

REVIEW

The triangular fibrocartilage complex in the human wrist: A scoping review toward uniform and clinically relevant terminology

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Abstract

The aim of this scoping review was to assess the composition, terminology, and anatomy of the triangular fibrocartilage complex (TFCC) of the wrist and propose unambiguous terminology regarding the individual components. The review was conducted according to the methodological framework by Arksey and O'Malley (International Journal of Social Research Methodology, 2005, 8, 19–32). Electronic databases were searched from inception until September 1, 2021 for original anatomical studies, using MeSH terms and keywords on terminology and anatomy of TFCC components. Studies using gross dissections or macro- or microscopic histology were included. Animal studies, fetal studies and studies with unknown disease status, were excluded. A total of 24 studies were included. The articular disc, the radioulnar ligaments, the meniscus homologue and the extensor carpi ulnaris tendon (sub)sheath were unanimously classified as TFCC components. One study did not include the ulnolunate and ulnotriquetral ligaments and only one study did include the ligamentum subcruentum. The largest disagreement existed regarding the inclusion of the ulnar collateral ligament. Terminological ambiguity was seen in “triangular fibrocartilage,” “triangular ligament,” “ligamentum subcruentum,” and the “proximal and distal lamina.” Anatomical ambiguity existed especially regarding the radioulnar ligaments, the ulnar attachments of the TFCC and the ulnar collateral ligament. Definitions of the individual TFCC components are redundant, ambiguous, and ill-defined and therefore subject to different interpretations. In order to preclude confusion, consensus regarding terminology is recommended. We proposed a concise definition of the healthy TFCC that can be used as a starting point for future studies and current clinical practice.

KEYWORDS

anatomy, terminology, triangular fibrocartilage complex, wrist

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1 | INTRODUCTION

The triangular fibrocartilage complex (TFCC) is a structure that is located at the ulnar side of the wrist (Palmer, 1989). It consists of cartilaginous and ligamentous elements that provide axial load transmission, distal radioulnar joint (DRUJ) stability and ulnocarpal stability (Palmer, 1989). The first reference to the term “TFCC” has been published by Palmer and Werner (1981), who subdivided the seemingly homogenous structure into the articular disc, dorsal and volar radioulnar ligament, meniscus homologue, ulnar collateral ligament, and sheath of the extensor carpi ulnaris. Injury to this structure, chronic or acute, is considered a common cause of ulnar sided wrist pain (Watanabe et al., 2010). The overlapping anatomy in this small anatomical area is often referred to as the black box and the extent of differential diagnoses make ulnar sided wrist pain a challenging problem (Jens et al., 2017; Pang & Yao, 2017; Sachar, 2012).

Magnetic resonance imaging (MRI) is increasingly used to diagnose TFCC injury and to determine the need for (diagnostic) arthroscopy (Burns et al., 2011; Lee et al., 2018). Improved visualization of individual TFCC components has been established by the ongoing development of strong magnetic field MRIs at 3 and even 7 Tesla combined with improved dedicated wrist coils (Nobauer-Huhmann et al., 2012). Dynamic evaluation of TFCC anatomy using high-resolution ultrasound techniques has even been reported (Hung et al., 2016; Wu et al., 2019). This advancement in image quality has led to recent reports of novel TFCC injury types in addition to the original Palmer classification types (Zhan, Zhang, et al., 2017). The clinical relevance of radiological TFCC injury types and optimal treatment strategy on the other hand, is currently being questioned (Bendre et al., 2018).

A crucial factor in diagnosing TFCC injury on MRI is therefore to become familiar with the TFCC anatomy (Ng et al., 2019). However, inconsistency of terminology in the current literature obstructs this process. A recent systematic review on the prevalence of TFCC abnormalities in healthy subjects pointed out that the wide variety of definitions and criteria for diagnosing a TFCC abnormality was a major limitation (Chan et al., 2014). Ever since the first description of the TFCC, a large number of studies on this structure have been published and this has led to the current use of ambiguous definitions regarding the TFCC anatomy (Burns et al., 2011). Several studies reviewed portions of extensive information published on TFCC anatomy and pathology (Burns et al., 2011; Cody et al., 2015; Daunt, 2002; Kirchberger et al., 2015; Nobauer-Huhmann et al., 2012; Pidgeon et al., 2015; Skalski et al., 2016; Vezeridis et al., 2010; von Borstel et al., 2017; Wu et al., 2019; Zhan, Zhang, et al., 2017; Zlatkin & Rosner, 2006). In comparing these concise reviews however, the inclusion of TFCC components appears inconsistent. Additionally, a large variety in terminology of the TFCC components is used in these studies and anatomical definitions of TFCC components appear to be ambiguous, confusing, and even contradictory.

