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Impingement following anterior cruciate ligament reconstruction: comparing the direct versus indirect femoral tunnel position

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Abstract
Purpose During anterior cruciate ligament (ACL) reconstruction, authors have suggested inserting the femoral tunnel at the biomechanically relevant direct fibres, but this higher position can cause more impingement. Therefore, we aimed to assess ACL graft impingement at the femoral notch for ACL reconstruction at both the direct and indirect tunnel positions.
Methods A virtual model was created for twelve cadaveric knees with computed tomography scanning in which a virtual graft was placed at direct and indirect tunnel positions of the anteromedial bundle (AM), posterolateral bundle (PL) or centre of the both bundles (C). In these six tunnel positions, the volume (mm^3) and mid-point location of impingement (°) were measured at different flexion angles.
Results Generally, more impingement was seen with the indirect position compared with the direct position although this was only significant at 90° of flexion for the AM position (97 ± 28 vs. 76 ± 20 mm^3, respectively; $p = 0.046$). The direct tunnel position impinged higher at the notch, whereas the indirect position impinged more towards the lateral wall, but this was only significant at 90° of flexion for the AM (24 ± 5° vs. 34 ± 4°, respectively; $p < 0.001$) and C position (34 ± 5° vs. 42 ± 5°, respectively; $p = 0.003$).
Conclusion In this cadaveric study, the direct tunnel position did not cause more impingement than the indirect tunnel position. Based on these results, graft impingement is not a limitation to reconstruct the femoral tunnel at the insertion of the biomechanically more relevant direct fibres.

Keywords Direct tunnel position · Indirect tunnel position · Anterior cruciate ligament reconstruction · Notchplasty · Impingement

Introduction

It has been shown that anterior cruciate ligament (ACL) reconstructions fail in approximately 12 % of the cases [9]. Technical errors are considered to be the most important cause of failure (63–90 %) of which femoral tunnel malpositioning is the most common technical error [2, 33, 43, 45]. Positioning the femoral tunnel in an anatomical position is shown to be superior in restoring knee kinematics and graft isometry when compared to a nonanatomical tunnel position [1, 6, 7, 10, 29, 30, 35, 42, 46]. In addition, it has been shown that an anatomical femoral tunnel position can decrease the risk of notch impingement [22, 24].

More recently, Iwahashi et al. [26] assessed the histological characteristics of the anatomical femoral footprint. The authors showed that there are two different ACL fibres at the femoral insertion: the direct and indirect fibres. The anatomical position of the direct fibres is located anterior

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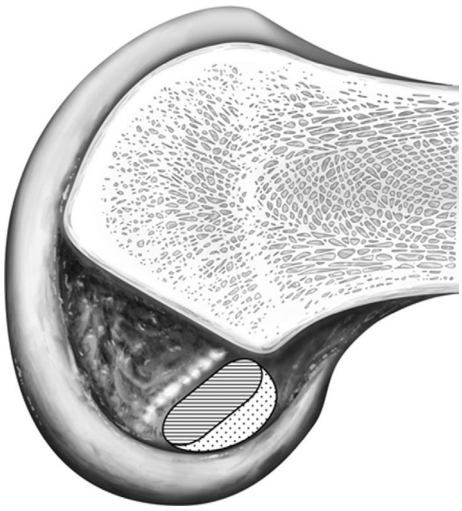

Fig. 1 The locations of the direct and indirect fibres are shown within the anatomical footprint. The direct insertion was located at the anterior (*high*) part of the ACL insertion (*shaded* portion), and the width was narrow. The indirect insertion was located at the posterior (*low*) part of the ACL insertion (*dotted* portion). Reprinted from Sasaki et al. [41] with kind permission of Elsevier

or high within the anatomical femoral footprint, while the position of the indirect fibres is located posterior or low within the footprint (Fig. 1) [21, 41]. The direct insertion fibres have a transitional zone that enables load distribution and is biomechanically more important in contributing to tibial translation and rotation when compared to the indirect fibres [3, 4, 26]. It is therefore suggested that in the setting of anatomical ACL reconstruction the femoral tunnel position should be positioned at the anterior or high location of the biomechanically more relevant direct fibres [40].

