitive versus resistive joint contact stress sensors. *Clin Orthop Relat Res.* 2006;447(447):214-220. doi:10.1097/01.blo.0000218730.59838.6a.

Figure Captions

Figure 1: A cadaver knee specimen mounted in the Oxford knee loading rig, which allowed 6 degrees of freedom between the femur and the tibia by allowing vertical translation, rotation, flexion and abduction of the hip as well as flexion and abduction of the ankle

Figure 2: Capacitative tibiofemoral pressure sensors (Novel GmbH) successfully implanted sub-meniscally in the medial and lateral compartments of the tibial plateau, as seen post-testing.

Figure 3: Coronal plane fluoroscopic image of the osteotomy in a cadaver specimen.

Figure 1: Tibiofemoral contact pressure plots displaying (A) medial compartment anterior-posterior translation (mm) of the centre of pressure (CoP), (B) lateral compartment anterior-posterior translation of the CoP, and (C) the proportion of tibiofemoral load in the medial compartment as a function of tibiofemoral flexion angle. For the CoP plots, a higher values specifies a more anterior position. In the legend, the first number denotes the wedge angle and the second number denotes the slope angle. For example, 7.5w-5s represents a wedge angle of 7.5° and a change in tibial slope of -5°.

Figure 5: Tibiofemoral kinematic plots displaying (A) tibiofemoral internal rotation, and (B) tibiofemoral anterior translation as a function of tibiofemoral flexion for all wedge-slope combinations, and for all specimens. In the legend, the first number denotes the wedge angle and the second number denotes the slope angle.

Figure 6: Patellofemoral kinematic plots displaying (A) patellofemoral spin (positive spin is more internal), and (B) patellofemoral tilt (where medial tilt is positive) as a function of tibiofemoral flexion for all wedge-slope combinations, and for all specimens. In the legend, the first number denotes the wedge angle and the second number denotes the slope angle.

Table 1: Linear mixed model results tables detailing the tibiofemoral contact pressure constant terms, β_0 , for each model and the difference in the constant terms, β_3 , for wedge-slope combinations at 10°, 45° and 80° of flexion.

Table 2: Linear mixed model results tables detailing the tibiofemoral kinematic constant terms, β_0 , for each model and the difference in the constant terms, β_3 , for wedge-slope combinations at 10°, 45° and 80° of flexion.

