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Postoperative Time Dependent Tibiofemoral Articular Cartilage Contact Kinematics during Step-up after ACL Reconstruction

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Abstract

This study was to investigate the in vivo tibiofemoral cartilage contact locations before and after anterior cruciate ligament (ACL) reconstruction at 6 and 36 months.

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AUTHOR CONTRIBUTIONS STATEMENT

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Willem A. Kernkamp: Data analysis, interpretation of data, assisting in paper writing and revising the paper
Ali Hosseini: Patient recruitment, imaging analysis, data analysis, assisting in paper writing
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Lianxin Wang: 3D model construction, data analysis and interpretation
Tsung-Yuan Tsai: Data interpretation, imaging analysis and critical review of manuscript
Peter Asnis: Patient evaluation, data interpretation
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All authors have read and approved the final submitted manuscript

CONFLICT OF INTEREST

Herewith we state that we have no conflict of interest declare.

Ten patients with unilateral ACL injury were included. A step-up motion was analyzed using a combined magnetic resonance modeling and dual fluoroscopic imaging techniques. The preoperative (i.e. ACL deficient and healthy contralateral) and postoperative cartilage contact locations at 6 and 36 months were analyzed.

Similar patterns of the cartilage contact locations during the step-up motion were found for the preoperative and postoperative knee states as compared to the preoperative healthy contralateral side. At the end of step-up motion, the medial contact locations at postoperative 36 months were more anterior when compared to the preoperative healthy contralateral (p=0.02) and 6 months postoperative knee states (p=0.01). The changes of the cartilage contact locations at 36 months after ACL reconstruction compared to the healthy contralateral side were strongly correlated with the changes at 6 months postoperatively.

This study showed that the tibiofemoral cartilage contact locations of the knee changes with time after ACL reconstruction, implying an ongoing recovery process within the 36 months after the surgery. There could be an association between the short-term (6 months) and longer-term (36 months) contact kinematics after ACL reconstruction. Future studies need to investigate the intrinsic relationship between knee kinematics at different times after ACL reconstruction.

Keywords

Anterior cruciate ligament reconstruction; Cartilage contact; Osteoarthritis; Biomechanics

INTRODUCTIONS

Although anterior cruciate ligament (ACL) reconstruction has been routinely performed to stabilize the knee joint after ACL injury, numerous studies have revealed a prevalent radiographic evidence of postoperative osteoarthritis (OA) up to 85% after 10-15 years of the surgery (Ajuied et al., 2014; Chalmers et al., 2014). Various assumptions have been proposed on the mechanisms that could lead to early onset of postoperative OA (Englund and Lohmander, 2004; Pernin et al., 2010; Salmon et al., 2006; Yamaguchi et al., 2006). It has been reported that ACL injury and reconstruction cause changes to knee joint kinematics as compared to the healthy contralateral side; the kinematic changes subsequently result in a shift in cartilage loading areas that are not commonly loaded in healthy knees (Andriacchi and Dyrby, 2005; Defrate et al., 2006; Hosseini et al., 2012). The loading change in the cartilage has been widely accepted to play an important role in the OA development of the knee.

In vitro studies have been extensively used to investigate the effect of ACL reconstruction on knee joint kinematics (Bates et al., 2015; Herbort et al., 2016), and have indicated that ACL reconstruction could restore knee joint stability at time-zero after the surgery (Bates et al., 2015). In vivo studies have reported on the postoperative knee kinematics during various functional knee joint activities, such as gait (Gao and Zheng, 2010; Zabala et al., 2013), lunge (Hosseini et al., 2012; Papannagari et al., 2006), step-up (Zabala et al., 2013), jump landing (Ristanis et al., 2009), downhill running (Hoshino and Tashman, 2012) etc. In general, these studies demonstrated that ACL reconstruction improved knee joint kinematics, but was unable to restore normal knee kinematics under weight-bearing, functional loading conditions.

However, different postoperative time points were used in these in vivo studies, with the majority performed within one year after the surgery (Gao et al., 2012; Gao and Zheng, 2010; Hosseini et al., 2012). It is well known that ACL reconstruction experiences postoperative graft healing/remodeling as was shown in animal model (Wei et al., 2011) as well as muscle strength recovery through rehabilitations (Grindem et al., 2014; Grindem et al., 2015). A paucity of data and inconsistencies exists in the current literature when it comes to changes of knee joint kinematics with postoperative time. Some investigators described significant changes over time (Webster et al., 2012; Zaid et al., 2015), while others described no changes (Tagesson et al., 2015). These differences might be explained due to the various measurement methods with limited accuracy: reflective-markers (Webster et al., 2012), electrogoniometer (Zaid et al., 2015) and a MRI kinematic loading technique (Zaid et al., 2015). In addition, it was suggested that a single time point measurement of knee kinematics might not reflect the long-term outcome of ACL reconstruction surgery (Webster et al., 2012). Therefore, it is important to quantitatively determine if there is a change in knee joint kinematics during functional knee activities with postoperative time and if there is a relationship between the knee kinematics changes at different postoperative time points in order to investigate the mechanisms of postoperative OA development in ACL reconstruction patients.

The objective of this study was to evaluate the in vivo tibiofemoral cartilage contact locations at three different time points (before operation, 6 and 36 months after ACL reconstruction) during a dynamic step-up motion. We hypothesize that the cartilage contact locations change over time and there could be an association between the short-term and long-term postoperative knee kinematics after ACL reconstruction during the same functional activity.

METHODS

Subjects

This study was approved by the Institutional Review Board and written consent was obtained from all subjects prior to participation in the study. Ten patients (sex: 5 males/5 females; age: 36.7 ± 9.3 years; body height: 171.3 ± 5.9 cm; body mass: 74.9 ± 8.6 kg; BMI: 25.5 ± 2.8 kg/m^2) with a unilateral ACL injured knee and no other ligamentous injuries, no evidence of gross cartilage damage at the time of ACL injury confirmed by magnetic resonance imaging (MRI) and arthroscopy (ICRS grade 0), and no history of contralateral knee injury or knee pain participated in this study. None of the patients had new onset of injury to either knee after ACL reconstruction (Table 1).

