연세대학교
YONSEI UNIVERSITY

Influence of knee flexion angle and transverse drill angle on creation of femoral tunnels in double bundle ACL reconstruction using transportal technique: 3D CT simulation analysis

Min Jung

Department of Medicine

The Graduate School, Yonsei University

Influence of knee flexion angle and transverse drill angle on creation of femoral tunnels in double bundle ACL reconstruction using transportal technique: 3D CT simulation analysis

Directed by Professor Chong Hyuk Choi

The Doctoral Dissertation
submitted to the Department of Medicine,
the Graduate School of Yonsei University
in partial fulfillment of the requirements for the degree of
Doctor of Philosophy

Min Jung

June 2017

연세대학교
YONSEI UNIVERSITY

This certifies that the Doctoral Dissertation of Min Jung is approved.

Thesis Supervisor : Chong Hyuk Choi

Thesis Committee Member#1 : Ick-Hwan Yang

Thesis Committee Member#2 : Sung-Il Shin

Thesis Committee Member#3 : Jin-Suck Suh

Thesis Committee Member#4 : Inkyung Jung

The Graduate School
Yonsei University

June 2017

ACKNOWLEDGEMENTS

Firstly, I would like to express my sincere gratitude to thesis supervisor Prof. Chong Hyuk Choi for the continuous support of my study and related research for his patience, motivation, and immense knowledge. His guidance helped me in all the time of research and writing of this thesis. I could not have imagined having a better supervisor and mentor for my study.

Besides my supervisor, I would like to thank the members of my thesis committee: Prof. Ick-Hwan Yang, Prof. Sung-Il Shin, Prof. Jin-Suck Suh and Prof. Inkyung Jung not only for their insightful comments and encouragement, but also for the hard question which incented me to widen my research from various perspectives.

I would like to appreciate all professors in the Department of Orthopedic Surgery and fellow colleagues. I would like to give my special gratitude to Prof. Sung-Jae Kim for guiding me steps in the path of medical scientist. Also I thank Prof. Yong-Min Chun and Prof. Sung-Hwan Kim for enlightening me as to the medical research

Last but not the least, I would like to thank my parents, parents-in-law and brothers for supporting me spiritually. I would like to give my love to my wife, Eun-Ah Cho who did not spare supports and sacrifice, and thank my first son, Seung-Joon Jung and second son who will be born soon for becoming my energy to work when I am exhausted.

June 2017

Written by author

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

Influence of knee flexion angle and transverse drill angle on creation of femoral tunnels in double bundle ACL reconstruction using transportal technique: 3D CT simulation analysis

Min Jung

Department of Medicine
The Graduate School, Yonsei University

(Directed by Professor Chong Hyuk Choi)

There has been no previous study on double bundle reconstruction dealing with the characteristics of femoral tunnel which change according to the combined effect of various flexion angles of knee and transverse drill angles. The purpose of the study was to find appropriate conditions of knee flexion angle and transverse drill angle for optimal femoral tunnels of anteromedial (AM) bundle and posterolateral (PL) bundle which include sufficient tunnel length without wall breakage, an obtuse graft-tunnel angle, an ellipsoidal tunnel aperture and no communication between two tunnels in double bundle ACL reconstruction using transportal technique. Three-dimensional reconstructed knee models were developed using customized software from computed tomography images of 30 patients. On the transepicondylar axis, the knee flexion angles were altered from 100º to 130º at intervals of 10º. Three transverse drill angles were set up according to the maximum transverse drill angle (MTA) in contact with medial femoral condyle and maximum angle minus 10° and 20° by moving drill laterally. Twelve different femoral tunnels determined by four flexion angles and three transverse drill angles were created for AM bundle and PL bundle, respectively. Following variables of femoral tunnels were assessed: (1) tunnel length; (2) tunnel wall breakage; (3) communication between tunnels of AM and PL bundle; (4) graft-tunnel angle; (5) length of long axis of femoral tunnel aperture. The mean length of tunnel of AM bundle was more than 30mm at 120° and 130° of flexion in all transverse drill angles. The mean length of tunnel of PL bundle was more than 30mm during every condition. There was no case of wall breakage of tunnel in creating PL bundle during every condition, but there were one or more cases of wall breakage except for 120° of flexion and MTA and 130° of flexion and MTA in creating AM bundle. Considering gap length of more than 2mm between two tunnels as having no communication, combination of AM bundle created at 120° of flexion and MTA with PL bundle created at 120° of flexion and MTA (gap length = 2.12±0.93mm), 130° of flexion and MTA (gap length = 2.08±1.17mm) and 130° of flexion and MTA-10° (gap length = 2.03±1.14mm) and combination of AM bundle created at 130° of flexion and MTA with PL bundle created at 120° of flexion and MTA (gap length = 2.48±1.11mm), 130° of flexion and MTA (gap length = 2.35±1.20mm) and 130° of flexion and MTA-10° (gap length = 2.29±1.16mm) were optimal conditions. Among these combinations, 120° of flexion and MTA was the most optimal conditions for both AM and PL bundles considering graft-femoral tunnel angle and tunnel aperture morphology. Flexion angle of knee and transverse drill angle had a combined effect on the characteristics of femoral tunnel in double bundle ACL reconstruction using transportal technique. Achieving a flexion angle of 120° and transverse drill angle close to the cartilage of medial femoral condyle could be recommended for optimal tunnels of both AM and PL bundles.

Key words: arthroscopy; anterior cruciate ligament; reconstruction; double bundle

Influence of knee flexion angle and transverse drill angle on creation of femoral tunnels in double bundle ACL reconstruction using transportal technique: 3D CT simulation analysis

Min Jung

Department of Medicine
The Graduate School, Yonsei University

(Directed by Professor Chong Hyuk Choi)

I. INTRODUCTION

Anterior cruciate ligament (ACL) insufficiency leads to an alteration of kinematics and functional impairment of the knee.[1] Over the past few decades, there have been various considerations on the surgical treatment method for ACL insufficiency to restore normal knee kinematics and improve the functional outcomes. In the early 2000s, several studies showed that only about 30% to 40% of patients treated with ACL reconstruction were reported as normal while the majority of patients had recurrent instability or an inability to recover function prior to injury.[2] Additionally, long term studies revealed drawbacks with arthritic change and poor functional outcomes after ACL reconstruction due to limitation in restoration of normal knee kinematics.[3-5] To redeem such defects, the double bundle concept was considered as one of the alternatives on the basis of native ACL anatomy. The double-bundle anatomy of the ACL was identified decades ago.[6] However, it began to receive attention in clinical practice in the 2000s.[7,8] Biomechanical studies supported double-bundle

ACL reconstruction by establishing differing kinematic roles of each bundle[9,10] and noted that double-bundle ACL reconstruction led to improvement of outcomes by restoring knee kinematics close to normal ACL.[10] Although controversy exists over clinical outcomes, double bundle ACL reconstruction has been considered to have more antero-posterior and rotational stability compared to single bundle reconstruction according to previous studies.[11]

In performing ACL reconstruction, the location of femoral tunnel is considered as a key factor to yield successful outcomes.[12] Efforts to place the femoral tunnel in the anatomical position of native ACL were devoted and anatomical ACL reconstruction using outside in technique and transportal technique was suggested.[13-15] There have been pros and cons on both techniques. Outside in technique has a shortcoming of need for lateral femoral dissection using an additional incision. On the contrary, transportal technique does not need additional incision, but has drawbacks such as insufficient tunnel length[16,17] and posterior wall blow-out.[17] In this regard, previous studies noted that flexion angle of knee[18-20] and transverse drill angle[20] affected the characteristics of femoral tunnel and suggested that flexion angle should be increased and the far anteromedial portal has to be made at a lower position[21] to achieve a sufficient length of tunnel without wall breakage. However, other important points are graft-tunnel angle and shape of tunnel aperture. Graft-tunnel angle increases with increased knee flexion angle. It results in higher tunnel acuity and contact pressure.[18] Change of transverse drill angle affects the trajectory and aperture shape of femoral tunnel in transportal technique.[20] In performing double bundle ACL reconstruction, to the best of our knowledge, there has been no previous study dealing with the characteristics of femoral tunnel including tunnel length, posterior wall breakage, graft-tunnel angle and shape of tunnel aperture which change according to the combined effect of various flexion angles of knee and transverse drill angles. Additionally, one of the most important elements of the double-bundle ACL reconstruction is to create two tunnels while preserving intact bone bridge between tunnels without inter-tunnel communication. Communication between two tunnels jeopardizes function of reconstructed graft and stability of knee, and leads to difficulty in revision surgery.[22,23] Accordingly, the purpose of the present study is to find appropriate conditions of knee flexion angle and transverse drill angle for optimal femoral tunnels of each bundle which include sufficient tunnel length without wall breakage, an obtuse graft-tunnel angle, an ellipsoidal tunnel aperture and no communication between two tunnels in double bundle ACL reconstruction using transportal technique. The present study was performed using three-dimensional (3D) computed tomography (CT) simulation.