Tibiofemoral Contact Pressure

		Medial CoP AP (mm)			Medial CoP ML (mm)			Lateral CoP AP (mm)			Lateral CoP ML (mm)			% Force in Medial Compartment (%)			
Tibiofemoral Flexion Angle	10°	β_0 (intercept)	26.26	(1.59)	***	11.81	(0.50)	***	19.30	(1.66)	***	10.83	(0.93)	***	49.13	(3.30)	***
		β_3 (intercepts difference)															
		$7.5w - 0w$	-4.64	(0.12)	***	-0.38	(0.05)	***	0.131	(0.09)		0.35	(0.03)	***	-14.01	(0.21)	***
		$15w - 0w$	-8.46	(0.12)	***	-0.37	(0.06)	***	1.82	(0.08)	***	-0.22	(0.03)	***	-28.00	(0.20)	***
		$15w - 7.5w$	-3.81	(0.71)	***	0.14	(0.03)		1.70	(0.05)	***	-0.57	(0.03)	***	-14.95	(0.11)	***
		$-5s - 0s$	-2.74	(0.08)	***	0.32	(0.03)	***	0.82	(0.06)	***	-0.20	(0.02)	***	-2.58	(0.13)	***
		$5s - 0s$	4.54	(0.08)	***	-0.76	(0.04)	***	-0.88	(0.06)	***	0.56	(0.02)	***	3.42	(0.14)	***
		$5s - -5s$	7.28	(0.08)	***	-1.08	(0.04)	***	0.07	(0.06)		0.76	(0.02)	***	6.00	(0.14)	***
	45°	β_0 (intercept)	19.78	(1.18)	***	13.3	(0.37)	***	14.13	(1.78)	***	10.52	(0.83)	***	42.07	(1.71)	***
		β_3 (intercepts difference)															
		$7.5w - 0w$	-2.65	(0.06)	***	-0.26	(0.03)	***	1.80	(0.04)	***	-0.10	(0.01)	***	-6.60	(0.10)	***
		$15w - 0w$	-5.93	(0.06)	***	-1.10	(0.03)	***	5.35	(0.04)	***	0.92	(0.01)	***	-14.05	(0.10)	***
		$15w - 7.5w$	-3.28	(0.38)	***	-0.84	(0.02)	***	3.55	(0.03)	***	-0.82	(0.01)	***	-7.45	(0.06)	***
		$-5s - 0s$	-0.68	(0.05)	***	-0.39	(0.02)	***	1.38	(0.03)	***	-0.30	(0.01)	***	-0.07	(0.08)	
		$5s - 0s$	0.30	(0.05)	***	0.16	(0.02)	***	-0.64	(0.03)	***	0.11	(0.01)	***	-0.43	(0.08)	***
		$5s - -5s$	0.97	(0.05)	***	0.55	(0.20)	***	-2.02	(0.03)	***	0.41	(0.01)	***	-0.36	(0.08)	***
	80°	β_0 (intercept)	20.58	(0.82)	***	14.1	(0.57)	***	14.09	(2.03)	***	9.69	(0.75)	***	42.45	(1.18)	***
		β_3 (intercepts difference)															
		$7.5w - 0w$	-2.75	(0.10)	***	-1.11	(0.04)	***	3.11	(0.07)	***	0.29	(0.02)	***	-5.90	(0.17)	***
		$15w - 0w$	-5.42	(0.10)	***	-2.77	(0.04)	***	6.25	(0.07)	***	-0.59	(0.02)	***	-6.50	(0.17)	***
		$15w - 7.5w$	-2.67	(0.07)	***	-1.67	(0.03)		3.14	(0.05)	***	-0.88	(0.02)	***	-0.59	(0.11)	***
		$-5s - 0s$	0.21	(0.08)	*	-0.39	(0.04)	***	0.75	(0.06)	***	-0.11	(0.02)	***	1.23	(0.14)	***
		$5s - 0s$	0.09	(0.08)		0.24	(0.03)	***	-0.42	(0.06)	***	0.04	(0.02)	*	-1.04	(0.13)	***
		$5s - -5s$	0.29	(0.08)	***	0.63	(0.04)	***	-1.17	(0.06)	***	0.15	(0.02)	***	-2.28	(0.14)	***