ACL Reconstruction Technique and Rehabilitation

All patients underwent ACL reconstruction within 6 weeks after injury. All surgeries were performed by one surgeon using a bone-patellar tendon-bone graft and a modified transtibial technique which is able to place the graft in more anatomic fashion (Sim et al., 2011).

Postoperatively, a simple knee brace was used to immobilize the reconstructed knee. Isometric knee muscle exercises were applied one day after surgery. Range of motion of the knee and weight bearing exercises were allowed 3-4 days after surgery and progressed gradually. Full-weight bearing without any crutch was encouraged within the first 4 weeks. Various sport activities were practiced step-by-step, and desired sport activities were allowed between 6 to 9 months after surgery if the patient had achieved at least 80% of the knee extension strength of the uninjured leg.

Imaging procedures

Both knees (i.e. healthy contralateral and ACL injured) were scanned using a 3-Tesla magnetic resonance (MR) scanner (MAGNETOM Trio, Siemens, Malvern, PA, USA) prior to surgery. The MR images were used to construct 3 dimensional (3D) models of both knees, including the femur, tibia, and cartilage surfaces, using an established protocol (Li et al., 2013). All patients then performed a step-up motion (14 cm high) prior to, at 6 and 36 months after ACL reconstruction. The knee motion was imaged using a dual fluoroscopic imaging system (**Fig. 1A**). The healthy contralateral knee was imaged once, prior to the ACL reconstruction.

To maintain the consistency of the primary measure in the longitudinal study design, the experimental setup was kept the same during the preoperative to 36 months postoperative measurements using the advantage of the compact buildup of the dual fluoroscopic system (**Fig. 1**). Prior to taking the fluoroscopic images, each patient was asked to practice the step-up motion several times. The images of the finale, single motor task motion were used for analyses.

The dual fluoroscopic images were imported into solid modeling software (Rhinoceros, Robert McNeel and Assoc, Seattle, WA, USA) and placed in the orthogonal planes that were created based on the positions of the actual fluoroscopes during the imaging of patient's knee motion. Two virtual cameras were setup in the software to represent the x-ray sources of the actual fluoroscopes. Therefore, a virtual dual fluoroscopic system was recreated in the software. The 3D knee model was then introduced in the software and viewed from the two orthogonal directions from the two virtual cameras. The 3D knee model could be independently manipulated in 6 degrees-of-freedom inside the software until the projections of the model matched the silhouettes of the corresponding bones on the two fluoroscopic images. In this way, the model reproduced the in vivo position of the knee. Using the series of images captured during the step-up motion, the knee positions along the motion path could be reproduced using a series of 3D knee models. This analysis method has been previously validated with an error of <0.1 mm and a repeatability of <0.38° in measuring the position and orientation of the knee, respectively (Defrate et al., 2006; Hosseini et al., 2012).

To analyze the tibiofemoral cartilage contact locations, the cartilage models of the femur and tibia were mapped to the corresponding bony models at each knee position. The cartilage contact area at a given knee position was determined by overlapping of the tibial and femoral cartilage surfaces (Li et al., 2013). The centroid of the overlapping area was defined as the cartilage contact location. In this study, the contact locations were depicted on the medial and lateral tibial cartilage surfaces in anterior-posterior and medial-lateral directions using a coordinate system constructed on the tibial plateau (**Fig. 1B**). The tibial long axis was defined parallel to the posterior wall of the tibial shaft. The medial-lateral axis was defined as a line connecting the centroids of the two circles fit to the medial and lateral tibial plateau surfaces (Chen et al., 2012). The anterior-posterior axis was perpendicular to the other two axes. For each patient, the coordinate system was built on the injured knee and mirror-mapped to the healthy contralateral side as used in our previous studies (Liu et al., 2010). The femoral long axis was defined along the femoral shaft. The knee flexion angle was defined as the angle between the tibial and femoral long axes in the sagittal plane.

Data analysis

In this study, the knee kinematics at different time points after ACL reconstruction, i.e. prior to, 6 months and 36 months after ACL reconstruction were analyzed. The tibiofemoral cartilage contact locations on the tibial plateau in both anterior-posterior and medial-lateral directions were acquired along the step-up motion. The cartilage contact locations and knee flexion angle at end of the step-up motion (i.e. 100%) was specifically analyzed since the ACL mainly functions at low flexion angles (Jordan et al., 2007; Wu et al., 2010). The healthy contralateral knee was used as a baseline reference for calculation of the changes of the cartilage contact locations at end of the step-up motion at different postoperative time points. This was done by subtracting the postoperative cartilage contact location data from that of the healthy contralateral knees.

Statistical analysis

Changes in cartilage contact location at every 10% of the step-up motion between healthy contralateral, preoperative and reconstructed knee conditions (i.e., 6 and 36 months postoperatively) were assessed using a repeated measure ANOVA test, having the Tukey post hoc test to determine statistically significant differences in cartilage contact locations between knee states. The differences at the end of the step-up motion were specifically analyzed. Pearson correlation analysis was used to evaluate the relationship between the changes of the cartilage contact locations at 6 and 36 months after ACL reconstruction. Significant difference was set when $p<0.05$.

RESULTS

Cartilage contact locations along step-up motion with postoperative time

Similar patterns for both medial and lateral cartilage contact locations during the step-up motion were seen in the anterior-posterior and medial-lateral directions among the healthy contralateral, preoperative and postoperative knee states at 6 and 36 months. Both the cartilage contact locations of the medial and lateral compartments moved anteriorly with increasing knee extension (**Fig. 2**, see **Appendix** for data of means and standard deviations).