Unambiguous interpretation of TFCC abnormalities is essential for improving future studies as well as optimal treatment in clinical practice (Chan et al., 2014). Based on our experiences in

multidisciplinary consultation meetings and international scientific meetings, musculoskeletal radiologists and wrist surgeons are unable to rely on uniform classifications of clinically relevant TFCC injury based on imaging. We therefore consider an extensive overview of the currently used terminology as an essential starting point in reaching unambiguous definitions. The aim of this study is to map existing research findings in anatomical studies and to determine discrepancies in (1) the components considered to be part of the TFCC and (2) the terminology and morphological definitions of these components. Additionally, we will propose a set of unambiguous terminology that future studies and current clinical practice can use as reference.

2 | MATERIALS AND METHODS

Considering the nature of the topic and the related research questions we chose a scoping review as the format for our study design. This scoping review is based on the methodological framework by Arksey and O'Malley (2005). It includes the five recommended stages of (1) identifying the research question, (2) identifying relevant studies, (3) study selection, (4) charting the data, and (5) collating, summarizing and reporting the results. Since this study is not a systematic review and no meta-analysis will be performed, the recommended methods for Evidence Based Anatomy by Henry et al. (2016) were adapted when deemed relevant. Medical Ethics Review Committee approval was not required.

2.1 | Research questions

We posed the following research questions.

1. What individual structures are considered components of the TFCC?
2. What terminology and morphological definition is used for these individual TFCC components?

2.2 | Objective

The objective is to provide an overview of the composition, terminology, and anatomy of the TFCC used in current anatomical literature in order to determine discrepancies and propose a set of unambiguous and unequivocal terminology regarding the individual components that can be recommended for future studies and clinical practice.

2.3 | Information sources and search strategy

The search strategy was performed by an experienced clinical librarian (JD). In preparation of the final electronic search, an overview of terminology on the individual TFCC components in anatomical reviews

was created. In addition, PubMed literature was hand-searched with basic search terms regarding TFCC, anatomy, histology, and morphology for relevant anatomical articles. The reference lists of these articles were snowballed for additional relevant articles in order to provide the most complete set of reference articles to build the final search.

The final electronic search strategy for the electronic databases Medline, Embase and Web of Science Conference Proceedings Index was constructed of controlled search terms and keywords relating to two components: (1) variations on the term TFCC complemented with collected terminology of individual TFCC components from anatomical reviews and (2) terminology or consensus on morphological anatomy (see Data S1 for final search strategy). During the building process of the final search, results were continuously compared with the list of reference articles, in order to guarantee a comprehensive final search strategy.

2.4 | Study selection

The final search was performed on September 1, 2021 and no study date limits were placed in order to be as comprehensive as possible. After duplicates were removed, study selection was performed by two researchers experienced in TFCC research (AP and SJ) independently using reference managing software from Rayyan (Ouzzani et al., 2016). Initial screening on title and abstract was performed using a screening list with questions based on the eligibility criteria. The full texts of the remaining articles were uploaded into EndNote X9.3.3 (Clarivate Analytics, PA) and screened in order to collect all relevant studies. Disagreement between the two reviewers was resolved by discussion. The reference lists of all included studies were then screened by one reviewer (AP) for additional relevant original studies that were not covered by the electronic search.

2.4.1 | Eligibility criteria

We included original anatomical studies on TFCC anatomy that used gross dissections, macroscopic histology, or microscopic histology to provide clear morphological definitions of the TFCC components in human cadaver wrists without known wrist pathologies. In case the presence of wrist pathology was unknown or disease status of the subjects was not explicitly stated, the studies were not included in the qualitative synthesis. However, in order to prevent missing out on potentially valuable anatomical studies, these studies were saved and used for reference (see Discussion). If studies reported results from anatomical methods combined with biomechanical or imaging methods, studies were included, yet only results from the anatomical study method were assessed. Intraoperative studies, case reports, book chapters, conference abstracts, and letters to the editors were excluded. In addition, studies on fetal cadavers were excluded.