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$

		Tibiofemoral Kinematics															
		Abduction (°)			Internal Rotation (°)			Proximal Translation (mm)			Medial Translation (mm)			Anterior Translation (mm)			
Tibiofemoral Flexion Angle	10°	β_0 (intercept)	5.36	(1.47)	***	2.81	(2.75)	-48.00	(1.53)	***	7.02	(1.00)	***	0.43	(1.40)		
		β_3 (intercepts difference)															
		$7.5w - 0w$	7.94	(0.09)	***	0.61	(0.15)	***	-3.23	(0.08)	***	-1.23	(0.05)	***	-1.33	(0.11)	***
		$15w - 0w$	17.67	(0.09)	***	-2.61	(0.15)		-9.41	(0.08)		-0.58	(0.05)	****	-4.57	(0.10)	***
		$15w - 7.5w$	9.73	(0.05)	***	-3.22	(0.09)	***	-6.12	(0.05)	***	0.66	(0.03)	***	-3.22	(0.06)	***
		$-5s - 0s$	-0.12	(0.06)	*	0.53	(0.10)	***	0.31	(0.05)	***	-0.54	(0.03)	***	3.84	(0.07)	***
		$5s - 0s$	-0.66	(0.06)	***	-0.81	(0.10)	***	0.55	(0.05)	***	0.06	(0.04)		9.71	(0.07)	***
		$5s - -5s$	0.54	(0.06)	***	0.09	(0.10)	***	0.24	(0.05)	***	-0.60	(0.00)	***	5.86	(0.07)	***
	45°	β_0 (intercept)	6.17	(1.31)	***	11.22	(2.68)	***	-44.10	(2.17)	***	3.37	(0.97)	**	-23.27	(1.47)	***
		β_3 (intercepts difference)															
		$7.5w - 0w$	6.99	(0.04)	***	-4.35	(0.07)	***	-1.53	(0.04)	***	0.15	(0.02)	***	-3.13	(0.05)	***
		$15w - 0w$	14.88	(0.04)	***	-13.56	(0.07)	***	-5.28	(0.04)	***	0.80	(0.02)	***	-7.43	(0.05)	***
		$15w - 7.5w$	7.89	(0.03)	***	-9.21	(0.07)	***	-3.74	(0.02)	***	0.65	(0.02)	***	-4.31	(0.03)	***
		$-5s - 0s$	-0.28	(0.03)	***	0.90	(0.05)	***	-2.40	(0.03)	***	-0.40	(0.02)	***	4.28	(0.04)	***
		$5s - 0s$	-0.03	(0.03)		1.65	(0.05)	***	-5.54	(0.03)	***	-0.33	(0.02)	***	9.24	(0.04)	***
		$5s - -5s$	0.31	(0.03)	***	0.75	(0.07)	***	-3.14	(0.03)	***	0.07	(0.02)	***	4.96	(0.04)	***
	80°	β_0 (intercept)	6.66	(1.21)	***	12.35	(2.76)	***	-28.92	(2.60)	***	2.50	(1.25)	*	-41.30	(1.10)	***
		β_3 (intercepts difference)															
		$7.5w - 0w$	6.37	(0.07)	***	-8.64	(0.12)	***	1.87	(0.06)	***	0.46	(0.04)	***	-3.61	(0.08)	***
		$15w - 0w$	14.05	(0.07)	***	-17.85	(0.12)	***	1.20	(0.06)	***	0.66	(0.04)	***	-9.56	(0.08)	***
		$15w - 7.5w$	7.68	(0.05)	***	-9.21	(0.07)	***	-0.67	(0.04)	***	0.20	(0.03)	***	-5.96	(0.05)	***
		$-5s - 0s$	-0.50	(0.07)	***	0.36	(0.09)	***	-3.93	(0.05)	***	-0.37	(0.03)	***	1.76	(0.06)	***
		$5s - 0s$	-0.75	(0.05)	***	0.90	(0.09)	***	-9.40	(0.05)	***	-0.32	(0.03)	***	4.37	(0.06)	***
		$5s - -5s$	-0.25	(0.05)	***	0.55	(0.09)	***	-5.45	(0.05)	***	0.05	(0.03)	***	2.61	(0.06)	***

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$

465 Table 1: Linear mixed model results tables detailing the patellofemoral contact pressure constant terms, β_0 , for each model and the difference in the constant terms,
466 β_3 , for wedge-slope combinations at 10°, 45° and 80° of flexion.