II. MATERIALS AND METHODS

1. 3D reconstruction of computed tomography scans

Knee CT images of subjects who took a CT scan to evaluate the trauma of the knee from January 2011 to December 2012 were retrospectively reviewed after approval by the institutional review board of our institution. The CT evaluation was performed with the CT scanner Sensation 64 (Siemens healthcare, Erlangen, Germany). The tube parameters were 120kVp and 135~253mAs. The acquisition matrix was 512 x 512 pixels. The scan field of view was 134~271mm, and the slice thickness was 0.6~1mm. A CT scan was performed with the knee in full extension. Subjects were included in the current study according to the following criteria: (1) no ligament injury of knee; (2) no osseous deformity including fracture of femur and tibia; (3) no previous operation history; (4) no osteoarthritis above Kellgren-Lawrence grade I.[24] CT images of thirty subjects were included in the present study. Digital Imaging and Communications in Medicine (DICOM) data were extracted from the picture archiving and communication system (Centricity PACS, GE Medical System Information Technologies, Milwaukee, Wisconsin). Extracted CT images were imported into Mimics software (version 17; Materialise, Leuven, Belgium) and 3D model of femur and tibia was reconstructed (Fig. 1).

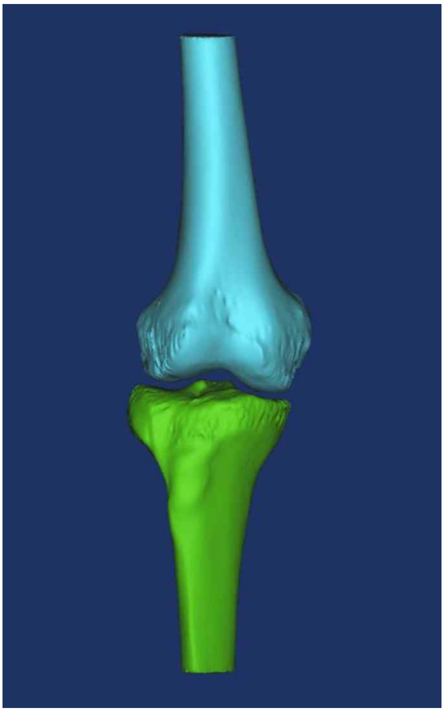


Figure 1. Computed tomography images extracted from the picture archiving and communication system were imported into Mimics software (version 17; Materialise, Leuven, Belgium) and three-dimensional model of femur and tibia was reconstructed.

2. Simulation of femoral tunnel drilling on 3D reconstructed model

To establish footprint centers of anteromedial (AM) and posterolateral (PL) bundles of ACL on femur, 3D reconstructed model of femur was aligned in a true lateral position where both femoral condyles were superimposed as noted by Bernard et al.[25] and the medial femoral condyle was virtually removed from the 3D reconstructed model at the most anterior aspect of the intercondylar notch to improve visualization of the medial wall of the lateral femoral condyle.[26] Footprint centers of each bundle were determined according to the previous study dealing with 3D CT using cadaver.[27] Similar to the quadrant method for standard lateral radiographs, 4 x 4 grid was drawn on the medial wall of the lateral femoral condyle from a true medial view of the femur established at 90° flexion of knee. Because there was no Blumensaat line on a 3D reconstructed model, the most anterior edge of the femoral notch roof was regarded as the reference for the grid alignment. The femoral footprint center of each bundle were located according to reference point coordinates determined by the segments of the grid along the Blumensaat line and the segments of the grid perpendicular to the Blumensaat line. The point which was located at 21.7% of the distance measured from the posterior border of the medial wall of the lateral condyle along the line parallel to the Blumensaat line and at 33.2 % of the distance measured from the Blumensaat line along the line perpendicular to the Blumensaat line was set for the center of femoral footprint of AM bundle. The point which was located at 35.1% of the distance measured from the posterior border of the medial wall of the lateral condyle along the line parallel to the Blumensaat line and at 55.3 % of the distance measured from the Blumensaat line along the line perpendicular to the Blumensaat line was set for the center of femoral footprint of PL bundle (Fig. 2). And then, the medial condyle-removed 3D model was restored to the original 3D model including both condyles.

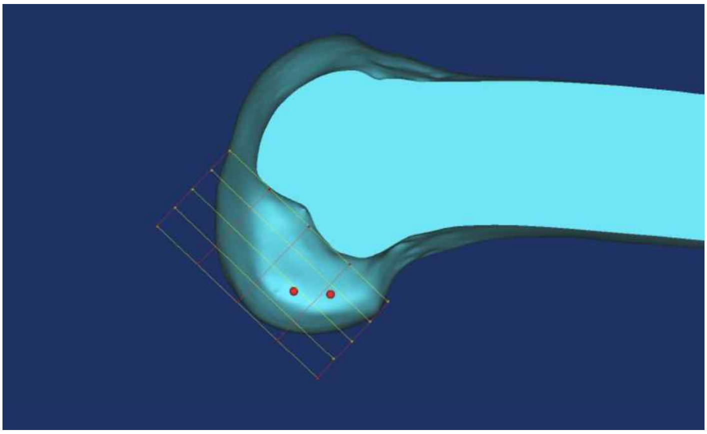


Figure 2. The location of the femoral footprint centers of anteromedial and posterolateral bundles. The point which was located at 21.7% of the distance measured from the posterior border of the medial wall of the lateral condyle along the line parallel to the Blumensaat line and at 33.2 % of the distance measured from the Blumensaat line along the line perpendicular to the Blumensaat line was set for the center of femoral footprint of AM bundle. The point which was located at 35.1% of the distance measured from the posterior border of the medial wall of the lateral condyle along the line parallel to the Blumensaat line and at 55.3 % of the distance measured from the Blumensaat line along the line perpendicular to the Blumensaat line was set for the center of femoral footprint of PL bundle.

Various knee flexion angles and transverse drill angles were applied to the 3D knee models. To vary the flexion angle, transpeicondylar axis was established as rotation axis of flexion according to the previous study.[28,29] On the transepicondylar axis, the knee flexion angles were altered from 100º to 130º at intervals of 10º (Fig. 3-A). 90º of flexion angle was not included in this study because Basdekis et al. reported that the femoral tunnel tended to blow out the posterior cortex of the lateral femoral condyle at 90° of flexion.[18] The transverse drill angle was set to three positions according to methods of the previous study (Fig. 3-B).[20] The center of far anteromedial portal made just above the medial meniscus during real operation with transportal technique was virtually located at 10mm above the tibia plateau considering thickness of medial meniscus and radius of femoral tunnel. The maximum angle of drill rotation can be achieved when coming into contact with the cartilage of medial femoral condyle. The first position of drill with maximum transverse drill angle (MTA) was in contact with medial femoral condyle. The other positions were angles of the first position minus 10° and 20° by moving drill laterally. The drill bit for tunneling was simplified to the virtual cylinder in the present study using 3D model. The diameter of drill bit for each bundle was set to 6mm considering bone bridge between two bundles and the length of axis of each bundle footprint reported by previous studies.[30,31] Femoral tunnels of each bundle were made along the extension of the line from the virtual center of far anteromedial portal to the centers of the footprint of each bundle (Fig. 3-B). Three tunnels of each bundle were created at each of four angles of flexion. Twelve tunnels were made for AM bundle and PL bundle, respectively.

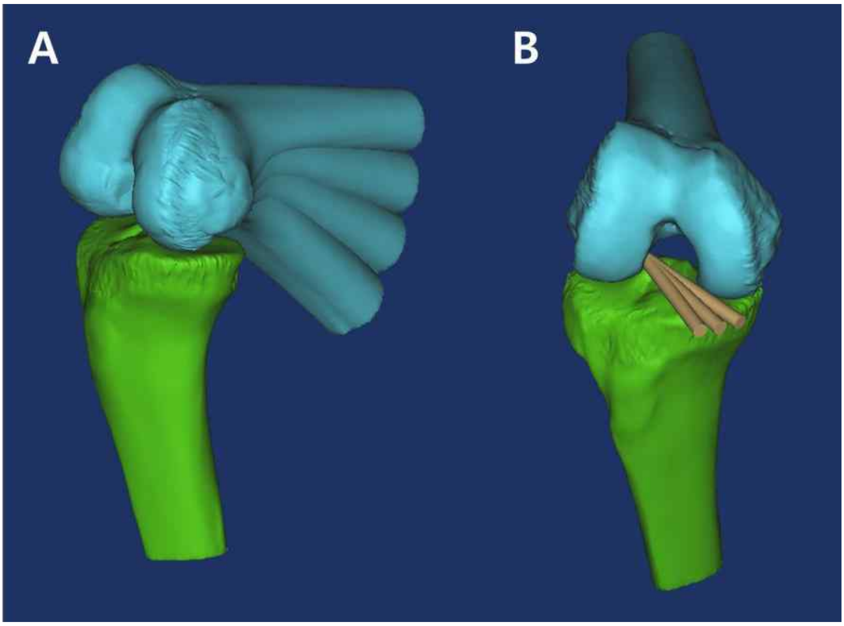


Figure 3. Various knee flexion angles and transverse drill angles were applied to the three-dimensional knee models. A: On the transepicondylar axis, the knee flexion angles were altered from 100º to 130º at intervals of 10º. B: The transverse drill angle was set to three positions. The first position of drill with maximum transverse drill angle was in contact with medial femoral condyle. The other positions were angles of the first position minus 10° and 20° by moving drill laterally.