2.5 | Charting the data

Data extraction of relevant general study information and TFCC definitions was performed by one author experienced in research on TFCC anatomy and imaging (AP) using a pre-defined data charting form in Microsoft Excel (2016). This form was modified and revised when necessary during the process of extracting data from each included paper. The extracted data included general study information (author, title, journal, year of publication), study methodology (method, tissue preparation), subgroup data (sample size, sex, side, age, disease status), specific details about structures considered as TFCC components, terminology of each individual TFCC component and their descriptive anatomy (definitions, attachments, orientation, histology, relations, vascularity, and innervation).

2.6 | Patient and public involvement

Patients and the public were not involved in the development of this review.

3 | RESULTS

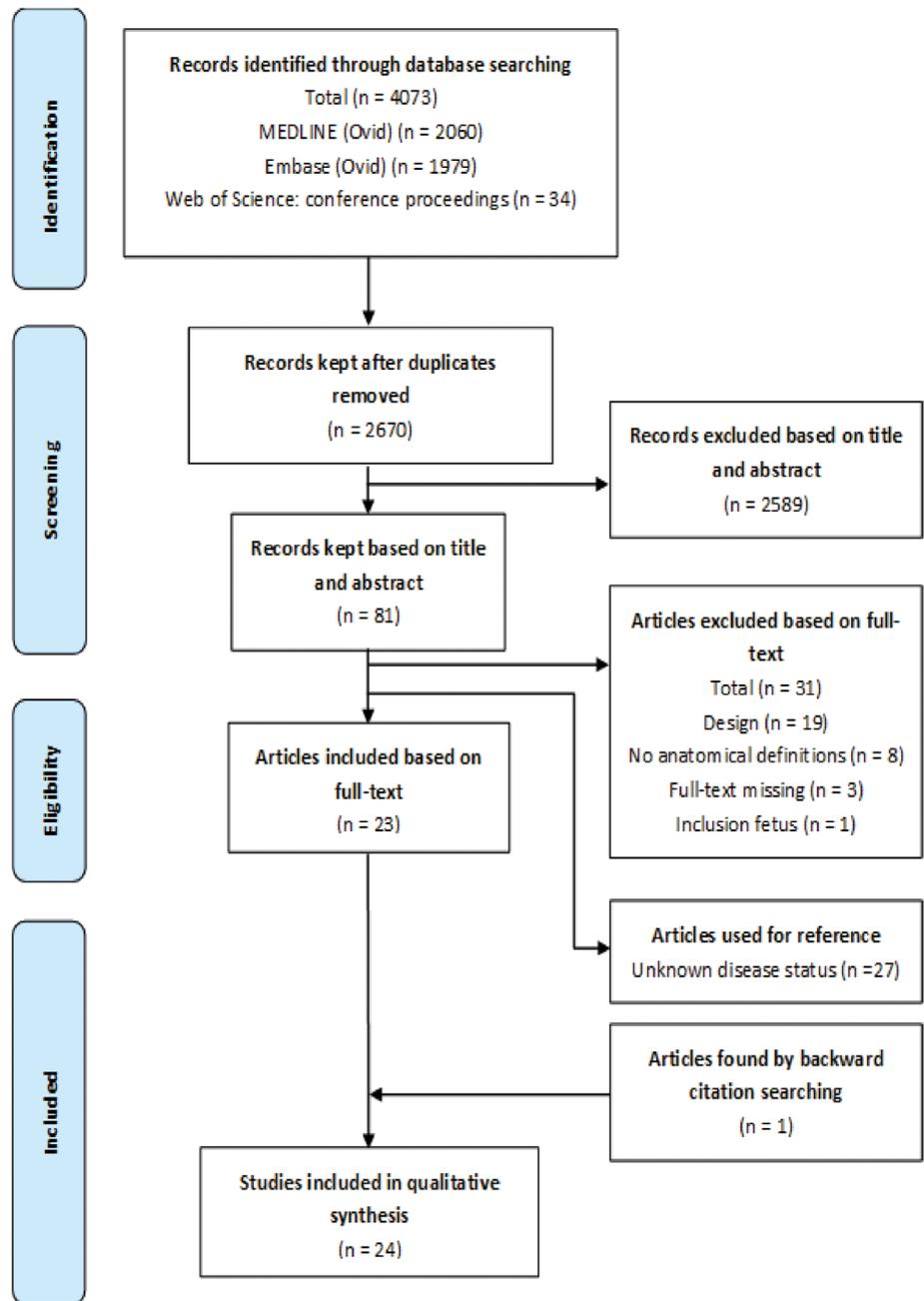
The electronic database search yielded 2670 results after duplicates were removed. Screening of title and abstract included 82 studies for full text review, which resulted in 23 included studies and 27 studies saved for reference. We also included one additional study (Ekenstam & Hagert, 1985) found by screening citations making a total number of 24 included studies. See Figure 1 for the preferred reporting items for systematic reviews and meta-analyses for scoping reviews (PRISMA-ScR) flow diagram. Most studies were excluded due to absence of information regarding disease information of cadaver wrists. Study designs that were excluded involved reviews, author replies, conference abstracts, and studies with an exclusive focus on intraoperative or imaging anatomy. Other reasons for exclusion are presented in Figure 1. General study information of the included studies is depicted in Table 1.

