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Evidence-Based Systematic Reviews

Radiographic Assessment of Bone Union in Proximal Tibia and Distal Femur Osteotomies

A Systematic Review

Eva A. Bax, MSc, Netanja I. Harlianto, MD, Roel J.H. Custers, MD, PhD, Nienke van Egmond, MD, PhD, Wouter Foppen, MD, PhD, and Moyo C. Kruyt, MD, PhD

Investigation performed at University Medical Center Utrecht, Utrecht, the Netherlands

Background: Osteotomies around the knee are a well-established treatment option for early and moderate unicompartmental osteoarthritis combined with a lower extremity malalignment. Moreover, osteotomies are often combined with cartilage treatment. Current image-based bone union assessments lack an accepted definition despite widespread use in research and clinical settings. The aim of this systematic review was to identify definitions and classification systems for bone union on radiographs after a proximal tibia or distal femur osteotomy.

Methods: Following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines, we systematically searched MEDLINE and Embase database, applying specific inclusion and exclusion criteria. Two independent reviewers screened abstracts and full-texts. The modified Cochrane Risk of Bias Tool and Risk of Bias in Nonrandomized Studies of Interventions tool were used. Data extraction included study characteristics, imaging modality, bone union definition, classification systems, assessment of gap fillers, use of modifiers, and osteotomy type.

Results: Of the 1,180 screened titles and abstracts, 105 studies were included, with the majority (69 studies [65.7%]) using a retrospective design. Fifty-five studies (52.4%) defined bone union based on one or more criteria, while 50 studies (47.6%) used a classification system. There were 13 different criteria for bone union and 9 different classification systems. Interestingly, none of the classification systems incorporated negative criteria, such as hardware failure. Notably, 137 studies (49.1%) described bone union as either a primary or secondary outcome but do not describe a system for assessing bone union.

Conclusion: This systematic review highlights the lack of consensus in the literature in defining bone union after a proximal tibia or distal femur osteotomy, revealing many criteria and different classifications. None of the classification systems were applicable to osteotomies with and without gap filler. This systematic review shows the need for a straightforward, reproducible, and accurate method to assess bone union after a proximal tibia or distal femur osteotomy.

Level of Evidence: Level III. See Instructions for Authors for a complete description of levels of evidence.

Introduction

Knee osteoarthritis (OA) is the most prevalent joint disease, causing chronic pain, stiffness, and disability[1,2]. Osteotomies around the knee are a well-established treatment of early and moderate unicompartmental OA with lower extremity malalignment, as it reduces the mechanical force on the affected compartment[3,4]. Osteotomies are often combined with cartilage treatment[5]. The most commonly described osteotomy techniques are the closed-wedge and the open-wedge osteotomy[6]. Many surgeons prefer to fill the open-wedge osteotomy with autograft, allograft, or ceramic materials to enhance early mechanical stability, reduce local blood loss, and improved bone union[7]. Traditionally, the gap is filled with autologous iliac crest; however, this is associated with complications, including pain, infection, and hematoma at the

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donor site[8,9]. To eliminate these complications, allograft and ceramics can be used which may contribute to accelerated bone union and remodeling[8]. The choice to use a bone graft is largely based on its ability to facilitate healing of the osteotomy gap.

Image based bone union assessment is a commonly used outcome measure in osteotomy studies. According to the Concise Medical Dictionary, union is defined as "the successful result of healing of a fracture, in which the previously separated bone ends have become firmly united by newly formed bone"[10]. Despite this clear definition, authors have used multiple other definitions for the evaluation of bone union after an osteotomy, but there are no comprehensive studies to guide us[7,11-14]. The lack of consensus on image-based bone union assessment impedes meaningful comparisons of outcomes across osteotomy studies, including those focused on osteotomy gap treatments, thereby diminishing the clinical and scientific value of these studies[15].

Furthermore, bone union after an osteotomy is crucial for guiding patient care decisions, including the timing of hardware removal and modifying rehabilitation protocols[16,17]. Premature or delayed hardware removal can lead to complications or unnecessary discomfort[16]. Moreover, a clear definition of osseous union is crucial for facilitating decision making regarding the necessity of surgical intervention in cases of nonunion[17,18]. Without such a definition, clinical decision making remains challenging and uncertain.