		Patellofemoral Kinematics																		
		Internal Spin (SE) (°)			Medial Tilt (SE) (°)			Flexion (SE) (°)			Proximal Translation (SE) (mm)			Medial Translation (SE) (mm)			Anterior Translation (SE) (mm)			
Tibiofemoral Flexion Angle	β_0 (intercept)	-0.74	(1.53)		-0.70	(2.17)		10.85	(1.88)	***	33.86	(1.91)	***	4.56	(1.30)	***	59.06	(0.96)	***	
	β_3 (intercepts difference)																			
	10°	7.5w – 0w	2.51	(0.07)	***	2.21	(0.10)	***	1.72	(0.15)	***	-5.46	(0.16)	***	0.27	(0.05)	***	-2.70	(0.39)	***
		15w – 0w	5.35	(0.07)	***	8.02	(0.09)	***	2.55	(0.15)	***	-9.09	(0.16)	***	2.00	(0.05)	***	-1.62	(0.37)	***
		15w – 7.5w	2.84	(0.04)	***	5.80	(0.06)	***	0.83	(0.09)	***	-3.63	(0.10)	***	1.73	(0.03)	***	1.08	(0.23)	***
		-5s – 0s	-0.18	(0.02)	***	-0.08	(0.07)	***	-0.51	(0.10)	***	-0.37	(0.12)	***	0.12	(0.03)	***	-1.30	(0.10)	***
		5s – 0s	-0.01	(0.02)		0.60	(0.07)	***	-1.90	(0.10)	***	4.04	(0.12)	***	0.95	(0.03)	***	1.91	(0.10)	***
		5s – -5s	0.20	(0.02)	***	0.68	(0.07)	***	-1.40	(0.10)	***	4.41	(0.11)	***	0.83	(0.03)	***	0.09	(0.01)	***
	45°	β_0 (intercept)	-1.19	(1.52)		-2.93	(1.47)	*	32.06	(2.31)	***	-2.36	(1.46)		5.23	(1.15)	***	46.54	(2.18)	***
		β_3 (intercepts difference)																		
		7.5w – 0w	3.12	(0.03)	***	2.40	(0.04)	***	2.67	(0.07)	***	-2.78	(0.08)	***	0.71	(0.02)	***	-4.33	(0.18)	***
		15w – 0w	6.96	(0.03)	***	5.90	(0.04)	***	4.37	(0.07)	***	-5.02	(0.08)	***	2.21	(0.02)	***	-5.26	(0.18)	***
		15w – 7.5w	3.84	(0.02)	***	3.50	(0.03)	***	1.70	(0.04)	***	-2.24	(0.05)	***	1.50	(0.01)	***	-0.93	(0.12)	***
		-5s – 0s	-0.18	(0.02)	***	0.32	(0.04)	***	-1.33	(0.05)	***	-0.18	(0.06)	**	-0.25	(0.02)	***	-1.30	(0.10)	***
		5s – 0s	0.01	(0.02)		0.97	(0.03)	***	-4.27	(0.05)	***	2.18	(0.06)	***	-0.38	(0.02)	***	1.90	(0.10)	***
		5s – -5s	0.19	(0.02)	***	0.66	(0.03)	***	-2.94	(0.05)	***	2.36	(0.06)	***	-0.13	(0.02)	***	3.21	(0.10)	***
	80°	β_0 (intercept)	-0.90	(1.84)		-4.14	(1.21)	**	58.17	(2.24)	***	-38.58	(1.14)	***	6.71	(0.96)	***	24.36	(3.31)	***
		β_3 (intercepts difference)																		
		7.5w – 0w	3.52	(0.05)	***	0.67	(0.08)	***	3.27	(0.12)	***	-0.09	(0.15)		0.62	(0.04)	***	-4.34	(0.30)	***
		15w – 0w	7.84	(0.05)	***	2.07	(0.08)	***	4.81	(0.12)	***	-0.94	(0.15)	***	2.01	(0.04)	***	-5.02	(0.29)	***
		15w – 7.5w	4.31	(0.04)	***	1.40	(0.05)	***	1.54	(0.08)	***	-0.85	(0.10)	***	1.39	(0.02)	***	-0.68	(0.21)	**
		-5s – 0s	-0.18	(0.02)	***	-0.08	(0.06)		-0.28	(0.09)	***	0.00	(0.12)		-0.02	(0.03)		-1.30	(0.10)	***
		5s – 0s	0.01	(0.02)	***	-0.09	(0.06)		-2.75	(0.09)	***	0.32	(0.12)	**	0.08	(0.03)	**	1.91	(0.10)	***
		5s – -5s	0.19	(0.02)	***	0.16	(0.08)	**	-2.47	(0.09)	***	0.32	(0.12)	**	0.01	(0.03)	**	3.21	(0.10)	***
*P<0.05, **P<0.01, ***P<0.001																				

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$

467

468

Table 2: Linear mixed model results tables detailing tibiofemoral contact results showing the general model 0w0s (0 wedge 0 slope) and the changes with wedge and slope.