At the end of the step-up motion (100%), no statistically significant differences in cartilage contact locations were found between the healthy contralateral, preoperative and 6 months postoperative knee states in the anterior direction. When compared to the healthy contralateral side, at 36 months postoperatively, the cartilage contact locations were located significantly more anteriorly in medial compartment ($p=0.02$), but did not change significantly in the lateral compartment ($p=0.21$). At 36 months, the cartilage contact locations of both the medial and lateral compartment were located significantly more anteriorly when compared to the preoperative ($p=0.05$, $p=0.02$, respectively) and at 6 months postoperative ($p=0.01$, $p=0.04$, respectively) knee states. No significant differences were found for the medial-lateral translation in both the medial and lateral compartment (**Fig. 3)**.

Changes of cartilage contact locations with postoperative time

At the end of step-up motion, when compared to the healthy contralateral side, both the medial and lateral cartilage contact locations did not change significantly in the anterior-posterior direction at 6 months postoperatively (by −1.5 ± 3.6 mm and −0.9 ± 3.4 mm, respectively). In the medial-lateral direction, the contact locations also did not change significantly at the medial and lateral compartments (by −0.1 ± 2.4 mm and −1.0 ± 3.4 mm, respectively). At 36 months postoperatively, the medial contact location changed by 1.6 ± 1.7 mm ($p=0.02$) and the lateral side not significantly by 0.9 ± 2.1 mm in the anterior-posterior direction as compared to the contralateral knee. In the medial-lateral direction, the contact location did not change significantly for the medial and lateral compartments (by −0.6 ± 2.7 mm and −0.6 ± 3.2 mm, respectively).

The changes of anterior-posterior contact locations at 6 and 36 months postoperatively were found to have strong correlations at the medial compartment ($r=0.65$, $p=0.03$) (**Fig. 4A**) and at the lateral compartment ($r=0.73$, $p=0.02$) (**Fig. 4B**). No significant correlation was found for the changes in medial-lateral direction between 6 and 36 months postoperatively at the medial compartment ($r=0.43$, $p=0.22$) (**Fig. 4C**), but a strong correlation was found at the lateral compartment between the changes of the contact location in the medial-later direction at 6 and 36 months ($r=0.78$, $p=0.01$) (**Fig. 4D**).

DISCUSSION

This study investigated the in vivo tibiofemoral cartilage contact locations of the knee during a dynamic step-up motion at three time points: preoperatively (healthy contralateral and ACL deficient knees) and postoperatively (ACL reconstructed knee at 6 and 36 months). The data indicated that although the cartilage contact locations showed similar patterns at the three time points along the step-up motion, at the end of the motion, the contact locations were located more anteriorly at 36 months postoperatively when compared to those of the healthy contralateral, preoperative, and 6 months postoperative knee states. A strong correlation was found between the changes in contact locations in anterior-posterior direction of both medial and lateral compartments measured at 36 months and those measured at 6 months after ACL reconstruction. These data are in agreement with our hypothesis that the cartilage contact locations change with postoperative time and there could be a possible association between the short-term and long-term postoperative knee kinematics after ACL reconstruction during the step-up activity.

Postoperative knee kinematics after ACL reconstruction have been reported extensively in literature (Bates et al., 2015; Herbort et al., 2016). However, these studies investigated knee motion at different time points after the surgery. For example, Gao et al. studied the gait kinematics of the knee within 1 year of operation (Gao et al., 2012). Hosseini et al. reported

ACL reconstruction knee kinematics 6 months after the surgery (Hosseini et al., 2012). Scanlan et al. investigated the relationship between peak knee extension at heel strike of walking and the location of thickest femoral cartilage after 2 years of operation (Scanlan et al., 2013). In general, these studies reported that ACL reconstruction significantly improved knee kinematics, but was unable to restore functional knee kinematics to normal.

Several recent studies also indicated that the knee kinematics could change with time postoperatively. For example, Webster et al. found greater extension of the knee at terminal stance of the gait cycle and increased internal rotation at 3-years after ACL reconstruction when compared to the kinematics data at 10 months follow-up (Webster et al., 2012). Zaid et al. found that the ACL reconstructed knee at 6 months follow-up was significantly more anteriorly as compared to the contralateral healthy knee, but no differences were found at 1-year follow-up (Zaid et al., 2015). Our data further corroborate on that cartilage contact locations might change with postoperative time after ACL reconstruction at the end of the step-up motion.

The change of knee kinematics with time after ACL reconstruction has a profound impact on investigation of ACL reconstruction biomechanics. In clinical practice, patients are usually considered healed from the surgery at 6 months after ACL reconstruction, and at 8 to 12 months patients are recommended for full activities. (Kruse et al., 2012) These recommendations to patients after ACL reconstruction were mostly based on investigation of ACL reconstruction healing using animal models. For example, the ACL graft properties were shown to sharply deteriorate after surgery until 6 to 8 weeks and then slowly to recover (Wei et al., 2011). Therefore, most postoperative knee kinematics research did not consider the postoperative time effect. Our data and recent literature reports indicate that measurement of the knee kinematics after ACL reconstruction at only one postoperative time point may be insufficient to fully demonstrate the effect of the surgery on knee joint biomechanics.

Despite the recent recognition on the changes of knee kinematics at different postoperative times after ACL reconstruction (Webster et al., 2012), no data has been reported on the relationship of the knee joint motion at different postoperative times. Our data showed that the cartilage contact locations of both the medial and lateral compartments at 36 months after surgery were different from that measured at 6 months after surgery. The changes of the anteriorly located tibiofemoral cartilage contact locations at the end of the step-up motion at 6 and 36 months after the surgery were positively correlated, implying that there may be a relationship between the cartilage contact locations at 6 months follow up and the longer postoperative follow up time.