3. Measurement of variables of the femoral tunnel characteristics

Five major variables of the each tunnel were assessed: (1) tunnel length; (2) tunnel wall breakage; (3) communication between tunnels of AM and PL bundle; (4) graft-tunnel angle; (5) length of long axis of femoral tunnel aperture. Tunnel length was measured from the center of femoral footprint at the medial wall of lateral femoral condyle to the center of the far cortex penetrated by the virtual cylinder. Considering the length of the graft incorporated in the femoral tunnel and fixation device for suspensory method of endobutton (Smith & Nephew Endoscopy, Andover, Massachusetts), 30mm was set as a criterion for a minimum length of the femoral tunnel for the stable graft fixation.[32] The lengths of twelve tunnels of each bundle were measured. The posterior wall breakage was assessed for each tunnel. The breakage of tunnel wall included two kinds of breakage which were at the entrance and in the middle of the tunnel. After the appropriate conditions for the optimal tunnels which had sufficient length of more than 30mm without entrance breakage and mid-tunnel breakage were determined, the communication between optimal tunnels of each bundle were assessed. The overlaps between two tunnels throughout the whole length of tunnels were investigated and the shortest distance of the gap between two tunnels was measured (Fig. 4). 2mm was set as a criterion for a minimum gap to prevent postoperative femoral bone tunnel communication.[33,34] The combinations of AM and PL bundles which had sufficient tunnel length without wall breakage and no communication were determined. And then the graft-tunnel angle (Fig. 5) and the length of long axis of femoral tunnel aperture (Fig. 6) of each optimal tunnels were measured.

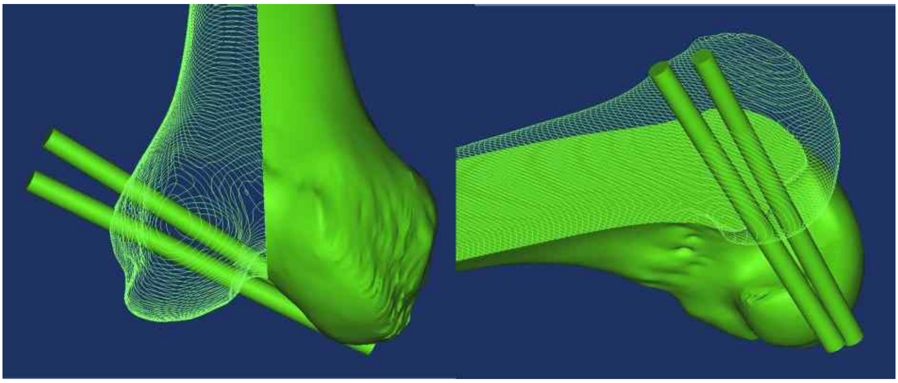
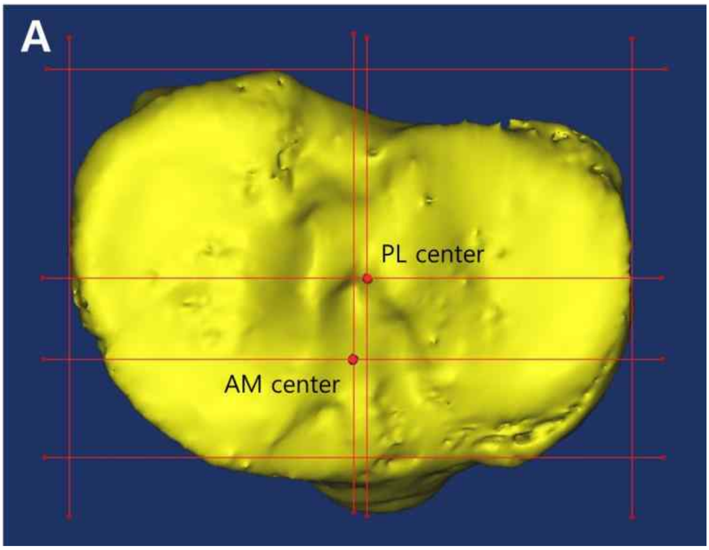


Figure 4. The overlaps between tunnel of two bundles throughout the whole length of tunnels were investigated and the shortest distance of the gap between two tunnels was measured. The relationship between anteromedial bundle created at 130° of flexion and maximum transverse drill angle and posterolateral bundle created at 120° of flexion and maximum transverse drill angle is shown.



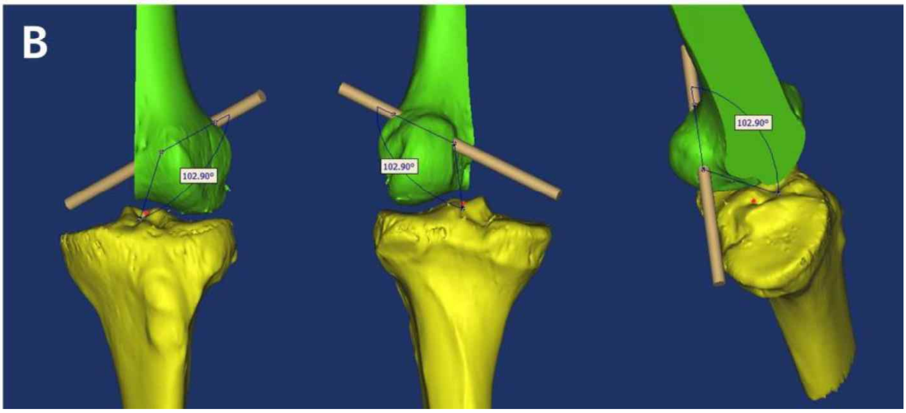


Figure 5. The graft-femoral tunnel angle was measured. A. The tibial footprint centers of each bundle were located according to reference point coordinates determined. The anterior-to-posterior and medial-to-lateral tunnel positions were determined with use of a true proximal-to-distal view on the tibial plateau. The mean anterior-to-posterior distances for the AM and PL tunnel center locations were 25% and 46.4%, respectively, of the anterior-toposterior depth of the tibia measured from the anterior border. The mean medial-to-lateral distances for the AM and PL tunnel center locations were 50.5% and 52.4%, respectively, of the medial-to-lateral width of the tibia measured from the medial border. B. With the knee in full extension, the angle between the line from the tibial tunnel center to the femoral tunnel center and the virtual cylinder of graft was measured as a graft-femoral tunnel angle.

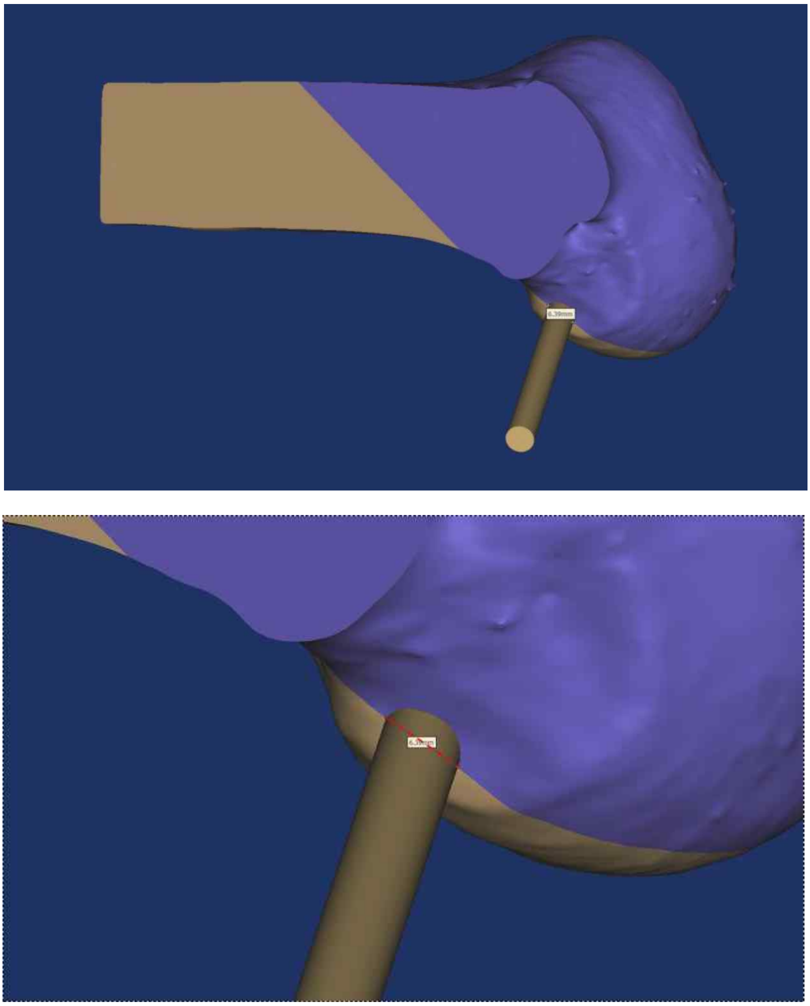


Figure 6. The length of long axis of femoral tunnel aperture was measured to evaluate the coverage of ACL footprint by the graft.