However, Iriuchishima et al. [24] showed in a biomechanical study that a higher femoral tunnel position is associated with more graft impingement. It is therefore possible that graft impingement might occur when the femoral tunnel is placed at the position of the direct fibres. Graft impingement is associated with the longevity of the graft, and an additional notchplasty might then be necessary to avoid this problem [14, 15]. Therefore, the purpose of this study was to assess the volume and location of graft impingement when using different high and low femoral tunnel positions. To our knowledge, this is the first study that assessed the role of graft impingement in the direct and indirect femoral tunnel positions. The hypothesis of the study was that, if the direct insertion is used, a larger volume of impingement occurs. The second hypothesis was that for the direct tunnel position the notch should be resected higher in the notch when compared to the indirect tunnel position.

Materials and methods

Cadaver preparation

Twelve fresh-frozen human cadaveric knees were included in this study (mean age 52.5 years, range 29–65). None had previous ligamentous injury, knee surgery or osteoarthritis. The cadavers underwent computed tomography (CT) scanning, and reference markers were fixed to each cadaveric specimen. With the CT scan (Mimics, Materialise Inc. Leuven, Belgium), an individual three-dimensional model was created with the CT dense reference markers. The knees were then mounted to a six-degree-of-freedom robot (ZX165U; Kawasaki, Tokyo, Japan), which enables moving the knee through the flexion–extension arch. The reference markers allowed linking the virtual joint model to the physical experiment and enabled determining the three-dimensional virtual flexion path of the knee.

Virtual graft positions

One author (DHN) experienced in ACL reconstructions identified the location of the tunnel positions. The axial, coronal and sagittal slices of the CT scan and the virtual three-dimensional model enabled finding the centre of the tibial and femoral footprints. The anatomy of the tibia was used to locate the centre of the tibial footprint. Subsequently, the anteromedial (AM) footprint of the tibia was identified in all virtual grafts. At the femoral footprint, the lateral intercondylar ridge [20], the lateral bifurcate ridge [11] and landmarks of the posterior articular cartilage were used to identify the centre of the femoral footprint. The centres of the AM, the posterolateral (PL) bundle and the centre of the entire ACL bundle insertion (C) were used to create virtual graft reconstructions with three-dimensional modelling software (Geomagic Studio 2013, Geomagic Inc. Rock Hill, SC, USA). The virtual ACL graft, consisting of a 9-mm (mm) rigid cylinder, was inserted between the tibial AM footprint and different femoral tunnel positions of both the direct (high) fibres and indirect (low) fibres as described by Pathare et al. [40]. This resulted in six graft positions (Fig. 2): (1) AM tibia to high AM femur (hAM), (2) AM tibia to high central (C) femur (hC), (3) AM tibia to high PL femur (hPL), (4) AM tibia to low AM femur (LAM), (5) AM tibia to low central femur (LC) and (6) AM tibia to low PL femur (LPL). The tibial tunnel position was identical for all six virtual grafts in order to assess the role of the femoral tunnel position on graft impingement. The AM position at the tibial footprint was chosen because this would maximize the amount of graft impingement and therefore maximizes the difference between the six femoral tunnel positions [16, 18, 19].

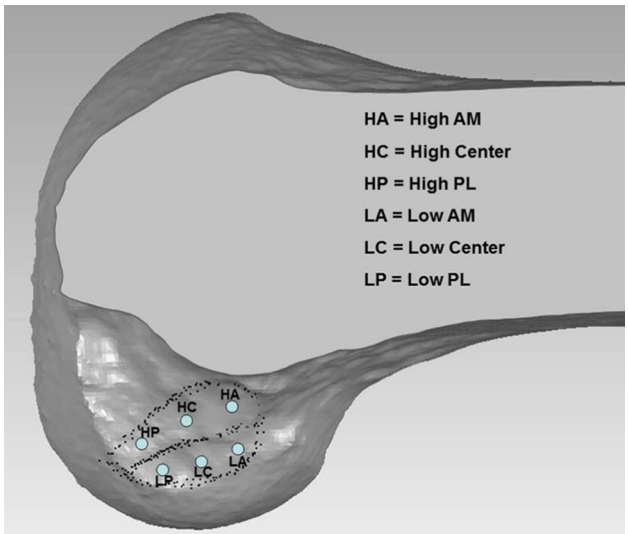

Fig. 2 The different direct (*high*) and indirect (*low*) tunnel positions at the femoral footprint