3.1 | TFCC composition

3.1.1 | Terminology

In eight out of the 24 studies, a definition of the TFCC was provided by explicitly stating all its individual components, as far as recognized by the authors (see Table 2). All of these eight studies consistently included (1) the articular disc (proper), (2) the dorsal and volar radioulnar ligaments (also referred to as proximal triangular ligament), (3) the meniscus homologue (also referred to as ulnocarpal meniscoid) and (4) the extensor carpi ulnaris tendon (sub)sheath (also referred to as the dense part of the ulnar collateral ligament) (Ishii et al., 1998; Nakamura et al., 1996; Nakamura & Yabe, 2000; Rein et al., 2015;

FIGURE 1 Preferred reporting items for systematic reviews and meta-analyses for scoping reviews (PRISMA-ScR) flow diagram of the study selection



Semisch et al., 2016; Shigemitsu et al., 2007; Totterman & Miller, 1995; Zhan, Li, et al., 2017).

Seven out of eight studies also included the ulnolunate and the ulnotriquetral ligaments in their definition (Ishii et al., 1998; Nakamura et al., 1996; Nakamura & Yabe, 2000; Rein et al., 2015; Semisch et al., 2016; Totterman & Miller, 1995; Zhan, Li, et al., 2017). One out of eight studies included the internal portion (identical to the ligamentum subcruratum) of the TFCC as a separate component (Shigemitsu et al., 2007).

The most prominent disagreement on TFCC components between studies existed for the ulnar collateral ligament. Three out of

eight studies claimed that the structure, or at least its loose part, was a TFCC component (Nakamura et al., 1996; Shigemitsu et al., 2007; Zhan, Li, et al., 2017). In five out of eight studies, authors stated that the ulnar collateral ligament was not a component or defined it as only a thickened ulnar capsule (Ishii et al., 1998; Nakamura & Yabe, 2000; Rein et al., 2015; Semisch et al., 2016; Totterman & Miller, 1995).

The study by Nakamura et al. (1996) made an additional subdivision of the TFCC into a proximal, a distal, and an ulnar component. The proximal component contained the triangular ligament that was defined as the true radioulnar ligament. The distal component contained the hammock-like structure that covered the articular disc, the

