

# Restoration of the tibial ACL footprint area and geometry using the Modified Insertion Site Table

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## Abstract

**Purpose** This article is based on the concept of complete footprint restoration. It introduces a “Modified Insertion Site Table” for individual size-matched single- (SB) and double-bundle (DB) ACL reconstruction, which gives surgical guidelines for graft diameters and drill angles according to the restored tibial insertion site area and geometry.

**Methods** Potential graft diameters and drill angles were matched for all individual tibial insertion site lengths between 8 and 21 mm. A “Modified Insertion Site Table” was calculated to achieve a maximum of area restoration of the tibial ACL footprint for each of these insertion site lengths. The geometry of the restored footprint was considered.

**Results** A wide ACL footprint up to a 16-mm-long insertion site might be best restored with a SB-, a narrow one with a DB-ACL reconstruction. In a 17-mm-long insertion site, SB- and DB-ACL reconstructions restore a similar amount of footprint area, so geometry considerations of the footprint may decide which surgical technique may be favoured. SB can restore a maximum length of 13.1 mm and DB up to 21 mm. The width of the restored area depends on the drill bit diameter(s) and is larger for SB in most cases. In larger footprints, DB can replicate up to 63% more area and 37% more length than SB-ACL reconstruction.

**Conclusions** Anatomical footprint restoration requires assessment of the length, width, and the orientation of the

tibial ACL insertion site. Both SB- and DB-ACL reconstruction may achieve a wide range of area and geometric restoration of the individual ACL footprint. While SB-ACL reconstruction may be best used for wide insertion sites with up to 16 mm in length, DB-ACL reconstruction has the potential to restore narrow and larger footprints up to 21 mm in length. The “Modified Insertion Site Table” resumes the concept for orientation during surgery.

**Keywords** ACL · Insertion site · Area · Geometry · Footprint · Modified Insertion Site Table · Concept · Indication · Double bundle · Single bundle

## Introduction

The concept of complete footprint restoration for anatomical ACL reconstruction was introduced recently to restore the individual ACL footprint in order to achieve a maximum of biomechanical stability and function [19, 20]. It is based on the hypothesis that the restored biomechanical envelope of the knee is a function of the amount of reconstructed insertion site area. The article defined indications for single-bundle (SB)- and double-bundle (DB) ACL reconstruction based on the percentage of restored individual insertion site length. The authors recommended SB-ACL reconstruction for “small” and “intermediate” footprints up to 15 mm in length and DB-ACL reconstruction for “large” insertion sites of 16 mm length or more [20]. Similar recommendations were given by van Eck et al. [22] presenting a flowchart for ACL reconstruction. They recommended DB-ACL reconstruction from an insertion site length of 15 mm or more.

However, the geometrical individuality of the oval or triangular shaped tibial ACL insertion is not only defined

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by the anatomical length of its insertion site, which is in the range of 9–21 mm but also by its anatomical width, which lays between 8 and 13 mm [1–11, 13, 15, 16, 18, 21, 24].

Therefore, the concept of complete footprint restoration also requires considering the width of the tibial footprint to restore a maximum amount of insertion site *area*. A perfect restoration of the insertion site length may not automatically achieve a maximum of *area* restoration of the tibial insertion site.

This article gives guidelines for restoring the individual area and geometry of the tibial insertion site. It introduces a “Modified Insertion Site Table” for individual size-matched SB- and DB-ACL reconstruction. Combinations of drill bit diameters and sagittal drill angles are presented to achieve a maximum amount of area-, length-, and width reconstruction of the individual tibial ACL footprint.

## Materials and methods

### Modified Insertion Site Table

The “Modified Insertion Site Table” (Table 1) is based on the concept of “complete footprint restoration,” which was recently published in this journal [20]. In contrast to the first “Insertion Site Table,” this modified table focuses on the restored area rather than the restored insertion site length. For each intraoperative measured tibial insertion site length from 8 to 21 mm, the table highlights the techniques with the highest amount of area restoration. Graft bit diameters of 5–11 mm as well as drill angles of 50°–65° were considered for calculation. Smaller drill angles were excluded since they have been considered technically difficult. A drill bit diameter of 11 mm is very large and was, therefore, only included to demonstrate the upper limit of area restoration with SB-ACL reconstruction.

The surface area of all possible tibial SB- and DB bone tunnels was calculated. In SB-ACL reconstruction, the restored area was calculated as an ellipse ( $P = \text{length}/2 (l/2) \times \text{width}/2 (w/2) \times \pi$ ) and in DB-ACL reconstruction as two ellipses including a 2-mm bone bridge ( $P1(\text{AM}) = 1/2 \times (l/2 \times w/2 \times \pi) + P2(\text{AM} + \text{bone bridge}) = w \times (l/2 + 2) + P3(\text{PL}) = w \times l/2 + P4(\text{PL}) = 1/2 \times (l/2 \times w/2 \times \pi)$ ). In DB-ACL reconstruction, only drill bit combinations for AM to PL areas between 50:50 and 60:40 were considered anatomical and were therefore included in the calculations [7, 11, 16, 18] (Table 1).