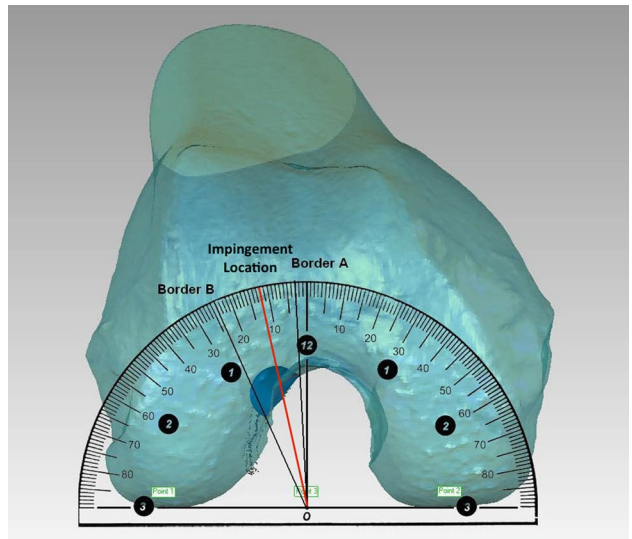

Fig. 3 Using a protractor overlay, the location of impingement was measured. *Border A* represents the most proximal border of impingement, and *border B* represents the most distal border of impingement. The impingement location is the *mid-point* between borders A and B

Impingement measurements

Impingement volume was measured by the overlap between the bony notch of the femoral condyle and the virtual graft and was measured using a Boolean operation. The volume of impingement was presented in mm^3. Measurement accuracy using the combination of the aforementioned software programs is shown to be well within 1 mm [5]. The location of impingement was measured by a protractor overlay with the centre of the overlay exactly at the middle of the femoral condyles as is performed in other studies [47]. Two lines were drawn from the centre of the protractor to the borders of the impingement area (Fig. 3). The mid-point between these two borders was used to define the location of impingement. Border A represented the border that is most proximal to the notch, whereas border B is most distal to the notch. The mid-point location of impingement and the proximal (border A) and distal border (border B) were presented in degrees (°). The institutional review board (IRB) of Hospital for Special Surgery approved this study (IRB-approval: 14010).

Statistical analysis

Statistical analysis was performed with SPSS 21.0 (SPSS, Inc., IBM, Chicago, IL, USA). The Kolmogorov–Smirnov test and Shapiro–Wilk test were used to assess whether the impingement volume was normally distributed. These tests showed that a normal distribution was seen in all tunnel positions for all flexion angles (all $p > 0.05$). Therefore, independent *t* tests were used to compare impingement volumes and locations between femoral tunnel positions. Finally, the direct and indirect tunnel positions were combined which enabled comparing graft impingement between the AM, C and PL tunnel positions using independent *t* tests. It was assumed that there was statistical significance when $p < 0.05$.

Post hoc power analysis showed that using 8 virtual direct and 8 virtual indirect tunnel positions were sufficient to show a 150-mm^3 difference with a 100-mm^3 standard deviation using an alpha of 0.05 and power of 0.80. Similarly, 8 virtual tunnel positions were sufficient to show a 5° difference with 4° standard deviation with an alpha of 0.05 and power of 0.80.

Results

Impingement volumes

At 90° of flexion, the indirect AM tunnel position (LAM) caused significant more graft impingement than the direct AM tunnel position (hAM) (97 ± 28 vs. 76 ± 20 mm^3, respectively, $p = 0.046$). At the other flexion angles (e.g. 0°, 15° and 30°) for all tunnel positions (e.g. AM, C and PL), the indirect tunnel position impinged more than the direct tunnel position, but this was not statistically significant (Tables 1, 2, 3; Figs. 4, 5, 6).