To assess the graft-femoral tunnel angle, the tibial footprint centers of each bundle were located according to reference point coordinates determined by the previous study.[27] The anterior-to-posterior and medial-to-lateral tunnel positions were determined with use of a true proximal-to-distal view on the tibial plateau. The mean anterior-to-posterior distances for the AM and PL tunnel center locations were 25% and 46.4%, respectively, of the anterior-to-posterior depth of the tibia measured from the anterior border. The mean medial-to-lateral distances for the AM and PL tunnel center locations were 50.5% and 52.4%, respectively, of the medial-to-lateral width of the tibia measured from the medial border. Maximum contact pressure of the graft was observed at the anterior portion with the knee in full extension[35]. Accordingly, with the knee in full extension, the angle between the line from the tibial tunnel center to the femoral tunnel center and the virtual cylinder of graft was measured as a graft-femoral tunnel angle (Fig. 5). The length of long axis of femoral tunnel aperture was measured to evaluate the coverage of ACL footprint by the graft (Fig. 6). The length of short axis of femoral tunnel was 6mm which was same as the diameter of the tunnel.

4. Statistical Analysis

For comparative analyses of continuous variables, the paired t-test was performed between two variables and the repeated measures analysis of variance (ANOVA) was used between three variables. The post-hoc analysis with adjusted p-value obtained by Bonferroni correction was performed to make pairwise comparisons. The Cochran's Q test for determination of differences on dichotomous dependent variables was used. The level of significance was set at $p<0.05$. Statistical analysis was performed with use of the IBM SPSS Statistics for Windows software program (version 23.0; IBM, Armonk, New York).

III. RESULTS

There were eighteen male (60%) and twelve female (40%) patients. The average age was 37.4±11.5 years (range, eighteen to fifty-six years). The affected side was right in sixteen patients (53.3%) and left in fourteen patients (46.7%). The average height of patients was 170.6±8.4 cm (range, 158 to 182 cm) and the average weight of patients was 63.9±11.2 kg (range, 50 to 84 kg).

The mean lengths of femoral tunnel of AM bundle and PL bundle were shown in Table 1. The mean length of tunnel of AM bundle was more than 30mm at 120° and 130° of flexion in all transverse drill angles. The mean length of tunnel of PL bundle was more than 30mm during every condition regardless of flexion angle and transverse drill angle. Comparison of tunnel lengths between three different transverse drill angles in each angle of knee flexion was done. At 100°, 120° and 130° of flexion, there were significant differences of tunnel lengths of AM bundle between MTA, MTA-10° and MTA-20° ($p<0.001$) (Table 1). According to the Post-hoc analysis with use of Bonferroni correction, all comparison had significant differences with one exception of comparison between MTA and MTA-10° in 120° of flexion ($p=0.110$) (Table 2). At 110° of flexion, there was no significant difference of tunnel lengths of AM bundle according to the transverse drill angles. In terms of PL bundle, there were significant differences of tunnel lengths at all flexion angles (Table 1). Post-hoc analysis with use of Bonferroni correction showed that all comparison had significant differences with one exception of comparison between MTA and MTA-20° in 100° of flexion ($p>0.999$) (Table 2). Comparison of tunnel lengths between the four different knee flexion angles in each transverse drill angle was also performed. Tunnel lengths of both AM and PL bundles significantly differed according to the flexion angle in every transverse drill angle ($p<0.001$) (Table 1).

Table 1

Comparison of mean femoral tunnel length of anteromedial bundle and posterolateral bundle in each condition

Bundle	Transverse drill angle / Angle of flexion	MTA (mm)	MTA-10° (mm)	MTA-20° (mm)	p-value
AM	100° of flexion	22.3±4.8 (12.6~31.5)	19.0±5.3 (10.0~30.6)	14.6±5.0 (6.4~28.6)	<0.001
	110° of flexion	27.8±4.6 (16.7~36.7)	26.7±6.3 (11.6~37.5)	26.8±10.3 (7.7~46.1)	0.434
	120° of flexion	30.5±4.0 (18.2~38.5)	31.1±4.2 (19.4~39.1)	33.8±6.6 (10.7~45.8)	<0.001
	130° of flexion	32.4±4.1 (18.4~39.7)	33.3±3.9 (20.0~41.3)	35.7±4.3 (24.3~47.2)	<0.001
	p-value	<0.001	<0.001	<0.001	
PL	100° of flexion	30.7±3.7 (22.7~39.5)	31.9±3.9 (23.2~40.7)	30.9±3.9 (21.4~39.0)	0.011
	110° of flexion	32.6±4.4 (23.8~40.6)	34.5±4.3 (25.0~42.0)	35.4±4.3 (23.6~41.3)	<0.001
	120° of flexion	33.1±4.0 (23.3~41.1)	35.5±3.7 (26.6~41.5)	36.8±3.5 (26.6~42.0)	<0.001
	130° of flexion	33.4±4.1 (23.4~41.1)	36.1±3.6 (28.6~42.0)	37.3±3.6 (27.6~42.8)	<0.001
	p-value	<0.001	<0.001	<0.001	

MTA = Maximum transverse drill angle in contact with the cartilage of medial femoral condyle

AM = Anteromedial; PL = Posterolateral

The values are given as mean ± standard deviation (range)

Table 2

Post-hoc test of tunnel lengths between three different transverse drill angles in each angle of knee flexion with use of Bonferroni correction

Angel of knee flexion	Bundle	MTA vs MTA-10° Adj p-value	MTA vs MTA-20° Adj p-value	MTA-10° vs MTA-20° Adj p-value
100° of flexion	AM	<0.001	<0.001	<0.001
	PL	<0.001	>.999	0.013
110° of flexion	AM	0.169	>.999	>.999
	PL	<0.001	<0.001	0.026
120° of flexion	AM	0.110	<0.001	<0.001
	PL	<0.001	<0.001	<0.001
130° of flexion	AM	0.001	<0.001	<0.001
	PL	<0.001	<0.001	<0.001

MTA = Maximum transverse drill angle in contact with the cartilage of medial femoral condyle

AM = Anteromedial; PL = Posterolateral

Adj p-value: Adjusted p-value (with use of Bonferroni correction)

According to the Post-hoc analysis with use of Bonferroni correction, there was significant difference in all pairwise comparison regarding AM bundle. In terms of PL bundle, pairwise comparison between 120° and 130° did not have significant difference in every transverse drill angle. In MTA, pairwise comparison of 110° versus 120° ($p=0.960$) and 110° versus 130° ($p=0.235$) did not show significant difference. For the rest of pairwise comparison, there were significant differences (Table 3).

The proportions of tunnel wall breakage in each condition were shown in Table 4. There was no case of tunnel wall breakage in creating PL bundle during every condition. Regarding AM bundle, there was no tunnel wall breakage at 120° of flexion and MTA and 130° of flexion and MTA. Except for those two conditions, there were one or more cases of wall breakage (Table 4). The proportion of tunnel wall breakage of AM bundle showed decrease as flexion angle increased and transverse drill angle was made closer to the cartilage of medial femoral condyle (Table 4).