			0w0s			7.5w – 0w			15w – 0w			15w – 7.5w			-5s – 0s			5s – 0s			5s – -5s		
Tibiofemoral Contact	Lateral CoP ML (mm)	b₀ (SE)	10.82 (0.96)	***	b₃ (SE)	0.64 (0.05)	***	0.17 (0.05)	***	0.47 (0.03)	***	b₇ (SE)	-0.13 (0.03)	***	0.76 (0.03)	***	-0.89 (0.03)	***					
		b₁ (SE)	0.00 (0.01)		b₄ (SE)	-0.03 (0.00)	***	-0.04 (0.00)	***	0.01 (0.00)	***	b₇ (SE)	-0.01 (0.00)	***	-0.02 (0.00)	***	0.01 (0.00)	***					
		b₂ (SE)	-0.00 (0.00)	*	b₅ (SE)	0.00 (0.00)	***	0.00 (0.00)	***	-0.00 (0.00)	***	b₉ (SE)	0.00 (0.00)	***	0.00 (0.00)	***	-0.00 (0.00)	*					
	Lateral CoP AP (mm)	b₀ (SE)	21.72 (1.71)	***	b₃ (SE)	-0.42 (0.15)	**	0.33 (0.14)	*	-0.75 (0.08)	***	b₇ (SE)	0.44 (0.09)	***	1.64 (0.10)	***	-1.20 (0.10)	***					
		b₁ (SE)	-0.26 (0.03)	***	b₄ (SE)	0.06 (0.01)	***	0.16 (0.01)	***	-0.10 (0.00)	***	b₇ (SE)	0.04 (0.01)	***	-0.08 (0.01)	***	0.13 (0.01)	***					
		b₂ (SE)	0.00 (0.00)	***	b₅ (SE)	0.00 (0.00)	*	0.00 (0.00)	***	0.00 (0.00)	***	b₉ (SE)	-0.00 (0.00)	***	0.00 (0.00)	***	-0.00 (0.00)	***					
	Medial CoP ML (mm)	b₀ (SE)	11.24 (0.58)	***	b₃ (SE)	-0.59 (0.09)	***	-0.33 (0.08)	***	-0.26 (0.05)	***	b₇ (SE)	0.66 (0.06)	***	-1.17 (0.06)	***	1.83 (0.06)	***					
		b₁ (SE)	0.06 (0.01)	***	b₄ (SE)	0.025 (0.00)	***	0.00 (0.00)		0.03 (0.00)	***	b₇ (SE)	-0.04 (0.00)	***	0.05 (0.00)	***	-0.08 (0.00)	***					
		b₂ (SE)	-0.00 (0.00)	**	b₅ (SE)	-0.00 (0.00)	***	-0.00 (0.00)	***	-0.00 (0.00)		b₉ (SE)	0.00 (0.00)	***	-0.00 (0.00)	***	0.00 (0.00)	***					
	Medial CoP AP (mm)	b₀ (SE)	29.46 (1.95)	***	b₃ (SE)	-5.60 (0.20)	***	-9.56 (0.19)	***	3.96 (0.12)	***	b₇ (SE)	-3.63 (0.13)	***	6.50 (0.14)	***	-10.13 (0.14)	***					
		b₁ (SE)	-0.35 (0.06)	***	b₄ (SE)	0.10 (0.01)	***	0.12 (0.01)	***	-0.01 (0.01)	*	b₇ (SE)	0.09 (0.01)	***	-0.21 (0.01)	***	0.31 (0.01)	***					
		b₂ (SE)	0.0030 (0.00)	***	b₅ (SE)	-0.00 (0.00)	***	-0.00 (0.00)	***	-0.00 (0.00)		b₉ (SE)	-0.00 (0.00)	***	0.00 (0.00)	***	-0.00 (0.00)	***					
	Load in Medial Compartment (%)	b₀ (SE)	52.51 (4.16)	***	b₃ (SE)	-17.36 (0.35)	***	-34.58 (0.00)	***	17.21 (0.20)	***	b₇ (SE)	-3.52 (0.23)	***	5.12 (0.23)	***	-8.64 (0.24)	***					
		b₁ (SE)	-0.37 (0.11)	**	b₄ (SE)	0.36 (0.02)	***	0.59 (0.02)	***	-0.23 (0.01)	***	b₇ (SE)	0.59 (0.02)	***	-0.18 (0.01)	***	0.28 (0.01)	***					
		b₂ (SE)	0.00 (0.00)	***	b₅ (SE)	0.00 (0.00)	***	0.00 (0.00)	***	0.00 (0.00)	***	b₉ (SE)	0.10 (0.01)	***	0.00 (0.00)	***	0.00 (0.00)	***					