At 0° of flexion, the combined AM tunnel positions (714 ± 245 mm^3) had significant more impingement compared with the C tunnel positions (571 ± 203 mm^3, $p = 0.033$) and the PL tunnel positions (537 ± 170 mm^3,

Table 1 Mean ± SD volume and location of impingement of direct and indirect AM tunnel positions

Flexion (°)	Direct				Indirect			
	Volume (mm^3)	Location (°)	Proximal border (°)	Distal border (°)	Volume (mm^3)	Location (°)	Proximal border (°)	Distal border (°)
0	643 ± 202	16 ± 4	7 ± 4	25 ± 5	785 ± 271	18 ± 5	12 ± 6	26 ± 5
15	372 ± 124	18 ± 5	9 ± 5*	27 ± 6	477 ± 174	21 ± 5	14 ± 5*	29 ± 7
30	250 ± 89	21 ± 7	13 ± 8	29 ± 8	312 ± 134	26 ± 7	19 ± 7	35 ± 12
90	76 ± 20*	24 ± 5*	13 ± 6*	34 ± 6*	97 ± 28*	34 ± 4*	23 ± 5*	46 ± 5*

AM indicates anteromedial bundle

* Indicates a significant difference ($p < 0.05$) between direct and indirect tunnel positions

Table 2 Mean ± SD volume and location of impingement of direct and indirect C tunnel positions

Flexion (°)	Direct				Indirect			
	Volume (mm^3)	Location (°)	Proximal border (°)	Distal border (°)	Volume (mm^3)	Location (°)	Proximal border (°)	Distal border (°)
0	526 ± 173	20 ± 7	13 ± 6	28 ± 8	615 ± 227	23 ± 4	15 ± 5	30 ± 5
15	323 ± 110	25 ± 7	17 ± 6	33 ± 9	371 ± 131	29 ± 6	20 ± 4	39 ± 7
30	214 ± 59	29 ± 8	19 ± 7	39 ± 9	239 ± 93	35 ± 7	26 ± 6	45 ± 13
90	61 ± 17	34 ± 5*	21 ± 6*	46 ± 5*	64 ± 16	42 ± 5*	29 ± 6*	55 ± 5*

C indicates central bundle

* Indicates a significant difference ($p < 0.05$) between direct and indirect tunnel positions

Table 3 Mean ± SD volume and location of impingement of direct and indirect PL tunnel positions

Flexion (°)	Direct				Indirect			
	Volume (mm^3)	Location (°)	Proximal border (°)	Distal border (°)	Volume (mm^3)	Location (°)	Proximal border (°)	Distal border (°)
0	490 ± 154	28 ± 7	19 ± 5	38 ± 9	559 ± 196	30 ± 4	19 ± 5	40 ± 6
15	322 ± 102	35 ± 7	23 ± 6	47 ± 9	351 ± 113	38 ± 7	25 ± 7	51 ± 8
30	222 ± 60	39 ± 9	27 ± 8	52 ± 10	232 ± 93	44 ± 7	33 ± 7	55 ± 14
90	70 ± 23	46 ± 6*	32 ± 8	61 ± 6	53 ± 17	52 ± 6*	37 ± 7	66 ± 6

PL indicates posterolateral bundle

* Indicates a significant difference ($p < 0.05$) between direct and indirect tunnel positions

$p = 0.006$). No significant differences were seen between the C and PL tunnel at 0° and 90° (both n.s.) and between the AM, C and PL tunnel positions at 15° and 30° of flexion (Table 4; Figs. 5, 6).

Impingement locations

At 90° of flexion, the direct AM position impinged more in the roof of the notch compared with the indirect AM tunnel position (24 ± 5° vs. 34 ± 6°, respectively; $p < 0.001$) and the direct C position also impingement higher in the notch compared with the indirect position (respectively, 34 ± 5° vs. 42 ± 5°, $p = 0.003$). At 0°, 15° and 30° of flexion, the direct tunnel position impinged higher in the notch, whereas the indirect tunnel position impinged more at the lateral wall, but this was not statistically significant (Tables 1, 2, 3; Figs. 5, 6).