Table 3

Post-hoc test of tunnel lengths between the four different knee flexion angles in each transverse drill angle with use of Bonferroni correction

Transverse drill angle	Bundle	100° vs 110° Adj p-value	100° vs 120° Adj p-value	100° vs 130° Adj p-value	110° vs 120° Adj p-value	110° vs 130° Adj p-value	120° vs 130° Adj p-value
MTA	AM	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
	PL	<0.001	<0.001	<0.001	0.960	0.235	>.999
MTA-10°	AM	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
	PL	<0.001	<0.001	<0.001	0.040	0.001	0.245
MTA-20°	AM	<0.001	<0.001	<0.001	0.001	<0.001	0.014
	PL	<0.001	<0.001	<0.001	<0.001	<0.001	0.062

MTA = Maximum transverse drill angle in contact with the cartilage of medial femoral condyle

AM = Anteromedial; PL = Posterolateral

Adj p-value: Adjusted p-value (with use of Bonferroni correction)

Table 4

Comparison of tunnel wall breakage of anteromedial bundle and posterolateral bundle in each condition

Bundle	Transverse drill angle / Angle of flexion	MTA	MTA-10°	MTA-20°	p-value
AM	100° of flexion	4 (3/1) (13.3%)	13 (12/1) (43.3%)	21 (20/1) (70.0%)	<0.001
	110° of flexion	1 (1/0) (3.3%)	6 (4/2) (20.0%)	17 (14/3) (56.7%)	<0.001
	120° of flexion	0 (0/0) (0%)	8 (2/6) (26.7%)	18 (9/9) (60.0%)	<0.001
	130° of flexion	0 (0/0) (0%)	1 (1/0) (3.3%)	5 (2/3) (16.7%)	0.030
	p-value	0.035	0.002	<0.001	
PL	100° of flexion	0 (0/0) (0%)	0 (0/0) (0%)	0 (0/0) (0%)	
	110° of flexion	0 (0/0) (0%)	0 (0/0) (0%)	0 (0/0) (0%)	
	120° of flexion	0 (0/0) (0%)	0 (0/0) (0%)	0 (0/0) (0%)	
	130° of flexion	0 (0/0) (0%)	0 (0/0) (0%)	0 (0/0) (0%)	

MTA = Maximum transverse drill angle in contact with the cartilage of medial femoral condyle

AM = Anteromedial; PL = Posterolateral

The values are given as the number of tunnel wall breakage (entrance breakage/mid-tunnel breakage) (%)

Considering optimal tunnels which had sufficient length of more than 30mm without entrance breakage and mid-tunnel breakage, appropriate condition for creating AM bundle was 120° of flexion and MTA and 130° of flexion and MTA. All conditions for creating tunnel for PL bundle had mean length of more than 30mm without wall breakage. Communication between two bundles was assessed between these conditions: AM bundle created at 120° of flexion and MTA and PL bundle created during every condition; AM bundle created at 130° of flexion and MTA and PL bundle created during every condition (Table 5). There was no case of communication of tunnels between AM bundle created at 120° of flexion and MTA and PL bundle created at 120° of flexion and MTA (gap length = 2.12±0.93mm), 120° of flexion and MTA-10° (gap length = 1.87±0.91mm), 130° of flexion and MTA (gap length = 2.08±1.17mm) and 130° of flexion and MTA-10° (gap length = 2.03±1.14mm). There was no case of communication of tunnels between AM bundle created at 130° of flexion and MTA and PL bundle created at 120° of flexion and MTA (gap length = 2.48±1.11mm), 130° of flexion and MTA (gap length = 2.35±1.20mm) and 130° of flexion and MTA-10° (gap length = 2.29±1.16mm). The proportion of inter-tunnel communication between two bundles showed decrease as flexion angle increased and transverse drill angle was made closer to the cartilage of medial femoral condyle regarding the condition of PL bundle creation (Table 5).

Table 5

Communication and gap length between AM bundle created at 120° of flexion and MTA and 130° of flexion and MTA and PL bundle created in every condition

Condition for creating PL bundle	Transverse drill angle / Angle of flexion	MTA		MTA-10°		MTA-20°		p-value[1]
		Comm	Gap length	Comm	Gap length	Comm	Gap length	
AM bundle created at 120° of flexion and MTA	100° of flexion	4 (13.3%)	-	24 (80.0%)	-	30 (100%)	-	<0.001
	110° of flexion	3 (10.0%)	-	24 (80.0%)	-	29 (96.7%)	-	<0.001
	120° of flexion	0 (0%)	2.12±0.93	0 (0%)	1.87±0.91	26 (86.7%)	-	<0.001
	130° of flexion	0 (0%)	2.08±1.17	0 (0%)	2.03±1.14	11 (36.7%)	-	<0.001
	p-value[1]	0.045		<0.001		<0.001		
AM bundle created at 130° of flexion and MTA	100° of flexion	10 (33.3%)	-	26 (86.7%)	-	30 (100%)	-	<0.001
	110° of flexion	2 (6.7%)	-	27 (90.0%)	-	30 (100%)	-	<0.001
	120° of flexion	0 (0%)	2.48±1.11	21 (70.0%)	-	29 (96.7%)	-	<0.001
	130° of flexion	0 (0%)	2.35±1.20	0 (0%)	2.29±1.16	20 (66.7%)	-	<0.001
	p-value[1]	<0.001		<0.001		<0.001		

MTA = Maximum transverse drill angle in contact with the cartilage of medial femoral condyle

Comm = Communication between two tunnels; The values are given as the number of communication (%) & gap length (mm)

[1]P-values were calculated by comparison of proportions of inter-tunnel communication.

The appropriate combinations which had sufficient tunnel length without wall breakage and no communication with more than 2mm gap were AM bundle created at 120° of flexion and MTA and 130° of flexion and MTA with PL bundle created at 120° of flexion and MTA, 130° of flexion and MTA and 130° of flexion and MTA-10°. Comparison of graft-femoral tunnel angle and length of long axis in femoral tunnel aperture was performed. Regarding AM bundle, graft-femoral tunnel angles were as follows: 101.4±4.9° for the tunnel created at 120° of flexion and MTA; 96.7±5.2° for the tunnel created at 130° of flexion and MTA ($p<0.001$). Lengths of long axis in femoral tunnel aperture were as follows: 6.5±0.5mm for the tunnel created at 120° of flexion and MTA; 6.4±0.4mm for the tunnel created at 130° of flexion and MTA ($p=0.001$). The femoral tunnel of AM bundle created at 120° of flexion and MTA had a more obtuse graft-tunnel angle and a longer axis of aperture (Table 6). Regarding PL bundle, graft-femoral tunnel angles were as follows: 96.2±6.1° for the tunnel created at 120° of flexion and MTA; 91.5±6.2° for the tunnel created at 130° of flexion and MTA; 92.2±6.4° for the tunnel created at 130° of flexion and MTA-10° ($p<0.001$) (Table 6). All Pairwise comparisons showed significant difference ($p<0.001$) (Table 7). Lengths of long axis in femoral tunnel aperture were as follows: 6.2±0.2mm for the tunnel created at 120° of flexion and MTA; 6.1±0.2mm for the tunnel created at 130° of flexion and MTA; 6.3±0.3mm for the tunnel created at 130° of flexion and MTA-10° ($p<0.001$) (Table 6). All Pairwise comparisons showed significant difference ($p\leq0.04$) (Table 7). The femoral tunnel of PL bundle created at 120° of flexion and MTA had the most obtuse graft-tunnel angle and the femoral tunnel of PL bundle at 130° of flexion and MTA-10° had the longest axis of aperture.

Table 6

Comparison of graft-femoral tunnel angle and length of long axis in femoral tunnel aperture

Bundle	Condition for creating tunnel	Graft-femoral tunnel angle (°)	Length of long axis (mm)
AM	120° of flexion and MTA	101.4±4.9	6.5±0.5
	130° of flexion and MTA	96.7±5.2	6.4±0.4
	p-value	<0.001	0.001
PL	120° of flexion and MTA	96.2±6.1	6.2±0.2
	130° of flexion and MTA	91.5±6.2	6.1±0.2
	130° of flexion and MTA-10°	92.2±6.4	6.3±0.3
	p-value	<0.001	<0.001

MTA = Maximum transverse drill angle in contact with the cartilage of medial femoral condyle

AM = Anteromedial; PL = Posterolateral

The values are given as mean ± standard deviation

Table 7

Post-hoc test of graft-femoral tunnel angles and lengths of long axis in femoral tunnel aperture between PL bundles created at 120° of flexion and MTA, 130° of flexion and MTA and 130° of flexion and MTA-10° with use of Bonferroni correction

	120° of flexion and MTA vs 130° of flexion and MTA	120° of flexion and MTA vs 130° of flexion and MTA-10°	130° of flexion and MTA vs 130° of flexion and MTA-10°
Graft-femoral tunnel angle (°)	<0.001	<0.001	<0.001
Length of long axis (mm)	0.04	<0.001	<0.001

MTA = Maximum transverse drill angle in contact with the cartilage of medial femoral condyle

PL = Posterolateral

IV. DISCUSSION

The technical difficulties of creating femoral tunnel through far anteromedial portal in ACL reconstruction with use of transportal technique includes the occurence risk for short tunnel length[16,17] and posterior wall blow-out.[17] The characteristics of femoral tunnel including tunnel length and wall breakage were reported to be influenced by flexion angle of knee[18-20,36,37] and transverse drill angle.[20] Obtuse graft-tunnel angle to decrease contact pressure of femoral tunnel[38-40] and ellipsoidal tunnel aperture that resembles the native ACL footprint are also important factors to affect outcomes of ACL reconstruction.[20] Both knee flexion angle and transverse drill angle had an integrated effect on creation of femoral tunnel. Regarding the location of femoral tunnel aperture, double bundle ACL reconstruction is different from single bundle ACL reconstruction. Therefore, the characteristics of tunnels of AM and PL bundle in double bundle ACL reconstruction have to be evaluated differently from the previous studies[18,20] dealing with single bundle ACL reconstruction. Additionally, double bundle ACL reconstruction is a technically demanding procedure with higher risk of inter-tunnel communication between two bundles. The present study focused on the appropriate conditions of knee flexion angle and transverse drill angle for the optimal femoral tunnels of each bundle regarding sufficient tunnel length without wall breakage, an obtuse graft-tunnel angle, an ellipsoidal tunnel aperture and no inter-tunnel communication between two bundles.