P* < 0.05, *P* < 0.01, ****P* < 0.001

474

475

476

Table 3: Linear mixed model results tables detailing tibiofemoral patellofemoral results showing the general model 0w0s (0 wedge 0 slope) and the changes with wedge and slope.

		0w0s			7.5w – 0w			15w – 0w			15w – 7.5w			-5s – 0s			5s – 0s			5s – -5s		
Patellofemoral Kinematics	Anterior Translation (mm)	b ₀ (SE)	60.87 (0.95)	***	b ₃ (SE)	-1.93 (0.63)	**	0.13 (0.61)			-2.06 (0.39)	***	b ₇ (SE)	-1.30 (0.10)	***	1.91 (0.10)	***	-3.21 (0.10)	***			
		b ₁ (SE)	-0.14 (0.06)	*	b ₄ (SE)	-0.08 (0.03)	**	-0.19 (0.03)	***	0.11 (0.02)	***	b ₇ (SE)	Not included in model		Not included in model		Not included in model					
		b ₂ (SE)	-0.00 (0.00)	***	b ₅ (SE)	0.00 (0.00)	*	0.00 (0.00)	***	-0.00 (0.00)	***	b ₉ (SE)	Not included in model		Not included in model		Not included in model					
	Flexion (°)	b ₀ (SE)	5.69 (1.77)	**	b ₃ (SE)	1.38 (0.25)	***	1.77 (0.24)	***	-0.39 (0.14)	**	b ₇ (SE)	0.08 (0.17)		-0.51 (0.17)	**	0.58 (0.17)	***				
		b ₁ (SE)	0.50 (0.06)	***	b ₄ (SE)	0.04 (0.01)	**	0.08 (0.01)	***	-0.05 (0.01)	***	b ₇ (SE)	-0.07 (0.01)	***	-0.16 (0.01)	***	0.09 (0.01)	***				
		b ₂ (SE)	0.00 (0.00)	**	b ₅ (SE)	-0.00 (0.00)		0.00 (0.00)	***	0.00 (0.00)	***	b ₉ (SE)	0.00 (0.00)	***	0.00 (0.00)	***	-0.00 (0.00)	***				
	Medial Translation (mm)	b ₀ (SE)	4.52 (1.42)	**	b ₃ (SE)	0.06 (0.08)		1.87 (0.08)	***	-1.81 (0.05)	***	b ₇ (SE)	0.33 (0.05)	***	1.65 (0.06)	***	-1.32 (0.05)	***				
		b ₁ (SE)	0.00 (0.03)		b ₄ (SE)	0.02 (0.00)	***	0.02 (0.00)	***	0.01 (0.00)	***	b ₇ (SE)	-0.02 (0.00)	***	-0.08 (0.00)	***	0.05 (0.00)	***				
		b ₂ (SE)	0.00 (0.00)		b ₅ (SE)	-0.00 (0.00)	***	-0.00 (0.00)	***	0.00 (0.00)	*	b ₉ (SE)	0.00 (0.00)	***	0.00 (0.00)	***	-0.00 (0.00)	***				
