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The concept of complete footprint restoration with guidelines for single- and double-bundle ACL reconstruction

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Abstract
Purpose This article introduces guidelines for single- (SB) and double-bundle (DB) ACL reconstruction based on the concept of complete footprint restoration. The goal is to reconstruct a maximum of anterior cruciate ligament (ACL) insertion site area to regain a maximum of ACL function. The concept is based on the hypothesis that the restored biomechanical envelope of the knee is a function of reconstructed ACL insertion site area.
Methods Individual combinations of graft diameters and drill angles were calculated and matched for all individual insertion site lengths between 8 and 21 mm to maximize the percentage of anatomical footprint restoration. An "insertion site table" was developed to propose individual guidelines during ACL surgery for SB and DB ACL reconstruction based on the intraoperative measurement of the tibial insertion site length.
Results Our calculations support the use of SB in "small footprints" up to 13 mm, which may restore more than 95% of the native insertion site length. "Intermediate footprints" between 14 and 15 mm may be restored by both a SB or DB ACL reconstruction. For "larger footprints" of 16 mm or more, DB has the potential to replicate 97% or more of the insertion site length which cannot be achieved by a SB ACL reconstruction.
Conclusions The concept of complete footprint restoration aims to reconstruct a maximum of ACL insertion site area to restore a maximum of functional envelope of the knee. Depending on the individual situation, different surgical approaches (SB/DB), graft diameters and drill angles may apply. An "insertion site table" was designed to give guidelines for SB and DB reconstruction during surgery. According to the new concept, DB ACL reconstruction is only considered as a surgical tool for large footprints and is not indicated for smaller ones.

Keywords Insertion site table · Concept · ACL · Footprint · Indication · Double bundle · Single bundle

Introduction

The concept of anatomical double-bundle (DB) ACL reconstruction was introduced recently to restore the anatomy and biomechanical function of the native ACL [4, 9–14, 16, 17, 19–21, 28, 30, 35, 39, 40, 46, 47, 54]. According to anatomical and biomechanical studies, the separate reconstruction of the anteromedial (AM) and posterolateral (PL) bundle was supposed to increase the overall postoperative stability and clinical results compared to single-bundle (SB) ACL reconstruction [3, 5, 6, 8, 15, 23, 34, 50–52, 55–58, 62, 63]. However, recent clinical studies document a rather mixed outcome between techniques with only view showing a significant advantage for DB [1, 2, 22, 24, 26, 29, 33, 45, 49, 59, 61]. This raised the question of its real advantage and it seems that only certain patients may benefit from the complex DB procedure—others may not.

An anatomical SB procedure is performed by placing one single bone tunnel in the centre of the tibial and femoral ACL footprints. The bone tunnels are drilled according to the diameter of the prepared graft without considering the relationship between the size of the natural insertion site area (ISA) and the reconstructed one. This

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results in a randomized percentage of surgically restored ACL footprint.

However, several biomechanical studies demonstrated that ACL fibres of different parts of the insertion sites add different to knee function [4, 9–14, 16, 17, 19, 20, 30, 35, 39, 46, 47]. Fibres attached to the tibial anteromedial part of the ACL footprint (AM-bundle fibres) add more to anterior stability compared to PL bundle fibres which add more to rotational stability close to extension. Consequently—by placing bone tunnels in a certain position of the ACL footprints the surgeon defines the individual biomechanical envelope of the ACL reconstruction [25]. For example, by positioning both SB bone tunnels in the ISA of the AM fibres imitates the biomechanical function of the native AM-bundle fibres but sacrifices the biomechanical function of the non-reconstructed PL-bundle fibres. Morimoto et al. [32] demonstrated that a DB procedure (which reconstructs a higher amount of ACL insertion site area than SB in large insertion sites) restored the normal contact area and pressure more closely in low flexion angles compared to SB.

To restore a maximum amount of stability and function, we developed the concept of "complete footprint restoration". It is based on the hypothesis that the restored biomechanical envelope of the knee is a function of reconstructed ISA—in other words—the higher the percentage of individual footprint reconstruction the better the functional outcome for the patient.