Therefore, the primary objective of this systematic review was to identify the various available methods in assessing bone union on radiographs after open and closed-wedge proximal tibia and distal femur osteotomies. Various definitions of union, delayed union, and nonunion will be addressed based on criteria and classification systems. In addition, we explore methods used to describe the development of bone union over time.

Materials and Methods

Search Strategy

This study was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines[19]. A structured literature search was performed in MEDLINE and Embase from inception till December 2023. The search was performed to identify articles related to bone union on radiographs after femoral or tibial osteotomies. The search terms used as single or combined terms were tibia osteotomy, femur osteotomy, healing, union, nonunion, gap, consolidation, and pseudoarthrosis (see Appendix A for the search string). Only studies published in English language were taken into consideration.

Article Identification and Selection

All published articles from the search were considered for inclusion in this systematic review. Two independent reviewers (E.B., N.H.) conducted screening of title and abstracts using Rayyan. Duplicates were systematically removed, and studies unrelated to bone union on radiographs after femoral or tibial osteotomies were excluded. Full-text assessment was performed on all articles meeting the eligibility criteria described in Table I. Only articles that described a definition of bone union, delayed union, or nonunion, or those describing a classification system to determine bone union were included. Disagreements were resolved through discussion, and in case of persistent disagreement, a third review author (W.F.) was consulted.

Quality Assessment

Two independent reviewers (E.B., N.H.) assessed the risk of bias for the included studies. The included randomized controlled trials (RCT) were assessed using the modified Cochrane Risk of Bias Tool[20,21]. Each domain was scored with high, low, and unclear risk of bias, which together resulted in the overall risk of bias. Nonrandomized studies were evaluated using The Risk Of Bias In Nonrandomized Studies of Interventions assessment tool[22]. Each domain was scored here with critical, serious, moderate, low, and no information, which together resulted in the overall risk of bias. Disagreements were resolved through discussion, and in case of persistent disagreement, a third review author (W.F.) was consulted.

Data Extraction

All data were extracted from the full-text articles into an Excel spreadsheet (Microsoft). The included articles were analyzed for (1) study characteristics including study design, year of publication, number of participants, age, gender, body mass index (BMI), country; (2) imaging modality; (3) bone union criteria; (4) classification system (if used); (5) use of modifiers; (6) assessment of gap fillers; (7) type of osteotomy (closed vs. open); and (8) degree of correction. All data were independently collected by 2 reviewers (E.B., N.H.). Disagreements were resolved through consensus.

Statistical Analysis

The bone union assessment was divided into "descriptive" criteria, in case of a description of union and "classification" if the criteria were structured in a grading or scoring system. Frequency of imaging modalities, bone union criteria, classification systems, modifiers, gap fillers, and type of osteotomy were determined. The (weighted) mean was determined for age, BMI, and degree of correction.

Results

Search Strategy

A total of 1,584 studies were identified. After removing duplicates, 1,180 studies remained. After screening abstract and titles, 279 studies were selected. The primary reasons for exclusion were nonhuman studies (N = 405 [34.4%]) or a lack of information regarding bone union (N = 209 [17.7%]) (Fig. 1). After reading full-text articles, a total of 105 studies were included according to the inclusion and exclusion criteria. The primary reason for full-text exclusion was that bone union was not described. A high percentage (N = 137 [49.1%]) of studies described bone union as either a primary or secondary outcome but did not describe a system for assessing bone union. The selection process, following the PRISMA guidelines, is illustrated in Fig. 1.

TABLE I Inclusion and Exclusion Criteria

Inclusion Criteria	Exclusion Criteria
Adult patients treated by distal femur or proximal tibia osteotomy for knee related problems	Osteotomy for limb lengthening
Human studies	Other imaging modalities than radiographs
Studies with outcome: bone union	Finite element studies
Imaging modality: radiographs	Cadaveric studies
	Reviews and meta-analysis
	Conference abstracts
	Case studies

Quality Assessment

The overall risk of bias in nonrandomized studies was low in only 2 studies[23,24]. The overall risk of bias was moderate for 58 studies (60.4%) and serious for 23 studies (24.0%) (See Appendix B). The most notable risk of bias included partial bilateral intervention, enrollment in groups was choice of surgeon or patient, use of different gap fillers in one intervention group, and the lack of blinding of radiologist and/or patient. Partial bilateral intervention refers to some patients having an osteotomy of both knees and some patients of one knee. This methodology may introduce selection bias as dissatisfied patients might avoid surgery on the untreated contralateral knee, affecting studies on patient satisfaction. For 13 studies, there was no information for one domain of the assessment tool, making the overall risk of bias no information.