At 0° of flexion, the AM tunnel position impinged most towards the notch compared to the C tunnel position (18 ± 5° vs. 23 ± 4°, respectively; $p = 0.001$) and PL tunnel position (18 ± 5° vs. 29 ± 5°, respectively; $p < 0.001$). At 15°, 30° and 90° of flexion, it was also noted that the AM position was located most towards the notch, whereas the PL position was located most towards the lateral wall (all $p < 0.005$) (Table 4; Figs. 5, 6).

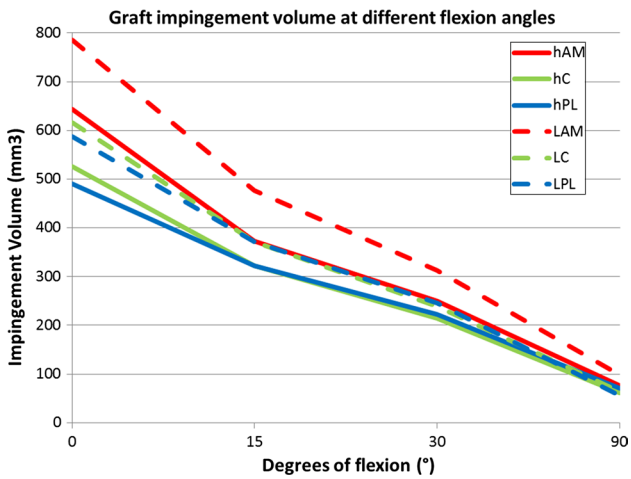

Fig. 4 Volume of graft impingement is shown for the six graft positions at different flexion angles

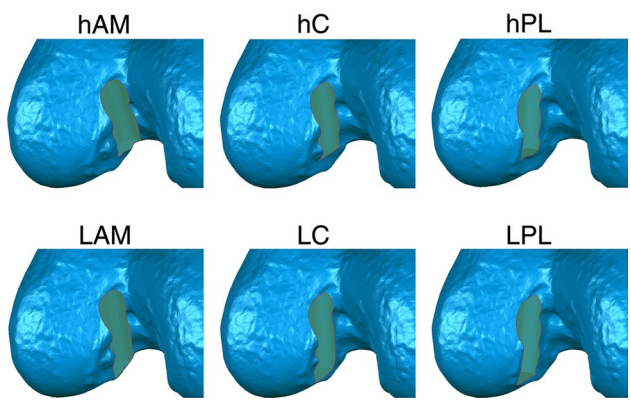

Fig. 5 Area of impingement is shown from the anteromedial portal view

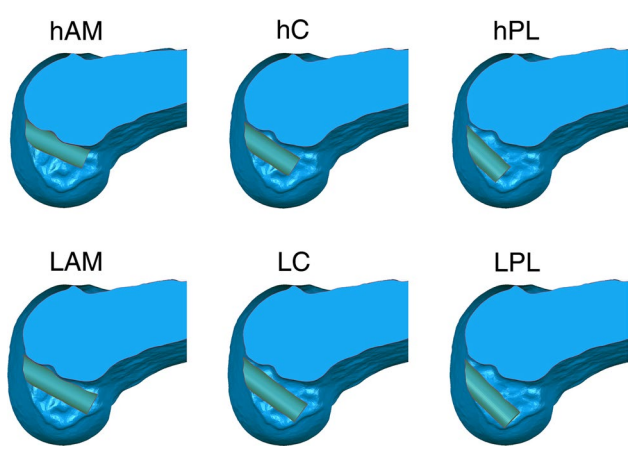

Fig. 6 Area of impingement is shown from a sagittal view after removing the medial epicondyle

Discussion

The main finding of this study was that no significant differences in impingement volume between the indirect tunnel and direct tunnel positions could be found although impingement occurred at all tunnel positions. Secondly, the results suggest that graft impingement high in the notch was correlated with the direct tunnel position, extension of the knee and the AM tunnel position, while lateral impingement at the femoral wall was correlated with the indirect tunnel position, flexion of the knee and the PL tunnel position.