### Operative procedure

In contrast to the usual order of surgical steps, the concept of complete footprint restoration requires assessment of the geometry of the tibial ACL insertion site prior to graft

preparation. First, the length and the width of the tibial footprint are measured intraoperatively using a ruler. Then, the surgical technique (SB- or DB-ACL reconstruction) with the specific drill bit diameter(s) and sagittal drill angle(s) is assessed from the “Modified Insertion Site Table.” Next, the hamstring-, patella tendon-, or quadriceps tendon graft is harvested and prepared according to the recommended diameter(s). The bone tunnel(s) are drilled, respectively (Table 1), and the ACL reconstruction is completed as usual.

### SB-ACL reconstruction for short insertion sites

According to the criteria “area restoration,” a SB-ACL reconstruction may be recommended for wide insertion sites up to 16 mm of length. A SB-ACL reconstruction using a 10-mm drill bit in a 50° sagittal drill angle restores a tibial elliptic surface area of 103 mm<sup>2</sup> compared to an area restoration of maximum 94 mm<sup>2</sup> using a 7-mm AM- and a 5.5-mm PL-bundle in DB-ACL reconstruction for a 16 mm length (Table 1). Lower sagittal drill angles or larger drill bits may be used for SB-ACL reconstruction, but can result in (too) large or (too) short bone tunnels increasing the risk for complications.

In case of less than 10-mm-wide insertions sites, DB-ACL reconstruction may reconstruct more footprint area compared to a 9.5- or 9-mm SB-ACL reconstruction and might therefore be advantageous for a 16-mm insertion site length (Table 1).

### SB- or DB-ACL reconstruction for intermediate insertion sites

For an insertion site length of 17 mm, a 10-mm SB-ACL reconstruction can achieve a similar amount of area restoration as a 7-mm AM (65°) combined with a 6.5-mm PL (65°) bundle DB-ACL reconstruction (103 versus 104 mm<sup>2</sup>). However, the reconstructed surface geometry is completely different between both techniques: the 10-mm SB-ACL reconstruction leads to a 10 mm wide but only 13.1-mm long-shaped footprint restoration, whereas the combination of a 7-mm AM- and a 6.5-mm PL-bundle DB-ACL reconstruction creates a 6.5–7 mm wide and 16.9-mm-long footprint restoration of the 17-mm ACL footprint. It is therefore necessary to assess, which drill diameter fits the width of the insertion site to maximize the area restoration.

### Double-bundle ACL reconstruction for long insertion sites

A patient with a long insertion site of, for example, 18 mm may be reconstructed in a SB technique with a large 11-mm SB bone tunnel (50°) resulting in an area