The overall risk of bias in RCTs was low in 4 studies, high in 4 studies, and unclear in one study (See Appendix B). The most notable risk of bias included the lack of blinding of the patient and radiologist and insufficient reporting of incomplete data.

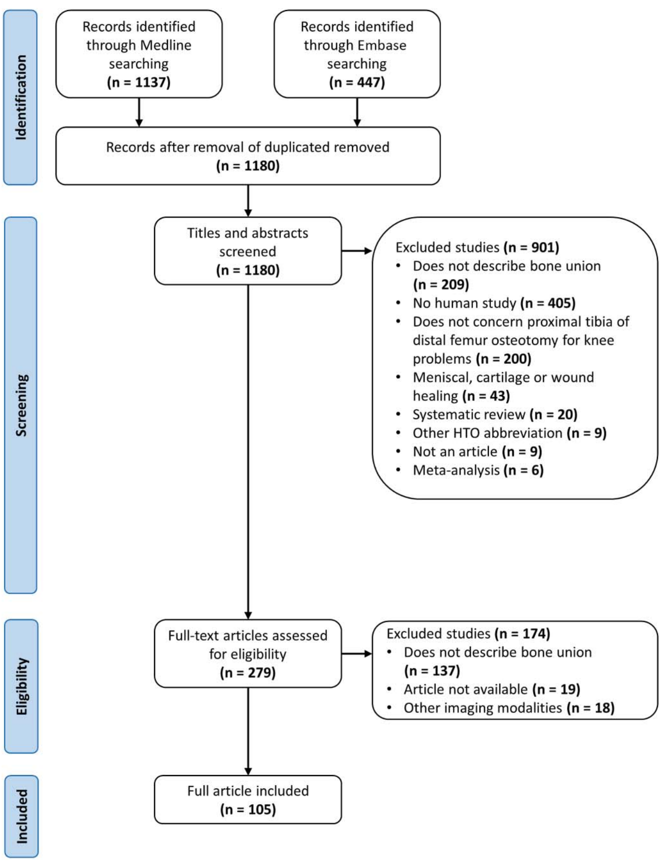

Fig. 1

Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flowchart of article selection.

Data Extraction

Study Characteristics

The first published study dated from 1971[25]. Since the 2000s, scientific interest in knee osteotomies has increased, mostly in the last decade. Included studies had a retrospective (N = 69 [65.7%]), prospective (N = 16 [15.2%]), unclear (N = 11 [10.5%]), or RCT (N = 9 [8.6%]) design. Most studies were published in South Korea (N = 23 [21.9%]), followed by Japan (N = 15 [14.3%]) and Germany (N = 13 [12.4%]). The number of knees included in the studies varied between 7 and 350, with a median of 58 knees (interquartile range 61 knees). In 62 studies (59%), a gap filler was used for the open-wedge osteotomy. The majority of studies focused on open-wedge tibial osteotomy, constituting (N = 87 [82.9%]). In addition, 6 studies (5.7%) addressed both open-wedge and closed-wedge osteotomies. The data extraction of the included studies can be found in Appendix C.

Imaging Modality

All included studies used conventional radiographs. Conventional radiographs were most often combined with computed tomography scans (N = 16 [15.2%])[23,26-40]. Only one study (1.0%) combined conventional radiographs with Dual-Energy X-ray absorptiometry[41]. In addition, there was one study (1.0%) that also used histology[42].

Criteria of Bone Union

In 55 studies (52.4%), bone union was based on descriptive criteria, mainly positive ones such as bone bridging, callus formation, disappearance of osteotomy line, and clinical signs such as no pain during weight-bearing (Fig. 2). Negative criteria, such as sclerosis at the osteotomy boundaries[27,36,43-47], resorption within the osteotomy[48,49], collapse[46,48,49], radiolucent