According to the results of present study, both knee flexion angle and transverse drill angle had a significant effect on the length of femoral tunnel. Under the condition of each fixed flexion angle of knee, as transverse drill angle decreased by moving drill laterally, tunnel length of AM bundle tended to decrease at 100° of flexion ($p<0.001$), and increase at 120° and 130° of flexion ($p<0.001$). In terms of PL bundle, as transverse drill angle decreased, tunnel length tended to increase at 110°, 120° and 130° of flexion ($p<0.001$). At high flexion angle of 120° and 130°, femoral tunnel lengths of both of AM and PL bundles tended to increase as transverse drill angle decreased. In terms of influence of portal position related to transverse drill angle on femoral tunnel length, it was noted that the standard anteromedial portal resulted in a significantly longer tunnel length compared with a far anteromedial portal more medial to the standard anteromedial portal.[36] Moving the far anteromedial portal more laterally towards the medial border of the patellar ligament produced a longer femoral tunnel length.[20,41] The results of the present study dealing with femoral tunnels of AM and PL bundles in double bundle ACL reconstruction accorded with these previous studies. Under the condition of each fixed transverse drill angle, as flexion angle increased, tunnel length of AM and PL bundle tended to increase with statistical significance ($p<0.001$). According to the previous cadaveric study dealing with single bundle ACL reconstruction using transportal technique, the femoral tunnel length was shorter at 90° of flexion than at 110° and 130° of flexion[18]. Other previous studies regarding single bundle ACL reconstruction also noted that femoral tunnel length showed a tendency to increase as the flexion angle of knee increases.[36,37] To obtain a longer femoral tunnel, attainment of a high flexion angle could be recommended. According to the results of the present study, mean tunnel length of AM bundle was more than 30mm at 120° and 130° of flexion regardless of transverse drill angle and mean tunnel length of PL bundle was more than 30mm regardless of knee flexion angle and transverse drill angle. Regarding the tendency of change in tunnel length, the femoral tunnel was longer at higher flexion angle of knee and transverse drill angle with more lateral position for both of AM and PL bundles. Longer tunnels of AM and PL bundles can be achieved by decrease of transverse drill angle at high flexion angle of 120° and 130° with regard to only a single factor of tunnel length.

Considering tunnel wall breakage in present study, there was no case of wall breakage of tunnel in creating PL bundle during every condition, but there were one or more cases of wall breakage except for 120° of flexion and MTA and 130° of flexion and MTA in creating AM bundle. The proportion of tunnel wall breakage of AM bundle showed decrease as extent of flexion angle increased and transverse drill was moved medially closer to the cartilage of medial femoral condyle. In previous study on single bundle reconstruction, the risk of wall breakage was reported to decrease as flexion angle increased.[18,37] To avoid posterior wall blow-out, the position of the far anteromedial portal is recommended to be a low medial position compared to standard anteromedial portal in transportal technique. The result of the present study also supported a more medial position for the far anteromedial portal without damage to the cartilage of medial femoral condyle, showing that the tunnel of AM bundle had more cases of wall breakage as the transverse drill angle moved more laterally. Regarding tunnel wall breakage, the appropriate condition was 120° of flexion and MTA and 130° of flexion and MTA for AM bundle and there was no limiting condition for PL bundle.

Considering both factors of tunnel length and wall breakage, 120° of flexion and MTA and 130° of flexion and MTA were suitable for creation of AM bundle and all conditions were suitable for creation of PL bundle. According to these results, inter-tunnel communication between two bundles was assessed. There was no case of inter-tunnel communication between AM bundle created at 120° of flexion and MTA and PL bundle created at 120° of flexion and MTA (gap length = 2.12±0.93mm), 120° of flexion and MTA-10° (gap length = 1.87±0.91mm), 130° of flexion and MTA (gap length = 2.08±1.17mm) and 130° of flexion and MTA-10° (gap length = 2.03±1.14mm). There was no case of inter-tunnel communication between AM bundle created at 130° of flexion and MTA and PL bundle created at 120° of flexion and MTA (gap length = 2.48±1.11mm), 130° of flexion and MTA (gap length = 2.35±1.20mm) and 130° of flexion and MTA-10° (gap length = 2.29±1.16mm). Regarding the condition of PL bundle creation, the proportion of inter-tunnel communication tended to decrease with the increase in the extent of flexion angle and with transverse drill angle made closer to the cartilage of medial femoral condyle. Inter-tunnel communication can occur intraoperatively because of technical problem and postoperatively due to tunnel enlargement at the aperture and mid portion of femoral tunnel. Bone tunnel communication had an effect on delayed healing of the graft in the bone tunnel resulting in increased laxity of reconstructed ACL and made revision surgery more difficult.[42] Previous studies reported 0~19% of intraoperative communication of femoral tunnels in double-bundle ACL reconstruction using transportal technique.[42,43] Regarding femoral tunnel communication caused by postoperative tunnel enlargement, previous studies reported 19~60% in double-bundle ACL reconstruction using transportal technique.[34,42] The mean enlargement of femoral tunnel was 34~35% for the AM bundle and 46~48% for the PL bundle.[42,44] Considering bone tunnel enlargement, maintaining more than 2mm of bone bridge between two tunnels was recommended to prevent postoperative femoral bone tunnel communication.[33,34] According to the serial evaluation regarding tunnel length, wall breakage and inter-tunnel communication, combination of AM bundle created at 120° of flexion and MTA with PL bundle created at 120° of flexion and MTA, 130° of flexion and MTA and 130° of flexion and MTA-10° and combination of AM bundle created at 130° of flexion and MTA with PL bundle created at 120° of flexion and MTA, 130° of flexion and MTA and 130° of flexion and MTA-10° were optimal conditions for creation of femoral tunnels in double bundle ACL reconstruction using transportal technique.

For these tunnels, the graft-femoral tunnel angle and the length of long axis of femoral tunnel aperture to estimate the ellipsoidal shape of tunnel aperture were measured. The femoral tunnels of AM and PL bundles created at 120° of flexion and MTA had more obtuse graft-tunnel angle. Acute femoral tunnel angle increases the mechanical stress on the graft and femoral tunnel wall. Repetitive motion of graft at the sharp edge of acute femoral tunnel can cause damage to graft and tunnel widening.[38-40] Otsubo et al. noted that 11% of the PL graft showed substantial damage at the femoral tunnel aperture due to graft tension in anatomical double-bundle ACL reconstruction.[39] Segawa et al. reported that the femoral tunnel angle was significantly smaller in patients with enlarged femoral tunnel than in patients without enlarged femoral tunnel.[40] As knee flexion angle increases at the creation of femoral tunnel, the graft-tunnel angle becomes more acute. The increased acuity of the femoral tunnel angle resulted in an increased contact pressure on the graft and the tunnel wall.[18,35] According to the present study, 120° of flexion and MTA were recommended as an optimal condition for creating femoral tunnels of AM and PL bundles. This study showed that the femoral tunnels of AM bundle created at 120° of flexion and MTA and PL bundle at 130° of flexion and MTA-10° had longer axis of aperture. The longer axis of aperture can make the tunnel aperture shape more ellipsoidal. One of the goals of anatomical ACL reconstruction is to create ellipsoidal tunnel apertures that resemble the native ACL attachment area.[20] A more ellipsoidal aperture of femoral tunnel would cover the native ACL footprint more and create more anatomical femoral tunnel.[45] Flexion angle and transverse drill angle affected morphology of femoral tunnel aperture in transportal technique.[20,30] According to the present study, low flexion angle of 120° and decreased transverse drill angle of MTA-10° made the tunnel aperture morphology more ellipsoidal by obtaining a longer axis of aperture.

In summary, serial evaluation of the present study including tunnel length, tunnel wall breakage, communication between tunnels of AM and PL bundle, graft-tunnel angle and length of long axis of femoral tunnel aperture demonstrated that the optimal condition for AM bundle was 120° of flexion and MTA. Regarding PL bundle, 120° of flexion and MTA and 130° of flexion and MTA-10° could be recommended. However, the difference of mean lengths of long axis in femoral tunnel aperture between PL bundles created 120° of flexion and MTA and 130° of flexion and MTA-10° was 0.1mm. This difference of 0.1mm was considered to have a limited effect on clinical outcomes. Accordingly, achieving a flexion angle of 120° and transverse drill angle close to the cartilage of medial femoral condyle could be recommended for optimal tunnels of both AM and PL bundle.