	Proximal Translation (mm)	b ₀ (SE)	44.20 (2.06)	***	b ₃ (SE)	-6.22 (0.20)	***	-10.25 (0.19)	***	4.03 (0.12)	***	b ₇ (SE)	-0.42 (0.15)	**	4.57 (0.15)	***	-4.99 (0.14)	***				
		b ₁ (SE)	-1.03 (0.02)	***	b ₄ (SE)	0.08 (0.00)	***	0.12 (0.00)	***	-0.04 (0.00)	***	b ₇ (SE)	0.01 (0.00)		-0.05 (0.00)	***	0.06 (0.00)	***				
		b ₂ (SE)	Not included in model		b ₅ (SE)	Not included in model		Not included in model		Not included in model		b ₉ (SE)	Not included in model		Not included in model		Not included in model					
	Internal Spin (°)	b ₀ (SE)	-0.49 (1.57)		b ₃ (SE)	2.30 (0.11)	***	4.76 (0.11)	***	-2.46 (0.07)	***	b ₇ (SE)	-0.18 (0.02)	***	0.01 (0.02)		-0.19 (0.02)	***				
		b ₁ (SE)	-0.03 (0.01)	**	b ₄ (SE)	0.02 (0.01)	***	0.06 (0.01)	***	-0.04 (0.00)	***	b ₇ (SE)	Not included in model		Not included in model		Not included in model					
		b ₂ (SE)	0.00 (0.00)		b ₅ (SE)	0.00 (0.00)		-0.00 (0.00)	***	0.00 (0.00)	***	b ₉ (SE)	Not included in model		Not included in model		Not included in model					
	Medial Tilt (°)	b ₀ (SE)	0.13 (2.61)		b ₃ (SE)	1.81 (0.16)	***	8.31 (0.15)	***	-6.49 (0.09)	***	b ₇ (SE)	-0.34 (0.11)	**	0.26 (0.11)	*	-0.60 (0.11)	***				
		b ₁ (SE)	-0.09 (0.07)		b ₄ (SE)	0.05 (0.01)	***	-0.02 (0.01)	**	0.07 (0.00)	***	b ₇ (SE)	0.03 (0.01)	***	0.04 (0.01)	***	-0.01 (0.01)					
		b ₂ (SE)	0.00 (0.00)		b ₅ (SE)	-0.00 (0.00)	***	-0.00 (0.00)	***	-0.00 (0.00)		b ₉ (SE)	-0.00 (0.00)	***	-0.00 (0.00)	***	0.00 (0.00)	**				

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$

477

478

479

Table 4: Linear mixed model results tables detailing tibiofemoral kinematics results showing the general model 0w0s (0 wedge 0 slope) and the changes with wedge and slope.