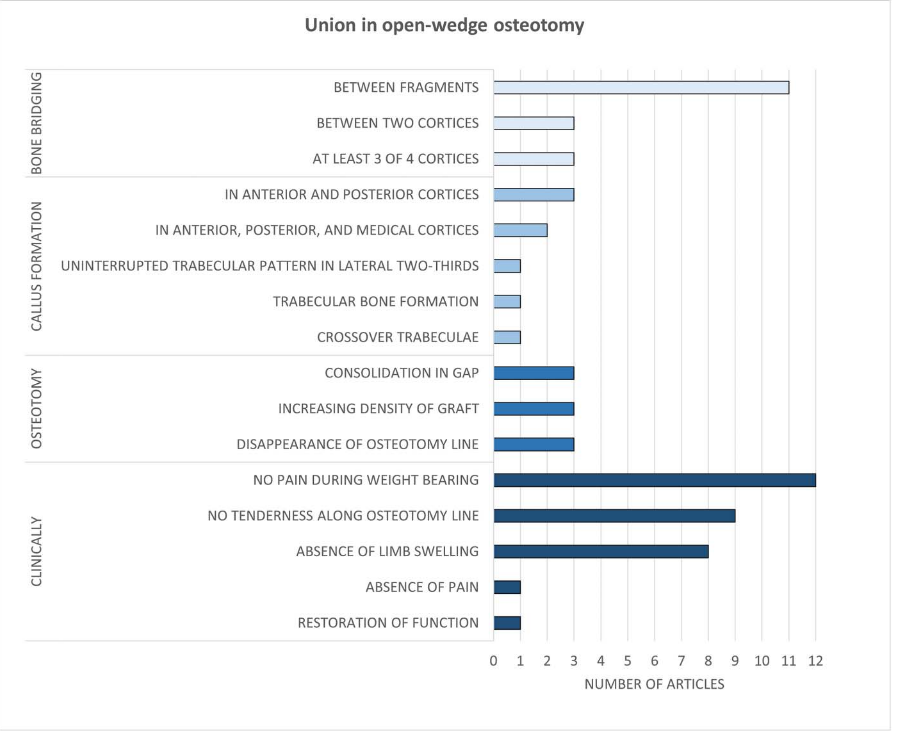

Fig. 2
Number of articles per union criterion.

areas within the osteotomy[50-52], hardware failure[46], and radiolucency around the implant[48] were used to define the lack of bone union. One or more of these negative signs were described in 12 studies (21.8%).

The time interval for delayed union after open-wedge osteotomy varied, with delayed union most commonly defined as the absence of union at 6 months after surgery (Fig. 3). Moreover, most studies (N = 12 [80%]) also defined nonunion as the absence of union at 6 months after surgery. The remaining 20% (N = 3) defined it as the absence of union at 1 year.

Six studies (5.7%) included both closed-wedge and open-wedge osteotomies but used identical time intervals for bone union, delayed union, and nonunion without distinguishing between the groups. For these studies, delayed union was described as the absence of union at 4 months (N = 1 [16.7%]), 6 months (N = 2 [33.3%]), or 8 months (N = 1 [16.7%]). The remaining studies (N = 2 [33.3%]) did not describe a time interval for delayed union. Nonunion was described as the absence of union at 6 months (N = 1 [16.7%]) or 1 year (N = 1 [16.7%]). The remaining studies (N = 4 [66.6%]) did not describe a time interval for nonunion.

Classification System for Bone Union

The bone union assessment was divided as a classification if the criteria were structured in a grading or scoring system. In 50 studies (47.6%), bone union was assessed using the classification, where a distinction must be made between gap filler and no gap filler. Among these studies, 26 (52.0%) used a gap filler, while 20 (40.0%) did not. In the remaining 4 studies (8.0%), a combination of both gap fillers and no gap fillers was used. Within the gap filler group, the Schröter[53] method was predominant (N = 7 [35%]), whereas in the group without gap filler, the most commonly applied classification was the van Hemert[7] (Table II) at a rate of (N = 8 [30.8%]) (Fig. 4). The Schröter method describes the percentage of the osteotomy that is filled with newly formed bone by dividing the distance of the osteotomy from medial to lateral by the part of the osteotomy gap that is not visible anymore (i.e., healed)[53]. None of the classification systems incorporated negative criteria or modifiers.