This article introduces the new concept of "complete footprint restoration" and defines indications for SB and DB ACL reconstruction based on the individual size of the ACL insertion sites. An "insertion site table" with guidelines for graft sizes and drill angles was calculated for the surgeon to match the surgical technique to the individual ACL insertion sites of the patient.

Guidelines for single-bundle and double-bundle ACL reconstruction

The surgically restored ISA of the ACL is defined by the width and the length of the oval bone tunnel outlet(s), which is a function of the drill (graft) diameter and drill angle [27, 47]. The average width of the native tibial and femoral insertion sites is between 9 and 11 mm [12, 47]. As this range is rather small, it may be sufficiently reconstructed by the width of the tunnel diameters during SB or DB ACL reconstruction in the majority of the patients.

However, big individual variations do exist for the long axis of the tibial ACL insertion site in anterior–posterior direction and for the long axis of the femoral insertion site in superior–inferior direction. The surgically relevant range is reported to be between 9 and 21 mm on the tibia and between 11 and 21 mm on the femur [4, 9–14, 16, 17, 19, 20, 30, 35, 39, 46, 47]. According to own anatomical studies, there is a close relationship between the length of the tibial and femoral insertion site areas [46, 47].

The new concept of complete footprint restoration aims to reconstruct the complete length of the ACL insertion sites to restore a maximum of biomechanical function of the ACL footprint. Details are described in the new "insertion site table" below.

Insertion site table

The "insertion site table" (Table 1) presents guidelines for SB and DB ACL reconstruction based on the concept of "complete footprint restoration". The length of the individual tibial insertion sites (first column) is matched to an individual drill (graft) diameter and drill angle (second column). Different grafts (third column) may be favourable depending on the size of the recommended drill diameters and individual patient requirements, e.g., kneeling profession, etc. The oval length of each articular bone tunnel outlet was calculated according to the formula: *drill size divided by* $\sin \alpha$ based on a parallel alignment of the long axis to the sagittal plane from anterior to posterior (Table 1). Oblique drilling directions to the sagittal plane were not considered, as these complex the calculation significantly and may not play a significant role. The surgically restored insertion site length (last column Table 1) is displayed in millimetres and percentage of the native insertion site length (Table 1). To clarify the concept and to avoid overdrilling of the insertion site length, the calculated numbers are given in millimetres with decimals. This accuracy cannot be achieved during drilling.

In contrast to the usual order of surgical steps, the concept makes it necessary to first measure the length of the tibial ACL insertion site with a ruler from anterior to posterior. The drill diameter and angle as well as the surgical technique (SB/DB) are assessed from the "insertion site table". Then the diameter of the graft is prepared according to the defined drill diameter and the ACL reconstruction is completed respectively (Table 1).

Short insertions

According to our calculations, a *short tibial ACL insertion site between 8 and 13 mm* may be restored to more than 95% by an individually matched SB technique (Table 1). A short insertion site of e.g., *10 mm length* may be reconstructed by an individual SB bone tunnel with a drill (and graft) diameter of 8 mm and a drill angle of 55° to the tibial plateau (Table 1). With exact drilling, this may result in a calculated reconstructed insertion site length of 9.8 mm,