**Table 1** Modified Insertion Site Table

Measured insertion site length (mm)		Drill diameter (mm) & drill angle			Reconstructed insertion site length (mm) + (%)			Reconstructed insertion area (mm <sup>2</sup> )			
<b>Single-Bundle</b>											
8		6.5		55°		7.9		99		41	
		6		50°		7.8		98		37	
9		7.5		60°		8.7		97		51	
		7		55°		8.6		96		47	
		6.5		50°		8.5		94		43	
10		8.5		60°		9.8		98		66	
		8		55°		9.8		98		61	
11		9.5		60°		11		100		82	
		9		55°		11		100		78	
		8.5		55°		10.4		95		69	
12		10		60°		11.6		97		91	
		9.5		55°		11.6		97		87	
		9		50°		11.8		98		83	
13		11		60°		12.7		98		110	
		10.5		55°		12.8		99		106	
		10		50°		13.1		101		103	
14		11		55°		13.4		96		116	
		10.5		50°		13.7		98		113	
15		11		50°		14.4		96		124	
<b>Double-Bundle</b>											
16	AM	7	6.5	6.5	6	6.5	6	6	5.5	5.5	5
	°	65°	65°	55°	55°	60°	55°	50°	50°	50°	50°
	PL	5.5	6	5.5	6	5	5.5	5	5.5	5	5
	°	60°	65°	65°	65°	50°	55°	55°	55°	50°	50°
	Length	16.1	15.8	16	16	16	16	15.9	15.9	15.7	15.1
	Area	94	90	89	87	86	84	81	79	75	68
17	AM	7	7	6.5	7	6.5	6.5	6	6	6.5	6
	°	65°	60°	60°	65°	55°	55°	50°	50°	60°	50°
	PL	6.5	6	6.5	5.5	6	5.5	6	5.5	5	5
	°	65°	60°	60°	50°	60°	55°	60°	50°	50°	50°
	Length	16.9	17	17	16.9	16.9	16.7	16.8	17	16	16.4
	Area	104	102	100	98	96	92	91	89	86	83
18	AM	8	7.5	7.5	7	7.5	7	7	6.5	7	6.5
	°	65°	65°	60°	60°	60°	55°	50°	50°	55°	50°
	PL	6.5	7	6.5	7	6	6.5	6	6.5	5.5	6
	°	65°	65°	65°	65°	55°	60°	60°	60°	50°	55°
	Length	18	18	17.8	17.8	18	18.1	18.1	18	17.7	17.8
	Area	121	119	115	113	112	111	108	106	103	102
19	AM	8	7.5	8	7.5	7.5	8	7	7.5	7	7
	°	60°	60°	65°	55°	55°	65°	55°	55°	50°	50°
	PL	7	7.5	6.5	7	6.5	6	7	6	6.5	6
	°	65°	65°	55°	65°	55°	50°	55°	50°	55°	50°
	Length	19	18.9	18.8	18.9	19.1	18.7	19.1	19	19.1	19
	Area	130	128	125	125	122	121	121	118	117	113
20	AM	8.5	8	8.5	8	8.5	8	7.5	8	7.5	7.5
	°	60°	60°	60°	55°	65°	55°	50°	55°	50°	50°
	PL	7.5	8	7	7.5	6.5	7	7.5	6.5	7	6.5
	°	65°	65°	60°	65°	50°	60°	65°	55°	60°	55°
	Length	20.1	20.1	19.9	20	19.9	19.9	20.1	19.7	19.9	19.7
	Area	147	145	142	141	137	136	136	132	131	127
21	AM	9	9	8.5	8.5	9	8.5	8	8.5	8	8
	°	65°	60°	65°	60°	65°	55°	55°	55°	55°	50°
	PL	8	7.5	8.5	8	7	7.5	8	7	7.5	7
	°	65°	60°	65°	60°	50°	60°	60°	55°	55°	55°
	Length	20.8	21.1	20.8	21.1	21.1	21	21	20.9	20.9	21
	Area	161	160	159	158	155	154	152	149	147	144

Guidelines for anatomical ACL footprint restoration for SB- and DB-ACL reconstruction based on the restored insertion site area  
 SB-ACL reconstruction: left column: intraoperatively measured length of tibial insertion site. Second column from left: matched drill diameter and drill angle to achieve a maximum of area reconstruction (right column) and length reconstruction (second column from right)  
 DB-ACL reconstruction: left column: intraoperatively measured length of tibial insertion site. Second column from left: AM anteromedial bone tunnel, “°” = sagittal drill angle, PL posterolateral bone tunnel, length = combined reconstruction of AM + PL + 2-mm bone bridge, area: restored area

restoration of 124 mm<sup>2</sup> but a reconstructed length of only 14.4 mm. However, to avoid such large bone tunnels DB-ACL reconstruction may be recommended. The combination of an 8-mm AM bundle (65°) and a 6.5-mm PL (65°) bundle restores an area of 121 mm<sup>2</sup>. The geometry of this restored area is characterized by a width of 6.5–8 mm and a length of 18 mm.

For patients with a very long insertion site of 21 mm, the geometry of the individual footprint can be best restored using a combination of a 9-mm AM (65°) and a 8-mm PL (65°) bundle DB-ACL reconstruction resulting in an area restoration of 161 mm<sup>2</sup>, a width of 8–9 mm and a length of 20.8 mm. This cannot be achieved with a 10- or 11-mm SB-ACL reconstruction using sagittal drill angles as low as 50°.

## Discussion

The study demonstrates that SB as well as DB-ACL reconstruction may achieve a wide range of area- and geometric restoration of the individual tibial ACL footprint. Based on geometrical considerations on the restored surface geometry, SB-ACL reconstruction may especially be recommended for wide tibial insertion sites up to 16 mm in length, whereas DB-ACL reconstruction has the potential to restore narrow footprints as well as large insertion sites up to 21 mm in length.

A “Modified Insertion Site Table” is introduced. Instead of only considering the length of the tibial insertion site to decide for the tibial footprint reconstruction, the “Modified Insertion Site Table” displays the maximum amount of area restoration for each individual (measured) insertion site length for orientation during surgery.

The concept supports individual size-matched ACL reconstruction using a SB reconstruction for tibial insertion sites up to 16 mm in length, which can restore up to 103 mm<sup>2</sup> of the tibial footprint using a 10-mm drill bit. However, DB-ACL reconstruction may be advantageous for a 16-mm-long tibial insertion site, especially when the footprint and/or the intercondylar notch is narrow and a 10-mm-wide SB-ACL reconstruction extends the anatomy (Table 1).