Various mechanisms have been proposed to play a role in the changes of functional knee kinematics after ACL reconstruction. The graft and graft-tunnel healing could affect the knee joint function, however no study has reported on human graft and graft-tunnel healing with time due to technical difficulties. The correlation between the changes of postoperative cartilage contact locations at 6 and 36 months imply that there could be an intrinsic biomechanical relationship in knee kinematics at the two postoperative times. Scientifically, this is an interesting observation and indicates that long-term knee kinematics after ACL reconstruction may be estimated using a early postoperative time measurement. A future study is warranted to quantitatively investigate the relationship between short-term and longer-term postoperative knee kinematics during various functional knee activities, so that the longer-term knee kinematics could be predicted using the short-term post-operative measurements of the knee kinematics. Future studies should also determine the postoperative time that is needed to reach a state in which knee kinematics remain unchanged with postoperative time.

Recently, biochemical MRI methods have been used to test the matrix changes of cartilage after ACL reconstruction by comparing with healthy populations or healthy contralateral knees (Bae et al., 2015; Li et al., 2011; Theologis et al., 2014; Van Ginckel et al., 2013). Van Ginckel et al. reported that T2 values of the medial femoral cartilage of ACL-reconstructed knees were higher than those of normal controls at 6 months following ACL reconstruction (Van Ginckel et al., 2013). Theologis et al. found that T1ρ values of the medial femoral condyle and medial tibia in ACL-reconstructed knees increased at 12-16 months of follow-up compared to the contralateral knees (Theologis et al., 2014). Bae et al. found that heterogeneously increased T2 values in the ACL reconstructed knees when compared to the contralateral knees at the 3-year follow-up (Bae et al., 2015), where most patients (9 out of 10) showed increases in T2 values in the weight-bearing areas of both the medial and lateral compartments of the ACL-reconstructed knees. The results of the current study showed that the cartilage contact locations changed with postoperative time during the same dynamic knee activity. It would be interesting to further investigate how the cartilage contact kinematics change could cause cartilage contact deformation change, and if the cartilage contact deformation change is associated to the postoperative OA development.

The data of this study should be explained under several limitations. First, the number of patients in the present study is relatively small although statistical significances were detected in kinematics changes at different postoperative time points. The high standard deviations relative to the magnitude of differences in the results could be due to the inter-subject different. However, this is a repeated measure experiment design. A post hoc power analysis showed that the data has 75% power in detecting the differences between the cartilage contact locations in anterior-posterior direction of the ACL reconstructed knee measured at 36 months after the surgery and of the intact contralateral side measured preoperatively. In future study, a larger number of patients should be recruited to help strengthen the statistical analysis power. Second, although all patients in the present study followed one rehabilitation program after the ACL reconstruction and all returned to normal functional activity, the alternations of muscle strength at 36 months following ACL reconstruction remain unclear. Third, the healthy contralateral knee was measured at one point. However, this should not affect the current data analysis since we used the intact contralateral side data measured preoperatively as a reference to calculate changes of knee kinematics postoperatively, and different research groups have described that the healthy contralateral knee kinematics do not change over time (Tagesson et al., 2015; Tashman et al., 2004). Forth, we acquired data only during one functional activity. The step-up motion was used because this has been described to be one of the most important daily activities. This activity creates a large joint moment together with quadriceps-hamstring co-contraction to help stabilize the knee and has been adopted as a closed-kinetic chain exercise in various lower extremity rehabilitation protocols (Bynum et al., 1995; Garling et al., 2008; McQuade and de Oliveira, 2011). Other in vivo activities such as lunging, walking and running should be considered in future studies. Finally, the cartilage contact locations were measured from a single motor-task step-up motion, future studies may use repeated series analyses. The accuracy and repeatability of the cartilage contact locations were not analyzed in this study. Further, the determination of cartilage surfaces and the assumptions of the centroid of the contact area approach could also affect the current results (Marouane et al., 2016).

In conclusion, the data of this study showed that tibiofemoral cartilage contact locations changed with postoperative time after ACL reconstruction. The changes of cartilage contact locations at 6 months postoperatively showed strong correlation with the changes of contact locations at 36 months after the surgery. This information is essential for investigation of the biomechanical mechanisms of postoperative OA development in ACL reconstructed knees. Improved understanding of the mechanism behind the kinematic changes with postoperative time may be valuable for developing future rehabilitation regimens and surgical techniques that can help return patients back to normal activities and reduce the risk of postoperative OA development.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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REFERENCES

Ajuied A, Wong F, Smith C, Norris M, Earnshaw P, Back D, Davies A. Anterior cruciate ligament injury and radiologic progression of knee osteoarthritis: a systematic review and meta-analysis. Am J Sports Med. 2014; 42:2242–2252. [PubMed: 24214929]

Andriacchi TP, Dyrby CO. Interactions between kinematics and loading during walking for the normal and ACL deficient knee. J Biomech. 2005; 38:293–298. [PubMed: 15598456]

Bae JH, Hosseini A, Wang Y, Torriani M, Gill TJ, Grodzinsky AJ, Li G. Articular cartilage of the knee 3 years after ACL reconstruction. Acta Orthop. 2015; 86:605–610. [PubMed: 25854533]

Bates NA, Myer GD, Shearn JT, Hewett TE. Anterior cruciate ligament biomechanics during robotic and mechanical simulations of physiologic and clinical motion tasks: a systematic review and meta-analysis. Clin Biomech (Bristol, Avon). 2015; 30:1–13.

Bynum EB, Barrack RL, Alexander AH. Open versus closed chain kinetic exercises after anterior cruciate ligament reconstruction. A prospective randomized study. The American journal of sports medicine. 1995; 23:401–406. [PubMed: 7573647]

Chalmers PN, Mall NA, Moric M, Sherman SL, Paletta GP, Cole BJ, Bach BR Jr. Does ACL reconstruction alter natural history?: A systematic literature review of long-term outcomes. The Journal of bone and joint surgery. American. 2014; 96:292–300.