Table 1 Insertion site table

Measured (intra-op) insertion site length [mm]	Drill diameter [mm] & drill angle: SB				Graft	Reconstructed insertion site length [mm]	[%]
8	6	50°			ST (2x)	7.8	98
	6.5	55°				7.9	99
9	7	55°			ST (3-4x)	8.5	94
10	7.5	50°			ST (3-4x)	9.8	98
	8	55°				9.8	98
11	8.5	55°			ST / ST + GT / BPTB / QTB	10.4	95
	9	55°				11	100
12	9.5	55°			ST + GT / BPTB / QTB	11.6	97
13	10	50°			BPTB / QTB	13	100
	10.5	55°				12.8	99
14	11	55°				13.4	96
15	11	50°			BPTB / QTB	14.4	96
	DB: AM		**DB: PL**			**... inclusive 2mm BB**	
14	5	60°	5	60°	ST (2x + 2x)	13.6	97
	5.5	60°	5	65°		14.0	100
15	5.5	60°	5.5	60°	ST (2x + 2x)	14.7	98
	6	60°	5	60°		14.7	98
16	6	55°	5.5	60°	ST (2x + 2x)	15.7	98
	6	60°	6	60°		15.9	99
	6.5	55°	5	60°	ST +GT	15.7	98
	6.5	60°	5.5	60°		15.9	99
	7	60°	5	60°		15.9	99
17	6.5	55°	6	60°	ST + GT	16.9	99
	6.5	60°	6.5	65°		16.8	99
	7	55°	5.5	60°		16.9	99
	7	60°	6	65°		16.8	99
	7.5	55°	5	60°		16.9	99
	7.5	60°	5.5	65°		16.8	99
	8	60°	5	65°		16.9	99
18	7	60°	6.5	60°	ST + GT	17.6	98
	7	60°	7	65°		17.9	99
	7.5	60°	6	60°		17.6	98
	7.5	60°	6.5	65°		17.9	99
	8	60°	5.5	60°		17.6	98
	8	60°	6	65°		18.0	100
19	7.5	60°	7	60°	ST + GT	18.7	98
	7.5	60°	7.5	65°		19.0	100
	8	60°	6.5	60°		18.7	98
20	8	55°	7	60°	ST + GT (+BPTB, QTB)	19.9	100
	8	60°	7.5	60°		19.9	100
21	8	60°	8	60°	ST + GT (+BPTB, QTB)	20.5	98

Recommendations for anatomical ACL footprint reconstruction to maximize the restored insertion site area

Intraoperatively measured long axis of tibial ACL insertion (column 1), calculated drill diameter(s) and drill angle(s) for SB or DB (column 2), graft type (column 3) and restored ap-length and percentage of insertion (in DB including a 2-mm bone bridge between AM and PL) ((last column)

ST semitendinosus 2x doubled, 3x trippled, 4x quadrupled, GT: gracilis tendon, BPTB: bone patella bone tendon, QTB: quadriceps tendon, BB: bone bridge between AM and PL

SB: drill angle: 50° or 55°; DB: drill angle for AM and PL: 55° or 60° or 65° to the tibial plateau

Fig. 1 Example 1: Short insertion site length of 10 mm measured intraoperatively: a drill diameter of 8 mm (SB) and a drill angle of 55° does result in a reconstructed ACL insertion site length of 98%. A threefold semitendinosus-tendon graft was used. **b**, **c** Anatomical tibial SB footprint reconstruction of 98%

a

Measured (intra-op) insertion site length [mm]	Drill diameter [mm] & drill angle		Graft	Reconstructed insertion site length	
	SB			[mm]	[%]
10	7.5	50°	ST (3-4x)	9.8	98
	8	55°		9.8	98

b

c

which is 98% of the original insertion site length on the tibia (Fig. 1). In contrast, an insertion site of *12 mm length* might be better reconstructed by a 9.5-mm SB bone tunnel drilled in a 55° angle resulting in a calculated restored insertion site length of 11.6 mm (=97%) (Fig. 2), and a *13-mm*-long insertion site may be reconstructed by a 10-mm bone tunnel in 50° resulting in 100% of reconstructed ISA (Table 1). Especially for larger drill diameters from 9.5 mm or more, a bone-patella-tendon-bone- or quadriceps-tendon bone graft may be considered over a hamstring graft to fill up the large bone tunnel defects at the insertion sites with one or two bone block(s).

Intermediate insertions

However, an insertion site length of *14–15 mm* is more critical to be reconstructed, as this length needs large SB bone tunnels of 10–11 mm (Table 1). To increase the reconstructed insertion site length even more, smaller drill angles as low as 45° may be used to create a longer oval of the bone tunnel outlet.