		0w0s			7.5w – 0w			15w – 0w			15w – 7.5w			-5s – 0s			5s – 0s			5s – -5s		
Tibiofemoral Kinematics	Abduction (°)	b₀ (SE)	5.07 (1.51)	**	b₃ (SE)	8.28 (0.15)	***	18.83 (0.14)	***	-10.55 (0.08)	***	b₇ (SE)	-0.08 (0.10)		-1.13 (0.10)	***	1.04 (0.10)	***				
		b₁ (SE)	0.03 (0.01)	*	b₄ (SE)	-0.04 (0.01)	***	-0.12 (0.01)	***	0.09 (0.00)	***	b₇ (SE)	0.00 (0.00)		0.05 (0.01)	***	-0.06 (0.01)	***				
		b₂ (SE)	0.00 (0.00)		b₅ (SE)	0.00 (0.00)		0.00 (0.00)	***	-0.00 (0.00)	***	b₉ (SE)	0.00 (0.00)		-0.00 (0.00)	***	0.00 (0.00)	***				
	Anterior Translation (mm)	b₀ (SE)	8.25 (1.40)	***	b₃ (SE)	-0.58 (0.18)	**	-3.61 (0.17)	***	3.03 (0.10)	***	b₇ (SE)	3.17 (0.11)	***	9.03 (0.12)	***	-5.86 (0.12)	***				
		b₁ (SE)	-0.80 (0.05)	***	b₄ (SE)	-0.08 (0.01)	***	-0.10 (0.01)	***	0.02 (0.01)	***	b₇ (SE)	0.08 (0.01)	***	0.09 (0.01)	***	-0.01 (0.01)					
		b₂ (SE)	0.00 (0.00)	***	b₅ (SE)	0.00 (0.00)	***	0.00 (0.00)	***	0.00 (0.00)	***	b₉ (SE)	0.00 (0.00)	***	-0.00 (0.00)	***	0.00 (0.00)	***				
	Internal Rotation (°)	b₀ (SE)	-0.93 (2.91)		b₃ (SE)	2.15 (0.25)	***	1.74 (0.24)	***	0.41 (0.14)	**	b₇ (SE)	0.26 (0.16)		-2.10 (0.17)	***	2.36 (0.17)	***				
		b₁ (SE)	0.40 (0.05)	***	b₄ (SE)	-0.16 (0.01)	***	-0.46 (0.01)	***	0.31 (0.01)	***	b₇ (SE)	0.03 (0.01)	***	0.14 (0.01)	***	-0.11 (0.01)	***				
		b₂ (SE)	-0.00 (0.00)	***	b₅ (SE)	0.00 (0.00)	*	0.00 (0.00)	***	0.00 (0.00)	***	b₉ (SE)	0.00 (0.00)	***	-0.00 (0.00)	***	0.00 (0.00)	***				
	Medial Translation (mm)	b₀ (SE)	8.58 (1.08)	***	b₃ (SE)	-1.83 (0.09)	***	-1.26 (0.08)	***	-0.58 (0.05)	***	b₇ (SE)	-0.60 (0.06)	***	0.25 (0.06)	***	-0.85 (0.06)	***				
		b₁ (SE)	-0.17 (0.02)	***	b₄ (SE)	0.06 (0.00)	***	0.074 (0.00)	***	-0.01 (0.00)	***	b₇ (SE)	0.01 (0.00)	*	-0.02 (0.00)	***	0.027 (0.00)	***				
		b₂ (SE)	0.00 (0.00)	***	b₅ (SE)	-0.00 (0.00)	***	-0.00 (0.00)	***	0.00 (0.00)	***	b₉ (SE)	-0.00 (0.00)		0.00 (0.00)	***	0.00 (0.00)	***				
	Proximal Translation (mm)	b₀ (SE)	-47.04 (1.33)	***	b₃ (SE)	-3.40 (0.13)	***	-10.16 (0.13)	***	6.76 (0.08)	***	b₇ (SE)	1.31 (0.09)	***	2.71 (0.09)	***	-1.40 (0.09)	***				
		b₁ (SE)	-0.14 (0.03)	***	b₄ (SE)	0.01 (0.01)		0.07 (0.01)	***	-0.06 (0.00)	***	b₇ (SE)	-0.10 (0.00)	***	-0.23 (0.00)	***	0.12 (0.00)	***				
		b₂ (SE)	0.00 (0.00)	***	b₅ (SE)	0.00 (0.00)	***	0.00 (0.00)	***	0.00 (0.00)	***	b₉ (SE)	0.00 (0.00)	***	0.00 (0.00)	***	-0.00 (0.00)	***				
*P=<0.05, **P=<0.01, ***P=<0.001																						

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$