Chen CH, Li JS, Hosseini A, Gadikota HR, Gill TJ, Li G. Anteroposterior stability of the knee during the stance phase of gait after anterior cruciate ligament deficiency. Gait Posture. 2012; 35:467–471. [PubMed: 22169387]

Defrate LE, Papannagari R, Gill TJ, Moses JM, Pathare NP, Li G. The 6 degrees of freedom kinematics of the knee after anterior cruciate ligament deficiency: an in vivo imaging analysis. The American journal of sports medicine. 2006; 34:1240–1246. [PubMed: 16636348]

Englund M, Lohmander LS. Risk factors for symptomatic knee osteoarthritis fifteen to twenty-two years after meniscectomy. Arthritis Rheum. 2004; 50:2811–2819. [PubMed: 15457449]

Gao B, Cordova ML, Zheng NN. Three-dimensional joint kinematics of ACL-deficient and ACL-reconstructed knees during stair ascent and descent. Hum Mov Sci. 2012; 31:222–235. [PubMed: 21798608]

Gao B, Zheng NN. Alterations in three-dimensional joint kinematics of anterior cruciate ligament-deficient and -reconstructed knees during walking. Clin Biomech (Bristol, Avon). 2010; 25:222–229.

Garling EH, Wolterbeek N, Velzeboer S, Nelissen RG, Valstar ER, Doorenbosch CA, Harlaar J. Co-contraction in RA patients with a mobile bearing total knee prosthesis during a step-up task. Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA. 2008; 16:734–740.

Grindem H, Eitzen I, Engebretsen L, Snyder-Mackler L, Risberg MA. Nonsurgical or Surgical Treatment of ACL Injuries: Knee Function, Sports Participation, and Knee Reinjury: The Delaware-Oslo ACL Cohort Study. J Bone Joint Surg Am. 2014; 96:1233–1241. [PubMed: 25100769]

Grindem H, Granan LP, Risberg MA, Engebretsen L, Snyder-Mackler L, Eitzen I. How does a combined preoperative and postoperative rehabilitation programme influence the outcome of ACL reconstruction 2 years after surgery? A comparison between patients in the Delaware-Oslo ACL Cohort and the Norwegian National Knee Ligament Registry. Br J Sports Med. 2015; 49:385–389. [PubMed: 25351782]

Herbort M, Domnick C, Raschke MJ, Lenschow S, Forster T, Petersen W, Zantop T. Comparison of Knee Kinematics After Single-Bundle Anterior Cruciate Ligament Reconstruction via the Medial Portal Technique With a Central Femoral Tunnel and an Eccentric Femoral Tunnel and After Anatomic Double-Bundle Reconstruction: A Human Cadaveric Study. Am J Sports Med. 2016; 44:126–132. [PubMed: 26574601]

Hoshino Y, Tashman S. Internal tibial rotation during in vivo, dynamic activity induces greater sliding of tibio-femoral joint contact on the medial compartment. Knee Surg Sports Traumatol Arthrosc. 2012; 20:1268–1275. [PubMed: 22041716]

Hosseini A, Van de Velde S, Gill TJ, Li G. Tibiofemoral cartilage contact biomechanics in patients after reconstruction of a ruptured anterior cruciate ligament. Journal of orthopaedic research : official publication of the Orthopaedic Research Society. 2012; 30:1781–1788. [PubMed: 22528687]

Jordan SS, DeFrate LE, Nha KW, Papannagari R, Gill TJ, Li G. The in vivo kinematics of the anteromedial and posterolateral bundles of the anterior cruciate ligament during weightbearing knee flexion. Am J Sports Med. 2007; 35:547–554. [PubMed: 17261571]

Kruse LM, Gray B, Wright RW. Rehabilitation after anterior cruciate ligament reconstruction: a systematic review. J Bone Joint Surg Am. 2012; 94:1737–1748. [PubMed: 23032584]

Li JS, Hosseini A, Cancre L, Ryan N, Rubash HE, Li G. Kinematic characteristics of the tibiofemoral joint during a step-up activity. Gait Posture. 2013; 38:712–716. [PubMed: 23541765]

Li X, Kuo D, Theologis A, Carballido-Gamio J, Stehling C, Link TM, Ma CB, Majumdar S. Cartilage in anterior cruciate ligament-reconstructed knees: MR imaging T1{rho} and T2--initial experience with 1-year follow-up. Radiology. 2011; 258:505–514. [PubMed: 21177392]

Liu F, Kozanek M, Hosseini A, Van de Velde SK, Gill TJ, Rubash HE, Li G. In vivo tibiofemoral cartilage deformation during the stance phase of gait. J Biomech. 2010; 43:658–665. [PubMed: 19896131]

Marouane H, Shirazi-Adl A, Adouni M. Alterations in knee contact forces and centers in stance phase of gait: A detailed lower extremity musculoskeletal model. J Biomech. 2016; 49:185–192. [PubMed: 26708962]

McQuade KJ, de Oliveira AS. Effects of progressive resistance strength training on knee biomechanics during single leg step-up in persons with mild knee osteoarthritis. Clinical biomechanics. 2011; 26:741–748. [PubMed: 21514018]

Papannagari R, Gill TJ, Defrate LE, Moses JM, Petruska AJ, Li G. In vivo kinematics of the knee after anterior cruciate ligament reconstruction: a clinical and functional evaluation. Am J Sports Med. 2006; 34:2006–2012. [PubMed: 16885514]

Pernin J, Verdonk P, Si Selmi TA, Massin P, Neyret P. Long-term follow-up of 24.5 years after intra-articular anterior cruciate ligament reconstruction with lateral extra-articular augmentation. Am J Sports Med. 2010; 38:1094–1102. [PubMed: 20305053]