An insertion site length of *14 mm* might be reconstructed by an 11-mm SB bone tunnel drilled in 55° to the tibial plateau resulting in a calculated restored insertion site length of 96%. A bone patellar tendon bone- or quadriceps tendon graft may be considered for this purpose. On the other hand, it might be critical to perform a DB ACL reconstruction in a 14-mm insertion site. As calculated in Table 1, a thin 5.5 mm AM and a 5-mm PL graft is necessary which may increase the risk of graft failure or rupture [36].

However, a *15-mm*-long insertion site might be the shortest insertion site length to be suitable for a DB ACL reconstruction. The potential advantages of a DB procedure in this situation are the two smaller AM- and PL-bone tunnels with a significantly higher tendon to bone contact (more than 30%) compared to an 11-mm SB ACL reconstruction (Table 1).

a

Measured (intra-op) insertion site length [mm]	Drill diameter [mm] & drill angle		Graft	Reconstructed insertion site length	
	SB			[mm]	[%]
12	9.5	55°	ST + GT / BPTB / QTB	11.6	97

b

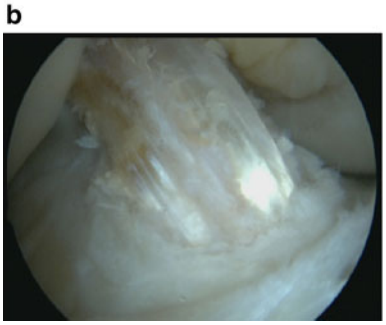
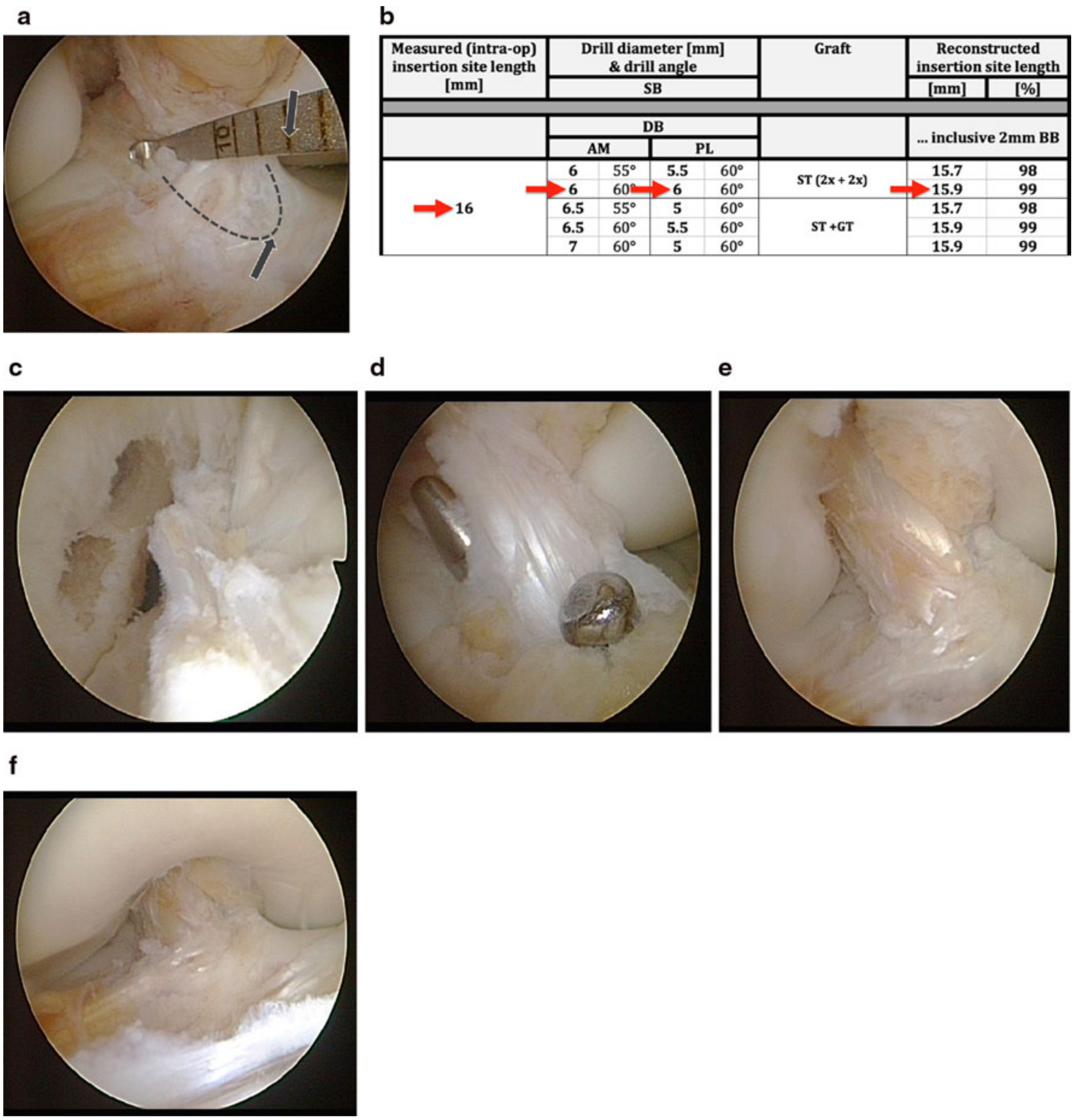