The direct fibres of the ACL are considered to play a more dominant role in knee kinematics when compared to the indirect fibres. Pathare et al. [40] assessed the knee kinematics with the ACL intact and after dissecting the indirect fibres and noted only a small increase in anterior tibial translation with anterior load and a small increase in posterior tibial translation and external rotation with a simulated pivot shift test. The authors concluded that the direct fibres were therefore more biomechanically relevant when compared to the indirect fibres. It is therefore recommended to position the femoral tunnel position high within the femoral footprint in order to recreate the biomechanically relevant direct fibres [21, 40]. Several studies have, however, shown that the femoral tunnel position can influence the risk of graft impingement [23, 24, 31, 44]. It is therefore important to assess the risk of graft impingement when the femoral tunnel is aimed at the direct insertion fibres high within the femoral footprint. When reviewing the results of this current study, not significantly more impingement with the direct fibres was seen when compared to the indirect fibres. A trend of the opposite might even be seen since generally more impingement was seen with all indirect tunnel positions compared with direct tunnel positions. The findings of this biomechanical study suggest that graft impingement is not a limitation ACL reconstruction at the insertion of the direct fibres.

Since the different ACL insertions are a relatively new concept in the ACL reconstruction literature, there are limited data available to compare the results with. Iriuchishima et al. [23] examined graft impingement in porcine knees by inserting a pressure-sensitive film between the ACL and the intercondylar notch. One graft was placed between the tibial AM tunnel position and the femoral AM (relatively indirect) position, whereas the other graft was placed between the tibial PL position and the femoral high AM (relatively direct) position. Similar to the findings of the current study, the authors found no significant differences in impingement pressure between both tunnel positions. However, the tibial tunnel positions were different between the relatively direct and indirect tunnel positions, and it has been shown that the

Table 4 Mean ± SD volume and location of impingement of AM, C and PL tunnel positions

Flexion (°)	AM		C		PL	
	Volume (mm^3)	Location (°)	Volume (mm^3)	Location (°)	Volume (mm^3)	Location (°)
0	714 ± 245[a,b]	18 ± 5[a,b]	571 ± 203[a]	23 ± 4[a,c]	537 ± 170[b]	29 ± 5[b,c]
15	419 ± 158	20 ± 5[a,b]	347 ± 121	27 ± 7[a,c]	346 ± 98	36 ± 7[b,c]
30	281 ± 116	24 ± 8[a,b]	227 ± 77	32 ± 8[a,c]	233 ± 71	42 ± 8[b,c]
90	86 ± 26[a,b]	29 ± 7[a,b]	63 ± 17[a]	38 ± 6[a,c]	63 ± 20[b]	49 ± 6[b,c]

AM indicates anteromedial bundle, *C* indicates central bundle, and *PL* indicates posterolateral bundle

[a] Indicates a significant difference ($p < 0.05$) between AM and C tunnel positions

[b] Indicates a significant difference ($p < 0.05$) between AM and PL tunnel positions

[c] Indicates a significant difference ($p < 0.05$) between C and PL tunnel positions

tibial tunnel position influences graft impingement [13–16, 18, 19, 27, 34]. Therefore, it is difficult to draw conclusions on the role of the femoral tunnel position in the study of Iriuchishima et al.

The same research group performed another study on graft impingement in which they assessed the impingement pressure in human cadaveric knees [24]. Using the same pressure-sensitive film method, they compared various tunnel positions including the tibial AM to femoral AM position and tibial AM to femoral high AM position. These positions approximated the indirect and direct tunnel positions in this study, respectively. As stated in the introduction, they found that the femoral high (direct) AM tunnel position had significantly more impingement pressure than the femoral AM tunnel position and this was not found in this current study. An explanation for the different results between their study and this current study might be the different methods. Iriuchishima et al. used a pressure-sensitive film that was placed between the ACL and the intercondylar notch, and they therefore mainly measured graft impingement high in the notch. Interestingly, as was shown in this current study, the direct tunnel position causes more impingement high in the notch, while the indirect tunnel position causes more impingement lateral at the femoral wall. Since the authors mainly measured the high impingement, it is not surprising that most impingement was found with the direct fibres. It is therefore likely that they might have underreported the graft impingement with the indirect tunnel position. Furthermore, the location of their relatively high femoral position was located outside the anatomical footprint, while the relatively low femoral position was located within the anatomical footprint. Because less risk for impingement is seen when an anatomical femoral tunnel position is chosen [8], this could also explain the results with this current study where both tunnel positions were located within the femoral footprint.