Ristanis S, Stergiou N, Siarava E, Ntoulia A, Mitsionis G, Georgoulis AD. Effect of femoral tunnel placement for reconstruction of the anterior cruciate ligament on tibial rotation. The Journal of bone and joint surgery. American. 2009; 91:2151–2158. [PubMed: 19723992]

Salmon LJ, Russell VJ, Refshauge K, Kader D, Connolly C, Linklater J, Pinczewski LA. Long-term outcome of endoscopic anterior cruciate ligament reconstruction with patellar tendon autograft: minimum 13-year review. Am J Sports Med. 2006; 34:721–732. [PubMed: 16399931]

Scanlan SF, Favre J, Andriacchi TP. The relationship between peak knee extension at heel-strike of walking and the location of thickest femoral cartilage in ACL reconstructed and healthy contralateral knees. J Biomech. 2013; 46:849–854. [PubMed: 23375789]

Sim JA, Gadikota HR, Li JS, Li G, Gill TJ. Biomechanical evaluation of knee joint laxities and graft forces after anterior cruciate ligament reconstruction by anteromedial portal, outside-in, and transtibial techniques. Am J Sports Med. 2011; 39:2604–2610. [PubMed: 21908717]

Tagesson S, Oberg B, Kvist J. Static and dynamic tibial translation before, 5 weeks after, and 5 years after anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc. 2015; 23:3691–3697. [PubMed: 25261221]

Tashman S, Collon D, Anderson K, Kolowich P, Anderst W. Abnormal rotational knee motion during running after anterior cruciate ligament reconstruction. Am J Sports Med. 2004; 32:975–983. [PubMed: 15150046]

Theologis AA, Haughom B, Liang F, Zhang Y, Majumdar S, Link TM, Ma CB, Li X. Comparison of T1rho relaxation times between ACL-reconstructed knees and contralateral uninjured knees. Knee Surg Sports Traumatol Arthrosc. 2014; 22:298–307. [PubMed: 23370983]

Van Ginckel A, Verdonk P, Victor J, Witvrouw E. Cartilage status in relation to return to sports after anterior cruciate ligament reconstruction. Am J Sports Med. 2013; 41:550–559. [PubMed: 23380160]

Webster KE, Feller JA, Wittwer JE. Longitudinal changes in knee joint biomechanics during level walking following anterior cruciate ligament reconstruction surgery. Gait Posture. 2012; 36:167–171. [PubMed: 22469773]

Wei X, Mao Z, Hou Y, Lin L, Xue T, Chen L, Wang H, Yu C. Local administration of TGFbeta-1/VEGF165 gene-transduced bone mesenchymal stem cells for Achilles allograft replacement of the anterior cruciate ligament in rabbits. Biochem Biophys Res Commun. 2011; 406:204–210. [PubMed: 21303664]

Wu JL, Hosseini A, Kozanek M, Gadikota HR, Gill T.J.t. Li G. Kinematics of the anterior cruciate ligament during gait. Am J Sports Med. 2010; 38:1475–1482. [PubMed: 20442323]

Yamaguchi S, Sasho T, Tsuchiya A, Wada Y, Moriya H. Long term results of anterior cruciate ligament reconstruction with iliotibial tract: 6-, 13-, and 24-year longitudinal follow-up. Knee Surg Sports Traumatol Arthrosc. 2006; 14:1094–1100. [PubMed: 16845548]

Zabala ME, Favre J, Scanlan SF, Donahue J, Andriacchi TP. Three-dimensional knee moments of ACL reconstructed and control subjects during gait, stair ascent, and stair descent. J Biomech. 2013; 46:515–520. [PubMed: 23141637]

Zaid M, Lansdown D, Su F, Pedoia V, Tufts L, Rizzo S, Souza RB, Li X, Ma CB. Abnormal tibial position is correlated to early degenerative changes one year following ACL reconstruction. J Orthop Res. 2015; 33:1079–1086. [PubMed: 25721417]

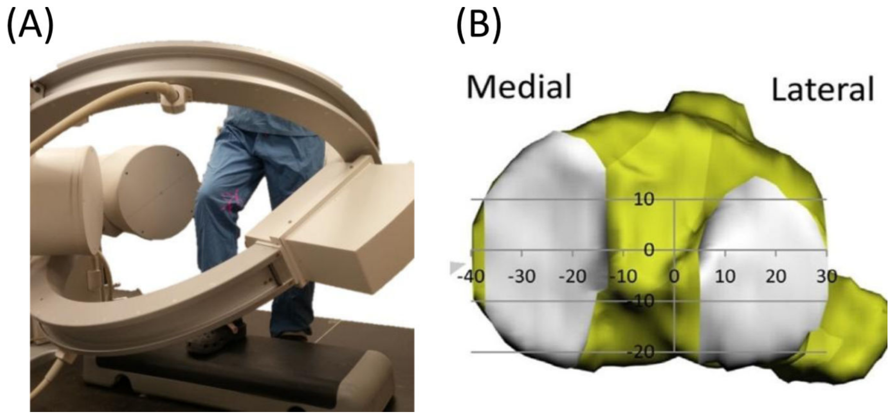

Fig. 1.
Schematic drawing showing (A) the step-up motion captured using a dual fluoroscopic imaging system; (B) coordinate system of the tibial plateau.