Fig. 2 Example 2: Short insertion site length of 12 mm measured intraoperatively: a drill diameter of 9.5 mm (SB) and a drill angle of 55° does result in a reconstructed ACL insertion site length of 97%. Different grafts may be recommended for reconstruction. **b** Anatomical tibial SB footprint reconstruction of 97%

Long insertions

However, *a long insertion site of 16 mm or more* cannot be completely reconstructed by one SB bone tunnel (Table 1; Fig. 3), and consequently, the deficit of non-reconstructed ISA increases significantly with larger insertion sites. These are the patients, which may have the highest biomechanical and clinical benefit from a DB procedure as the reconstructed area is significantly larger than with a SB procedure.

A patient with a large insertion site length of *18 mm* may be reconstructed in a SB technique with a (large) 11-mm SB bone tunnel resulting in 78% coverage of the ISA according to the insertion site table (Table 1). When the same patient is reconstructed in a DB technique with drill diameters of 8 mm for AM and 6 mm for PL, the reconstructed insertion site length is increased by 22% from 14 mm in SB to 18 mm in DB. In a patient with an



Measured (intra-op) insertion site length [mm]	Drill diameter [mm] & drill angle				Graft	Reconstructed insertion site length	
	SB					[mm]	[%]
	DB					... inclusive 2mm BB	
	AM		PL				
16	6	55°	5.5	60°	ST (2x + 2x)	15.7	98
	6	60°	6	60°		15.9	99
	6.5	55°	5	60°	ST +GT	15.7	98
	6.5	60°	5.5	60°		15.9	99
	7	60°	5	60°		15.9	99

Fig. 3 Example 3: Long insertion site length of 16 mm measured intraoperatively: a drill diameter of 6 mm for AM and 6 mm for PL and drill angles of 60° for both tunnels do result in a reconstructed ACL insertion site length of 99%. 2 doubled ST-grafts may be used for reconstruction. **a** Intraoperative measurement of tibial footprint: 16 mm ap-length. The *arrows* highlight the anterior border of the ACL stump. **c**, **d** Femoral bone tunnels (**c**), and tibial bone tunnels (**d**) for DB ACL reconstruction. **e**, **f** DB ACL reconstruction with a restored insertion site length of 99%

insertion site length of 20 mm, the deficit of restored insertion site length using SB is as high as 28% compared to a DB reconstruction.