The present study had several limitations. First, this study was based on simulation with 3D reconstructed CT model. Femoral tunnel was virtually created using a simplified cylinder. The data of the present study were derived from assessment with virtual measurements. Therefore, to add clinical significance to the results of the present study, comparative study based on actual clinical results could be needed. Second, consideration of the individual characteristics of patients is needed to apply the results of present study to actual surgery. The center of ACL femoral footprint was determined according to a previous study.[27] However, there is considerable variability of the ACL footprint between individual patients. Tunnel length is also different according to the physical characteristics including width of femoral condyle and height. Thigh circumference is different according to the muscle mass and extent of obesity from patient to patient. There is an inevitable limitation in applying the results of the present study uniformly to every individual patient. Weights and heights of included patients followed a normal distribution and comparison of the tunnel length was performed by repeated measurement in each patient. However, individual conditions of each patient should be considered in actual operation. Third, the knee flexion angles were altered on the transepicondylar axis in the present study. Knee has rotational movement while allowing for extension and flexion. Virtual flexion on the transepicondylar axis can be different from the practical motion. Additionally, range of motion along the transepicondylar axis is difficult to be measured in actual operation. Fourth, variables assessed in the present study included tunnel length, existence of posterior wall breakage, inter-tunnel communication, acuity of the femoral tunnel angle and aperture morphology. However, besides these variables, there can be more significant variables related with the characteristics of femoral tunnel including injury to the origin of the lateral collateral ligament.[46,47] To draw a more definite conclusion, a comprehensive study including all factors associated with characteristics of femoral tunnel is needed.

V. CONCLUSION

Flexion angle of knee and transverse drill angle had a combined effect on the characteristics of femoral tunnel in double bundle ACL reconstruction using transportal technique. Achieving a flexion angle of 120° and transverse drill angle close to the cartilage of medial femoral condyle could be recommended for optimal tunnels of both AM and PL bundles to avoid complication and obtain a sufficient tunnel length without wall breakage, an obtuse graft-tunnel angle, an ellipsoidal tunnel aperture and no communication between two tunnels. This study can be helpful for comprehension of the relationships between the parameters of knee flexion angle and transverse drill angle and the outcomes of tunnel length, wall breakage, inter-tunnel communication, graft-femoral tunnel angle and shape of femoral tunnel aperture.

REFERENCES

1. Yeow CH, Rubab SK, Lee PV, Goh JC. Inhibition of anterior tibial translation or axial tibial rotation prevents anterior cruciate ligament failure during impact compression. Am J Sports Med 2009;37:813-21.
2. Biau DJ, Tournoux C, Katsahian S, Schranz P, Nizard R. ACL reconstruction: a meta-analysis of functional scores. Clin Orthop Relat Res 2007;458:180-7.
3. Fithian DC, Paxton EW, Stone ML, Luetzow WF, Csintalan RP, Phelan D, et al. Prospective trial of a treatment algorithm for the management of the anterior cruciate ligament-injured knee. Am J Sports Med 2005;33:335-46.
4. Jarvela T, Paakkala T, Kannus P, Jarvinen M. The incidence of patellofemoral osteoarthritis and associated findings 7 years after anterior cruciate ligament reconstruction with a bone-patellar tendon-bone autograft. Am J Sports Med 2001;29:18-24.
5. Roe J, Pinczewski LA, Russell VJ, Salmon LJ, Kawamata T, Chew M. A 7-year follow-up of patellar tendon and hamstring tendon grafts for arthroscopic anterior cruciate ligament reconstruction: differences and similarities. Am J Sports Med 2005;33:1337-45.
6. Girgis FG, Marshall JL, Monajem A. The cruciate ligaments of the knee joint. Anatomical, functional and experimental analysis. Clin Orthop Relat Res 1975:216-31.
7. Zelle BA, Brucker PU, Feng MT, Fu FH. Anatomical double-bundle anterior cruciate ligament reconstruction. Sports Med 2006;36:99-108.
8. Yasuda K, Kondo E, Ichiyama H, Kitamura N, Tanabe Y, Tohyama H, et al. Anatomic reconstruction of the anteromedial and posterolateral bundles of the anterior cruciate ligament using hamstring tendon grafts. Arthroscopy 2004;20:1015-25.

9. Chhabra A, Starman JS, Ferretti M, Vidal AF, Zantop T, Fu FH. Anatomic, radiographic, biomechanical, and kinematic evaluation of the anterior cruciate ligament and its two functional bundles. J Bone Joint Surg Am 2006;88 Suppl 4:2-10.
10. Yagi M, Wong EK, Kanamori A, Debski RE, Fu FH, Woo SL. Biomechanical analysis of an anatomic anterior cruciate ligament reconstruction. Am J Sports Med 2002;30:660-6.
11. Bjornsson H, Desai N, Musahl V, Alentorn-Geli E, Bhandari M, Fu F, et al. Is double-bundle anterior cruciate ligament reconstruction superior to single-bundle? A comprehensive systematic review. Knee Surg Sports Traumatol Arthrosc 2015;23:696-739.
12. Zhang Y, Xu C, Dong S, Shen P, Su W, Zhao J. Systemic Review of Anatomic Single- Versus Double-Bundle Anterior Cruciate Ligament Reconstruction: Does Femoral Tunnel Drilling Technique Matter? Arthroscopy 2016;32:1887-904.
13. Lubowitz JH. Anteromedial portal technique for the anterior cruciate ligament femoral socket: pitfalls and solutions. Arthroscopy 2009;25:95-101.
14. Lubowitz JH, Konicek J. Anterior cruciate ligament femoral tunnel length: cadaveric analysis comparing anteromedial portal versus outside-in technique. Arthroscopy 2010;26:1357-62.
15. Garofalo R, Mouhsine E, Chambat P, Siegrist O. Anatomic anterior cruciate ligament reconstruction: the two-incision technique. Knee Surg Sports Traumatol Arthrosc 2006;14:510-6.
16. Golish SR, Baumfeld JA, Schoderbek RJ, Miller MD. The effect of femoral tunnel starting position on tunnel length in anterior cruciate ligament reconstruction: a cadaveric study. Arthroscopy 2007;23:1187-92.

17. Bedi A, Raphael B, Maderazo A, Pavlov H, Williams RJ, 3rd. Transtibial versus anteromedial portal drilling for anterior cruciate ligament reconstruction: a cadaveric study of femoral tunnel length and obliquity. Arthroscopy 2010;26:342-50.
18. Basdekis G, Abisafi C, Christel P. Influence of knee flexion angle on femoral tunnel characteristics when drilled through the anteromedial portal during anterior cruciate ligament reconstruction. Arthroscopy 2008;24:459-64.
19. Basdekis G, Abisafi C, Christel P. Effect of knee flexion angle on length and orientation of posterolateral femoral tunnel drilled through anteromedial portal during anatomic double-bundle anterior cruciate ligament reconstruction. Arthroscopy 2009;25:1108-14.
20. Hensler D, Working ZM, Illingworth KD, Thorhauer ED, Tashman S, Fu FH. Medial portal drilling: effects on the femoral tunnel aperture morphology during anterior cruciate ligament reconstruction. J Bone Joint Surg Am 2011;93:2063-71.
21. Zantop T, Haase AK, Fu FH, Petersen W. Potential risk of cartilage damage in double bundle ACL reconstruction: impact of knee flexion angle and portal location on the femoral PL bundle tunnel. Arch Orthop Trauma Surg 2008;128:509-13.
22. Christel P, Sahasrabudhe A, Basdekis G. Anatomic double-bundle anterior cruciate ligament reconstruction with anatomic aimers. Arthroscopy 2008;24:1146-51.
23. Pombo MW, Shen W, Fu FH. Anatomic double-bundle anterior cruciate ligament reconstruction: where are we today? Arthroscopy 2008;24:1168-77.
24. Kellgren JH, Lawrence JS. Radiological assessment of osteo-arthrosis. Ann Rheum Dis 1957;16:494-502.

25. Bernard M, Hertel P, Hornung H, Cierpinski T. Femoral insertion of the ACL. Radiographic quadrant method. Am J Knee Surg 1997;10:14-21; discussion -2.
26. Mochizuki T, Muneta T, Nagase T, Shirasawa S, Akita KI, Sekiya I. Cadaveric knee observation study for describing anatomic femoral tunnel placement for two-bundle anterior cruciate ligament reconstruction. Arthroscopy 2006;22:356-61.
27. Forsythe B, Kopf S, Wong AK, Martins CA, Anderst W, Tashman S, et al. The location of femoral and tibial tunnels in anatomic double-bundle anterior cruciate ligament reconstruction analyzed by three-dimensional computed tomography models. J Bone Joint Surg Am 2010;92:1418-26.
28. Churchill DL, Incavo SJ, Johnson CC, Beynnon BD. The transepicondylar axis approximates the optimal flexion axis of the knee. Clin Orthop Relat Res 1998:111-8.
29. Most E, Axe J, Rubash H, Li G. Sensitivity of the knee joint kinematics calculation to selection of flexion axes. J Biomech 2004;37:1743-8.
30. Siebold R, Ellert T, Metz S, Metz J. Femoral insertions of the anteromedial and posterolateral bundles of the anterior cruciate ligament: morphometry and arthroscopic orientation models for double-bundle bone tunnel placement--a cadaver study. Arthroscopy 2008;24:585-92.
31. Takahashi M, Doi M, Abe M, Suzuki D, Nagano A. Anatomical study of the femoral and tibial insertions of the anteromedial and posterolateral bundles of human anterior cruciate ligament. Am J Sports Med 2006;34:787-92.
32. Takeda Y, Iwame T, Takasago T, Kondo K, Goto T, Fujii K, et al. Comparison of tunnel orientation between transtibial and

anteromedial portal techniques for anatomic double-bundle anterior cruciate ligament reconstruction using 3-dimensional computed tomography. Arthroscopy 2013;29:195-204.