In 4 studies (8.0%), a combination of both gap fillers and no gap fillers was used. Among these, 2 studies used the Brosset

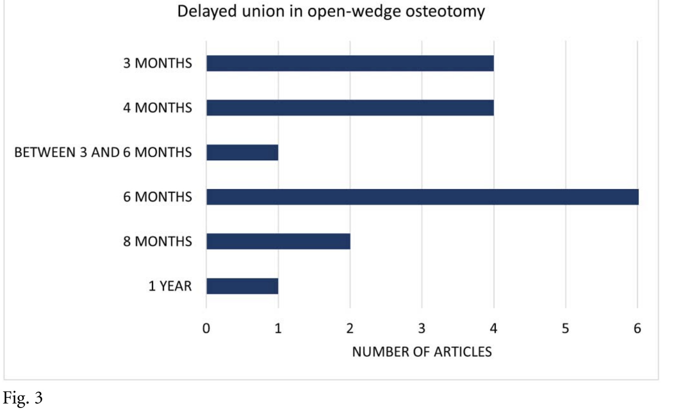

Fig. 3
Time interval for delayed union in open-wedge osteotomies.

TABLE II Hemert Classification System for Assessing Bone Union

	Phase Name	McKibbin	Explanation
0	Direct postoperative	Inflammation	Hematoma
1	Vascular phase	Soft callus	Osteopenic bone, rounded osteotomy sites, clear distinction between tricalcium phosphate and bone
2	Calcification phase	Soft and hard callus	Whitening of sites and blurred distinction between tricalcium phosphate and bone
3	Osteoblastic phase	Hard callus, remodeling	Distinction between tricalcium phosphate and bone slightly visible, though healed osteotomy
4	Consolidation phase	Hard callus and remodeling	Full reformation, though osteotomy recognizable, no tricalcium phosphate
5	Full reformation	Remodeling	No sign of osteotomy

classification[54,55], while another study integrated the Brosset classification with the modified van Hemert[56]. In addition, one study used the Hemert modified classification for the gap filler group and the Brosset classification for the group without gap fillers[57]. Different classification systems were used here because each classification system was developed for gap filler or without a gap filler, and therefore, no classification system was available for a RCT between gap filler and no gap filler.

Discussion

This systematic review identified many methods in assessing bone union on radiographs after a proximal tibia or distal femur osteotomy. The most important finding is that there is an enormous variation in both definitions and classification systems for the same purpose of defining union. There were 13 different criteria and 9 different classification systems, interestingly none of the classification systems incorporates negative criteria, such as hardware failure. Consequently, there is no consensus in the literature in defining bone union after knee osteotomies despite the widespread use in research and clinical settings; therefore, comparing between osteotomy studies is currently almost impossible.

Bone union criteria evaluated in these studies were primarily radiographic and clinical in nature. The most common of the criteria were the presence of bone bridging between fragments and lack of pain during weight-bearing. Only a few

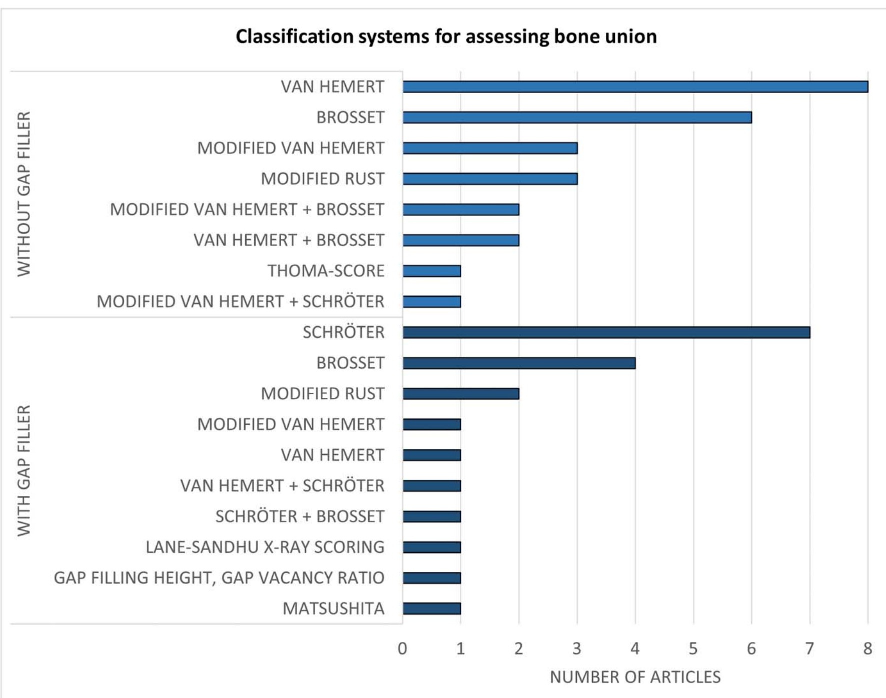

Fig. 4
The different classification systems for assessing bone union on radiographs, categorized into those applicable to cases without void fillers and those with void filler.