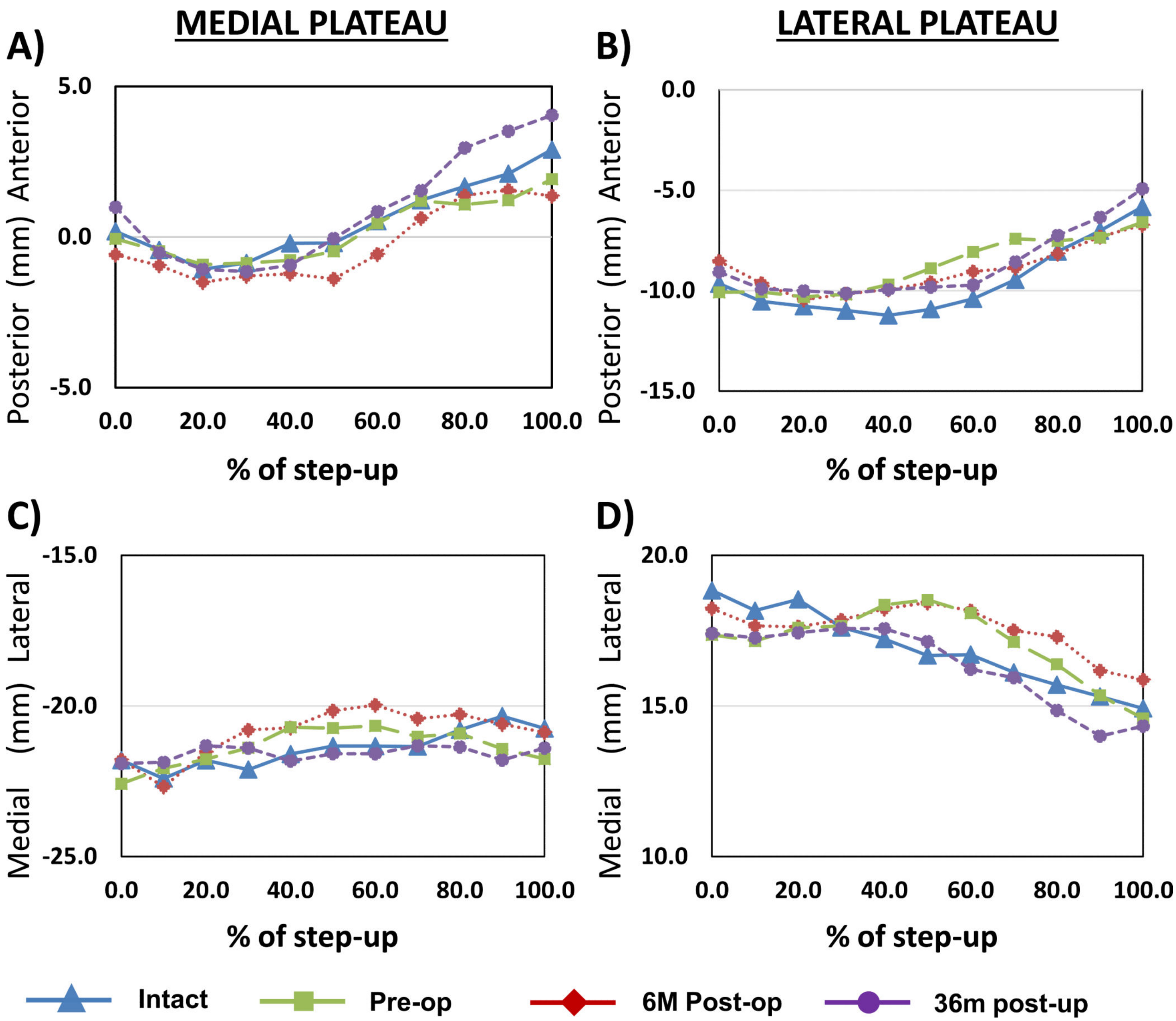

Fig. 2.

Cartilage contact locations after ACL reconstruction during the step-up motion. Anterior-posterior translation of cartilage contact locations on the (A) medial and (B) lateral tibial plateau; Medial-lateral translation of the cartilage contact locations on (C) medial and (D) lateral tibial plateau.

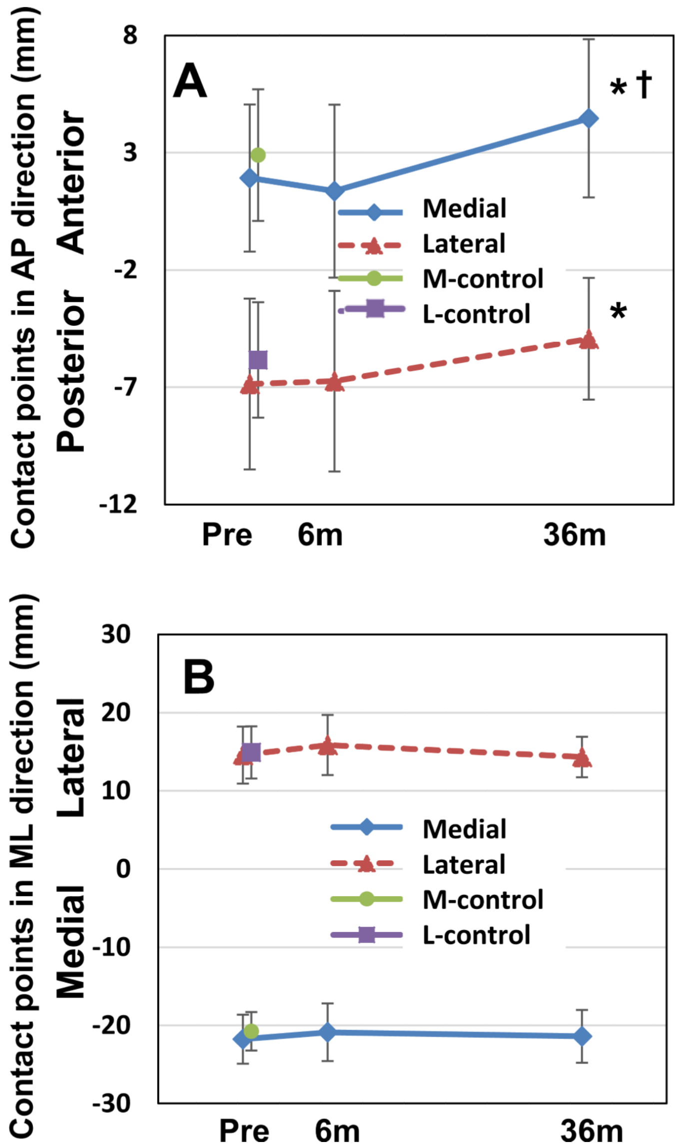

Fig. 3.