In a 17-mm-long insertion site, a similar amount of area can be restored by SB- and DB-ACL reconstruction, always depending on the width of the insertion site (Table 1). For larger footprints from 18-mm length individual, size-matched DB-ACL reconstruction can replicate significantly more area and length of the insertion site than SB-ACL reconstruction. For example, in a 21-mm-long tibial insertion site, a 9-mm AM bone tunnel combined with an 8-mm bone tunnel can restore 63% more of the tibial surface area and 37% more of the insertion site length than a 10-mm SB-ACL reconstruction (Table 1).

According to geometric considerations by Milankov et al. [14], there is no difference in size (102.5 mm<sup>2</sup>) of the restored tibial ACL surface between a 10-mm SB and an 8-mm (AM) and 6-mm (PL) DB-ACL reconstruction. This is true when only adding the area of the two ellipses in DB-ACL reconstruction. However, a bone bridge of 2 mm is usually preserved in DB between the AM- and PL bone tunnels [7, 18, 20, 23], when considering the elliptic areas of an 8-mm AM and 6-mm PL bone tunnel (both drilled in 50°) and the area of a 2-mm bone bridge all additions to 133 mm<sup>2</sup>.

This study more importantly shows that SB- and DB-ACL reconstruction has a different potential to restore the shape (geometry) of the tibial ACL insertion site. The length of the restored area depends on the drill bit diameter and the sagittal drill angle [12, 19, 20]. A SB-ACL reconstruction may be applied to all patients but can only restore a maximum length of 13.1 mm and a width of 10 mm using a 10-mm drill bit in a 50° sagittal drill angle (Table 1). In contrast, DB may restore very long insertion sites up to 21 mm or more depending on the combination of drill bits (Table 1). Sahasrabudhe et al. [17] evaluated 38 patients after DB-ACL reconstruction using three-dimensional computed tomography. They reported that the AP length of the reconstructed tibial footprint was as large as 17.1 ± 1.9 mm. This cannot be achieved using a SB-ACL reconstruction. However, the AM- and PL drill bit diameters are usually smaller compared to SB-ACL reconstruction. The shorter the tibial footprint the smaller the DB drill bit diameters and the width of the restored insertion site area compared to SB-ACL reconstruction—and vice versa (Table 1). This makes it necessary to intraoperatively measure both the length and the width of the tibial footprint to adapt the ACL reconstruction accordingly. However, when choosing a drill bit diameter (=graft diameter), there has to also be consideration of which graft diameter fits the width of the insertion site and also the width of the intercondylar notch in order to achieve a maximized reconstruction but to avoid overstuffing and/or notch impingement.

Finally, the long axis of the reconstructed ellipse(s) has to be parallel to the long axis of the tibial insertion site. This can be achieved by changing the transverse drill angle of the tibial bone tunnel in the coronal plane. Kopf et al. [12] evaluated the effect of tibial drill angles on bone tunnel aperture during ACL reconstruction. They found that the drill bit diameter, the sagittal drill angle, and transverse drill angle can all affect tibial tunnel aperture size and orientation. An improperly sized and/or orientated tunnel aperture may increase the risk of damaging surrounding structures. They suggest to choose an optimal combination of these three parameters during ACL reconstruction.

The “Modified Insertion Site Table” has some limitations. The amount of restored footprint is limited by the shape of the insertion site and the surgical technique applied. The advantage of complete footprint restoration over partial footprint restoration has to be proven in future biomechanical and clinical studies. It is also unknown if graft hypertrophy may lead to postoperative graft impingement. However, a hamstring tendon graft with a larger cross-sectional area has been shown to have a higher failure load [9].

Functional considerations are also important when deciding for a SB- or DB-ACL reconstruction. Activities of daily living as well as sports, work, the degree of osteoarthritis etc. are all important [19, 20, 22]. Any alternative technique or graft may be adequate to achieve the purpose of complete footprint reconstruction. Especially, for large SB bone tunnels but also for any DB bone tunnels, a graft with bone block(s) may be used to fill up large bony defects from the tunnel(s). In case of a patellar tendon or a quadriceps tendon graft, the geometrical shape of the graft may not be round, so the concept has to be adapted accordingly.

## Conclusion

Anatomical footprint restoration requires intraoperative assessment of the length, width, and orientation of the tibial ACL insertion site. Both, SB- and DB-ACL reconstruction may achieve a wide range of area and geometric restoration of the individual ACL footprint. SB-ACL reconstruction may especially be recommended for wide insertion sites up to 16 mm in length, whereas DB-ACL reconstruction has the potential to restore narrow footprints as well as large insertion sites up to 21 mm in length. The “Modified Insertion Site Table” resumes the concept for orientation during surgery.

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