studies focused on negative radiological criteria of union, such as sclerosis at the osteotomy boundaries, resorption within the osteotomy, collapse, radiolucent areas within the osteotomy, hardware failure, and radiolucency around the implant. Moreover, 6 different time intervals were defined for delayed union, not distinguishing between gap filler and without gap filler, and open-wedge vs. closed-wedge. This is surprising, since the use of gap fillers may result in accelerated bone union, and there is a perception that union occurs more rapidly with a closed-wedge compared with an open-wedge[54,55,57,58]. Furthermore, a high percentage of the studies (49.1%) described bone union as either a primary or secondary outcome, but then do not describe a definition for union. This is surprising, since there is not any consensus on union, delayed union, and nonunion.

The literature encompasses various classification systems applicable to knee osteotomies, with or without gap fillers. None of the classification systems incorporate negative radiological criteria or modifiers, which are recognized as clear signs of nonunion in spinal fusion surgery[59]. Moreover, each system has been designed for either an osteotomy with gap filler or without gap filler. However, our findings reveal that commonly used classification systems, including (modified) van Hemert[7,11,23,60], Brosset[14], and Schröter[53] classifications, are used for both an osteotomy with gap filler and without gap filler. Specifically, the (modified) van Hemert score[7,11,23,60] was initially developed for osteotomies involving gap fillers, whereas the Brosset[14] and Schröter[53] classifications were originally intended for osteotomies without. Intriguingly, Fig. 4 illustrates that these classification systems are used for both. The study by Nha et al.[57] used the modified van Hemert score and the Brosset classification to compare bone union between synthetic graft and without bone graft, yielding 2 different outcomes that complicate the comparison of bone union between synthetic graft and without bone graft. This emphasizes the importance of a classification system specifically developed for open-wedge osteotomies with and without a gap filler.

The strengths of this systematic review are that it is the first study offering a comprehensive overview of the absence of consensus in the evaluation of bone union after osteotomy. In addition, it reveals a noteworthy observation that a high percentage of studies do not describe a definition of bone union. Despite the strengths of the systematic review, this review has several limitations. First, only articles written in English were included, posing a risk of language bias. Second, animal studies were excluded, resulting in the absence of validation studies. These studies are valuable in assessing the correlation between radiographic bone union and functional bone union based on histology and/or manual palpation. Only one study included biopsies in the hydroxyapatite group to determine the ratio of bone tissue and remnant hydroxyapatite[42]. Third, various articles included in our systematic review exhibited a moderate-to-high risk of bias. We incorporated all studies in our analysis, focusing solely on the description of the radiological assessment of bone union without extracting additional results, such as patient-reported outcomes. Finally, this systematic review did not assess the relation with the size of the osteotomy gap, as the definitions of bone union, delayed union, and nonunion are generally independent of the size of the osteotomy gap.

In conclusion, our systematic review highlights the lack of consensus in defining bone union following a proximal tibia or distal femur osteotomy. Thirteen different criteria and 9 classification systems were identified for assessing bone union, none of which are universally applicable to osteotomies with and without gap fillers. Moreover, existing classification systems lack negative criteria for the absence of bone union. This systematic review confirms the need for a straightforward, reproducible, and accurate method to assess bone union after a proximal tibia or distal femur osteotomy.

Appendix

eA Supporting material provided by the author is posted with the online version of this article as a data supplement at jbjs.org (http://links.lww.com/JBJSOA/A690). This content has not been copyedited or verified. ■

Eva A. Bax, MSc[1]
Netanja I. Harlianto, MD[2]
Roel J.H. Custers, MD, PhD[1]
Nienke van Egmond, MD, PhD[1]
Wouter Foppen, MD, PhD[2]
Moyo C. Kruyt, MD, PhD[1]

[1]Department of Orthopaedic surgery, UMC Utrecht, Utrecht, the Netherlands

[2]Department of Radiology and Nuclear Medicine, UMC Utrecht, Utrecht, the Netherlands

E-mail address for E.A. Bax: e.a.bax-2@umcutrecht.nl

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