Locations of cartilage contact locations at the end of the step-up motion (100%) with time. A) Anterior posterior translation, B) Medial lateral translation. (Pre: preoperation; 6m: 6 months post operation; 36m: 36 months post operation; * $p < 0.05$, indicating that the data measured at 36 months are significantly different than those at preoperation and 6 months after operation).

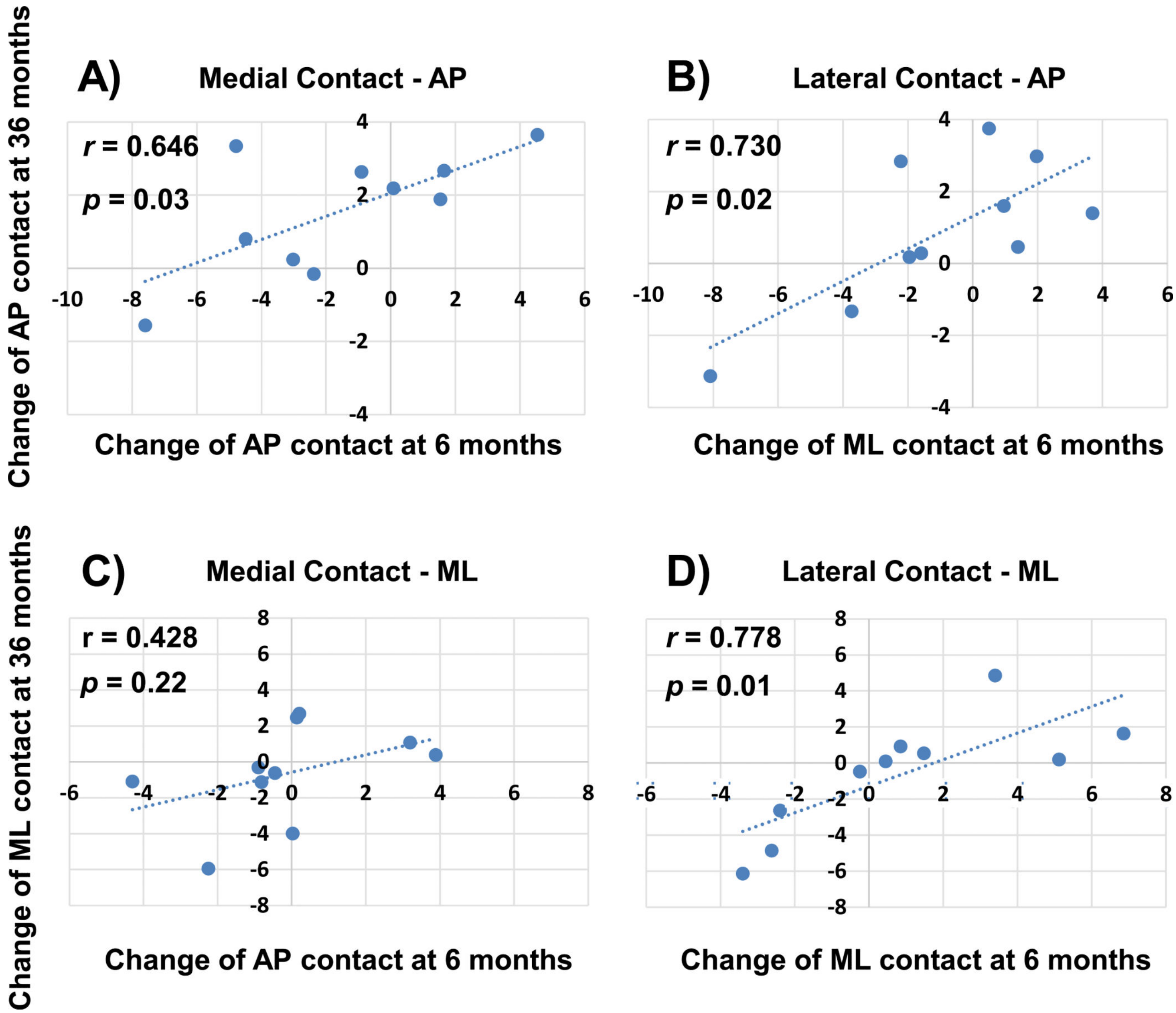

Fig. 4.

The correlation of the changes of articular contact location at 6 months and at 36 months after ACL reconstruction. Anterior-posterior translation in the (A) medial and (B) lateral compartments; medial-lateral translation in the (C) medial and (D) lateral compartments.

Table 1

Preoperative patient characteristics

Patients	Sex	Age (years)	BMI (kg/m2)	Injured Knee	Meniscus tear	Treatment of meniscus tear	Duration between injury and exam (days)	Follow-up duration (months)
# 1	F	31	25.1	Left	LMPH	PM	38	43
# 2	M	32	23.6	Right	LMPH	PM	13	44
# 3	M	28	26.4	Right	LMPH	PM	51	45
# 4	M	34	27.3	Left	NONE	NONE	69	44
# 5	M	43	27.4	Left	MMPH	PM	45	43
# 6	M	31	28.9	Left	MMPH	PM	40	46
# 7	F	20	22.8	Right	NONE	NONE	30	42
# 8	M	49	21.6	Right	LM/MMPH	PM	33	44
# 9	F	27	25.7	Left	LMPH	PM	45	39
# 10	F	43	29.3	Right	LMMB	PM	48	45

M: male, F: female, BMI: body mass index, MM: medial meniscus, LM: lateral meniscus, AH: anterior horn, MB: midbody, PH: posterior horn, NONE: no meniscal tear, PM: partial meniscectomy