33. Hantes ME, Liantsis AK, Basdekis GK, Karantanas AH, Christel P, Malizos KN. Evaluation of the bone bridge between the bone tunnels after anatomic double-bundle anterior cruciate ligament reconstruction: a multidetector computed tomography study. Am J Sports Med 2010;38:1618-25.

34. Tomihara T, Yoshida G, Hara Y, Taniuchi M, Shimada N. Transparent 3-dimensional CT in evaluation of femoral bone tunnel communication after ACL double-bundle reconstruction: comparison between outside-in and transportal technique. Knee Surg Sports Traumatol Arthrosc 2014;22:1563-72.

35. Segawa H, Koga Y, Omori G, Sakamoto M, Hara T. Influence of the femoral tunnel location and angle on the contact pressure in the femoral tunnel in anterior cruciate ligament reconstruction. Am J Sports Med 2003;31:444-8.

36. Alavekios D, Peterson A, Patton J, McGarry MH, Lee TQ. The relation between knee flexion angle and anterior cruciate ligament femoral tunnel characteristics: a cadaveric study comparing a standard and a far anteromedial portal. Arthroscopy 2014;30:1468-74.

37. Tompkins M, Milewski MD, Carson EW, Brockmeier SF, Hamann JC, Hart JM, et al. Femoral tunnel length in primary anterior cruciate ligament reconstruction using an accessory medial portal. Arthroscopy 2013;29:238-43.

38. Chhabra A, Kline AJ, Nilles KM, Harner CD. Tunnel expansion after anterior cruciate ligament reconstruction with autogenous hamstrings: a comparison of the medial portal and transtibial techniques. Arthroscopy 2006;22:1107-12.

39. Otsubo H, Shino K, Nakamura N, Nakata K, Nakagawa S, Koyanagi M. Arthroscopic evaluation of ACL grafts reconstructed with the anatomical two-bundle technique using hamstring tendon autograft. Knee Surg Sports Traumatol Arthrosc 2007;15:720-8.
40. Segawa H, Omori G, Tomita S, Koga Y. Bone tunnel enlargement after anterior cruciate ligament reconstruction using hamstring tendons. Knee Surg Sports Traumatol Arthrosc 2001;9:206-10.
41. Brown CH, Jr., Spalding T, Robb C. Medial portal technique for single-bundle anatomical anterior cruciate ligament (ACL) reconstruction. Int Orthop 2013;37:253-69.
42. Siebold R, Cafaltzis K. Differentiation between intraoperative and postoperative bone tunnel widening and communication in double-bundle anterior cruciate ligament reconstruction: a prospective study. Arthroscopy 2010;26:1066-73.
43. Kim JG, Wang JH, Lim HC, Ahn JH. Femoral graft bending angle and femoral tunnel geometry of transportal and outside-in techniques in anterior cruciate ligament reconstruction: an in vivo 3-dimensional computed tomography analysis. Arthroscopy 2012;28:1682-94.
44. Siebold R. Observations on bone tunnel enlargement after double-bundle anterior cruciate ligament reconstruction. Arthroscopy 2007;23:291-8.
45. Kim JG, Chang MH, Lim HC, Bae JH, Ahn JH, Wang JH. Computed tomography analysis of the femoral tunnel position and aperture shape of transportal and outside-in ACL reconstruction: do different anatomic reconstruction techniques create similar femoral tunnels? Am J Sports Med 2013;41:2512-20.
46. Gelber PE, Reina F, Torres R, Monllau JC. Effect of femoral tunnel length on the safety of anterior cruciate ligament graft fixation using

cross-pin technique: a cadaveric study. Am J Sports Med 2010;38:1877-84.

47. Nakamae A, Ochi M, Adachi N, Deie M, Nakasa T, Kamei G, et al. Far anteromedial portal technique for posterolateral femoral tunnel drilling in anatomic double-bundle anterior cruciate ligament reconstruction: a cadaveric study. Knee Surg Sports Traumatol Arthrosc 2014;22:181-7.

ABSTRACT (IN KOREAN)

슬관절의 굴곡 각도와 천공기의 회전 각도가 경삽입구 이중다발 전방십자인대 재건술의 대퇴골 터널 생성에 미치는 영향: 3 차원 전산화 단층 촬영 시뮬레이션 분석

<지도교수 최 종 혁>

연세대학교 대학원 의학과

정 민

다양한 슬관절 굴곡 각도와 천공기 수평각도의 통합적인 영향에 따라 변하는 대퇴 터널의 특성에 대해 이중다발 재건술을 대상으로 한 연구는 시행된 바가 없다. 본 연구의 목적은 경삽입구 술식을 이용한 이중다발 전방십자인대 재건술을 대상으로, 내벽의 파손이 없는 상태에서 충분한 터널 길이를 가지고, 이식건과 대퇴 터널이 둔각을 이루며, 터널 입구가 타원형을 이루고 두 다발의 터널 간에 연결이 없는 최적의 전내측 다발과 후외측 다발의 터널 생성을 위한 슬관절의 굴곡 각도와 천공기의 수평 각도가 이루는 적합한 조건을 찾는 것이다. 30 명의 컴퓨터 단층 촬영 이미지로부터 상용화된 프로그램을 이용하여 3 차원으로 재건된 슬관절 모델을 만들었다. 대퇴 상과간 축 (transepicondylar axis)을 중심으로 100°에서 130°까지 10° 간격으로 슬관절의 굴곡 각도에 변화를 주었다. 대퇴골 내과에 접촉하는 천공기의 최대 수평 각도와 천공기를 외측으로 움직이면서 최대 수평 각도에서 10°와 20° 감소 시킨 세 가지의 천공기 수평 각도를 설정하였다. 4 가지의 굴곡 각도와 3 가지의 천공기 수평 각도에 따라 전내측, 후외측 다발 각각에

12 가지의 터널을 생성하였다. 각 터널에 대해 다음의 변수를 측정하였다: (1) 터널 길이; (2) 터널 내벽의 파손; (3) 전내측, 후외측 다발의 터널 간의 연결 여부; (4) 이식건과 대퇴 터널 간의 각도; (5) 대퇴 터널 입구에서 장축의 길이. 전내측 다발의 평균 터널 길이는 120°와 130° 굴곡 각도에서 모든 천공기 수평 각도에서 30mm 이상을 보였다. 후외측 다발의 평균 터널 길이는 모든 조건에서 30mm 이상이 관찰되었다. 모든 조건에서 후외측 다발은 터널 내측벽의 파손이 없었으나, 전내측 다발의 경우 120° 굴곡 각도와 최대의 천공기 수평 각도, 130° 굴곡 각도와 최대의 천공기 수평 각도 조건을 제외한 모든 경우에서 한 례 이상의 내벽 파손이 관찰되었다. 120° 굴곡 각도와 최대의 천공기 수평 각도에서 만들어진 전내측 다발과 120° 굴곡 각도와 최대의 천공기 수평 각도, 130° 굴곡 각도와 최대의 천공기 수평 각도 및 130° 굴곡 각도와 최대의 천공기 수평 각도−10°의 조건에서 만들어진 후외측 다발의 조합과, 130° 굴곡 각도와 최대의 천공기 수평 각도에서 만들어진 전내측 다발과 120° 굴곡 각도와 최대의 천공기 수평 각도, 130° 굴곡 각도와 최대의 천공기 수평 각도 및 130° 굴곡 각도와 최대의 천공기 수평 각도−10°의 조건에서 만들어진 후외측 다발의 조합이 두 다발의 터널 간에 연결이 없고 간격이 2mm 를 넘는 조합을 이루었다. 이중에서 이식건-대퇴 터널 각도와 터널 입구의 형태를 고려하였을 때, 120° 굴곡 각도와 최대의 천공기 수평 각도가 전내측 및 후외측 모두를 형성하는 데에 있어 가장 최적의 조건으로 밝혀졌다. 경삽입구 술식을 이용한 이중다발 전방십자인대 재건술에서 슬관절의 굴곡 각도와 천공기의 수평 각도는 대퇴 터널의 특성에 대해 통합적인 영향을 미치는 것으로 나타났다. 120°의 굴곡 각도를 이루고 천공기의 수평 각도를 대퇴골 내측과에 근접시킴으로써 최적의 전내측 및 후외측 다발의 터널을 형성할 수 있을 것이다.

핵심되는 말: 관절경; 전방십자인대; 재건술; 이중다발