Discussion

This article introduces the new concept of "complete footprint restoration" by bone tunnel drilling. It aims to restore all of the individual ACL insertion sites to regain a maximum of biomechanical function and clinical stability. An "insertion site table" was designed to give guidelines for SB and DB reconstruction during surgery. As the SB technique may be suitable for "small" and "intermediate" footprints up to 14 mm in length, a DB ACL reconstruction may only be recommended for "intermediate" and "large" insertion sites from 15 mm or more.

To maximize the restored insertion site area, the concept requires larger ACL grafts, which do also increase the strength of the reconstruction. Hamner et al. [18] showed that the initial failure load of a hamstring tendon graft is linearly related to its cross-sectional area. A larger hamstring graft diameter with a higher number of fibres will increase the maximum load and stiffness. It will also replicate more of the native ACL fibre length changes as shown by Robinson et al. [42]. They demonstrated that the increasing graft size appears to capture more of the range of the native ACL fibre length change. For example, a 6-mm hamstring tendon graft does replicate 32% of the range of the native ACL fibre length changes, whereas a 9-mm graft restores 51%. In addition, Brophy et al. [7] showed that with optimal placement and orientation, anatomical SB graft fibres result in better replication of fibre length changes and strain compared to the native ACL and may resist pathologic anterior translation and internal rotation more than a suboptimal graft.

According to the new concept, the perfect indication for a SB ACL reconstruction may be a small ACL insertion site up to 14 mm in length. As shown in Table 1, one single bone tunnel may restore more than 95% of the original insertion site area in these patients. Therefore, a small footprint may not be an indication for a complex DB procedure as the reconstructed area is similar, the potential for pitfalls is higher and the additional functional benefit for the patient may not to be significant.

In contrast, an anatomical DB ACL reconstruction may be indicated for "larger knees" with longer anatomical footprints of 15 mm or more [48] resulting in a footprint reconstruction of more than 97% (Table 1). However, based on this concept and the "insertion site table", the DB technique may only be considered as a surgical tool for large insertion sites and may not be indicated for smaller footprints. This is reconfirmed by Sahasrabudhe et al. [43]. They evaluated 38 patients after DB ACL reconstruction using three-dimensional computed tomography and reported that the AP length of the reconstructed tibial footprint was as large as 17.1 mm + −1.9 mm.

In addition to anatomical indications, it may also be important to consider secondary functional indications for SB or DB. Activities of daily living and sports, work, degree of osteoarthritis etc. may also be important and may be included in the process of decision making [53]. Even for patients with larger ACL insertion sites, a SB ACL reconstruction may be indicated depending on the level of activity or other factors.

Any alternative technique and graft may be adequate to achieve the purpose of complete footprint reconstruction [31, 37, 38, 41, 44, 60]. Especially for large SB bone tunnels a graft with bone block(s) may be advantageous to fill-up large bony defect from the tunnels. In case of patellar tendon graft or quadriceps tendon graft, the geometrical shape of the graft may not be round and the concept has to be adapted accordingly.

The concept of "complete footprint restoration" has some limitations. The amount of footprint reconstruction is limited by the shape of the insertion sites and the surgical technique applied. In vivo it will be impossible to reconstruct 100% of ISA. The concept is based on the length of the tibial insertion site, which can easily be measured during surgery. At the femoral ACL insertion site—however—the concept may only be used as orientation for femoral bone tunnel drilling because of significant variations of the femoral drill angles and the difficulty of intraoperative femoral insertion site measurements. The advantage of maximized footprint reconstruction over partial footprint reconstruction has to be proven in biomechanical and clinical studies. Finally, it is unknown if intraarticular graft hypertrophy is of relevance in this concept.

Conclusion

The new concept of complete footprint restoration aims to maximize the reconstructed ACL insertion site areas to achieve an optimized functional outcome. An "insertion site table" was calculated for the surgeon, which defines drill diameters and drill angles as well as indications for SB and DB reconstruction depending on the length of the tibial insertion site. In this concept, the DB technique is only considered as a surgical tool for large footprints and may not be indicated for smaller insertion sites.

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