In this study, impingement occurred with all tunnel positions. This can be explained by the fact that an AM tibial tunnel position was chosen in order to maximize graft impingement [16, 18, 19]. While the role of the tibial tunnel position on graft impingement has been extensively described [13–16, 18, 19, 27, 34], less is known about the role of the femoral tunnel position on graft impingement. The data or the current study showed that the AM tunnel position was correlated with the largest amount of graft impingement and the PL tunnel position with the least amount of impingement (Table 4). These findings correspond to other studies [31, 44]. Maak et al. [31] compared three different femoral tunnel positions (AM, C and PL) with a virtual graft technique. They reported that the AM tunnel position caused significant earlier impingement through the flexion–extension arc than the C and PL tunnel positions with more maximum impingement. Voos et al. [44] used the virtual graft technique to assess the role of the femoral tunnel position on graft impingement with both the tibial AM and PL tunnel positions. Their results showed that for these tibial tunnel positions, the femoral AM position caused more impingement than the PL position. Although the authors did not dichotomize impingement for the femoral tunnel position, their data suggest that the femoral AM position caused more tunnel impingement than the PL tunnel position. The results of both studies echo the findings of this current study that an anteriorly orientated femoral tunnel position is more at risk for graft impingement, which should be kept in mind while performing ACL reconstruction.

In this study, it was noted that the location of graft impingement with direct fibres was higher in the femoral notch, while the indirect fibres impinged more lateral at the femoral wall. Several authors described the mechanisms and locations of impingement in flexion and extension [17, 32, 37–39]. Lane et al. [28] described in a case series different impingement locations: three patients underwent lateral notchplasty, two anterior notchplasty and one both anterior and lateral notchplasty. They advised to intraoperatively not only use knee extension for assessing anterior impingement but also use external rotation to assess lateral wall impingement. In this biomechanical study, it has been

shown that the direct and indirect and AM, C and PL femoral tunnel positions caused impingement at different locations in the femoral notch and this is influenced by the high or low femoral tunnel position, AM versus C or PL position and by flexion or extension. The graft impingement patterns showed that impingement high in the notch occurred with the direct (high) tunnel position, with knee extension and with the AM tunnel position, while impingement at the lateral wall occurred with the indirect tunnel position, flexion of the knee and the PL tunnel position. Although this study did not assess the absolute impingement but assessed the relative impingement in different tunnel positions, the relative volume and location of impingement should be kept in mind when intraoperatively testing graft impingement and subsequently performing notchplasty (Figs. 5, 6).

Several limitations were present in this study. Firstly, a virtual rigid graft cylinder was used to determine the volume and location of graft impingement, and a flexible graft model would more realistically imitate an ACL graft. However, this study was not designed to determine the absolute impingement but was designed to determine the relative positions between direct and indirect and between the three femoral tunnel positions. A second limitation is that not the virtual graft impingement on the posterior cruciate ligament (PCL) was assessed. Using this model, it was only possible to assess bony impingement, and therefore, further studies should examine the influence of high and low femoral tunnel positions on graft impingement on the PCL [12, 25, 36]. A third limitation is that no correction was performed for individual variations as notch width and notch osteophytes in the analysis of notch impingement.

Conclusion

Several studies have suggested that the femoral tunnel position should be aimed at the biomechanically more relevant direct fibres. The results of this study show that the direct tunnel position does not cause more impingement than the indirect tunnel position and even shows a trend towards less impingement. Therefore, the results of this study suggest that graft impingement is not a limitation for the orthopaedic surgeon to anatomically reconstruct the ACL using the direct insertion tunnel position.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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