TABLE 1 General study information of the 24 included anatomical studies

Author	Year	Method	Subjects		
			Wrists	Cadavers	Disease status
Mikic	1978	Gross anatomy and histology	162 wrists	81 fresh cadavers aged 0 to 94 years	Death unassociated with primary joint disease and no evidence of abnormality, injury or operative injury interference on the wrist joint
Ekenstam and Hagert	1985	Gross anatomy	Not stated	5 Fresh cadavers aged 23 to 55 years	Amputated because of malignancy in the shoulder region and Wrists were completely normal without any signs of post-traumatic or other changes
Viegas and Ballantyne	1987	Gross anatomy	100 wrists	Fresh and dissecting room cadavers (58 male, 42 female) aged 2 to 98 years	No wrist joints that had been previously dissected or had gross deformity or trauma
Benjamin et al.	1990	histology	8 wrists	Dissecting room cadavers aged 54 to 85 years	No perforated articular discs or severe degenerative changes
Bednar et al.	1991	histology	10 wrists	Fresh and fresh-frozen cadavers aged 60 to 100 years	No positive ulnar variance on radiograph
Chidgey et al.	1991	Gross anatomy and histology	20 wrists	Fresh cadavers aged 23 to 52 years ($n = 18$) and 10 to 13 years ($n = 2$)	No TFCC disease detected at gross anatomy or bone disease detected by radiograph
Totterman and Miller	1995	gross anatomy	not stated	11 fresh cadavers aged 49 to 81 years	Normal TFCC at dissection
Nakamura et al.	1996	gross anatomy and histology	20 wrists (12 right, 8 left)	fresh cadavers aged 17 to 94 years	No history of disease or injury at the wrists or obvious injuries at TFCC
Kleinman and Graham	1998	gross anatomy	8 wrists	6 fresh frozen cadavers aged 63 to 83 years	No obvious deformity about the forearm and wrist or any significant scars in this area
Ishii et al.	1998	Gross anatomy	27 wrists	embalmed cadavers	No pre-existing pathology on x-ray films
Ohmori and Azuma	1998	Histology	12 wrists (12 right)	12 fresh cadavers aged 40 to 90 years	No abnormalities other than degeneration due to aging
Nakamura and Makita	2000	Gross anatomy	15 wrists (10 right, 5 left)	fresh frozen cadavers aged 17 to 102 years	No history of trauma or disease at the wrist or disruptions of the TFCC
Nakamura and Yabe	2000	Histology	7 wrists (5 right, 2 left)	7 fresh frozen cadavers (6 male, 1 female) aged 17 to 56 years	No history of wrist disease or trauma
Nakamura et al.	2001	Gross anatomy and histology	8 wrists (5 right, 3 left)	8 fresh frozen cadavers (7 male, 1 female) aged 17 to 78 years	No history of disease or trauma to the wrists
Nishikawa and Toh	2002	Gross anatomy	87 wrists (40 right, 47 left)	51 embalmed cadavers (20 male, 31 female) aged 40 to 99 years	No wrists with severe osteoarthritis

TABLE 1 (Continued)

Author	Year	Method	Subjects		
			Wrists	Cadavers	Disease status
Hagert et al.	2007	Immunohistochemistry	5 wrists	Fresh frozen cadavers (3 male, 2 female) aged 66 to 81 years (2 age unknown)	No signs of ligament injury or osteoarthritis detected during dissection
Shigemitsu et al.	2007	Immunohistochemistry	8 wrists	4 cadavers aged 73 to 86 years	No history of disease or trauma to the wrist
Rein et al.	2015	Gross anatomy, histology and immunohistochemistry	11 wrists (5 right, 6 left)	9 fresh cadavers aged 68 to 100 years	No posttraumatic changes, arthritis, and/or bony lesions macroscopically or radiographically
Semisch et al.	2016	Histology and immunohistochemistry	11 wrists (5 right, 6 left)	Fresh cadavers aged 68 to 100 years	No fractures nor ligamentous lesions on macroscopic examination or radiograph
Shin et al.	2017	Gross anatomy and histology	9 out of 13 wrists (7 right, 6 left) ^a	Cadavers (6 male, 4 female) aged 54 to 75	No evidence of age-related change, degenerative or traumatic tears, known history of previous trauma, infection, or surgical trauma affecting the wrist
Zhan et al.	2017a	Gross anatomy	14 wrists	7 fresh frozen cadavers (4 male, 3 female) aged 30 to 60 years	No osseous abnormalities on radiographs
Horiuchi et al.	2020	Gross anatomy and histology	10 wrists (3 right, 9 left)	9 embalmed cadavers (2 male, 7 female) aged 49 to 96	No wrists with remarkable instability of or deformation around the distal radioulnar joint
Maniglio et al.	2020	Gross anatomy	21 wrists	Fresh frozen cadavers (16 male, 5 female) aged 47 to 76	No known history of previous surgery or abnormalities such as obvious TFC lesions or ulnar styloid pseudoarthrosis
Saka et al.	2021	Gross anatomy and histology	18 wrists (12 right, 6 left)	13 embalmed cadavers (6 male, 7 female) aged 38 to 94	No specimen with severe TFCC calcification on CT

^aUnclear which cadavers (age, sex, and side) were used for the anatomical part of the research.

meniscus homologue, the ulnolunate ligament, and the ulnotriquetral ligament together. The ulnar component contained the ulnar collateral ligament.

4 | TFCC COMPONENTS

4.1 | Articular disc

4.1.1 | Terminology

The terminology used in the anatomical studies for this structure showed a large variety with articular disc (proper) ($n = 9$) (Benjamin

et al., 1990; Chidgey et al., 1991; Ekenstam & Hagert, 1985; Ishii et al., 1998; Kleinman & Graham, 1998; Ohmori & Azuma, 1998; Rein et al., 2015; Semisch et al., 2016; Shigemitsu et al., 2007), disc/disk proper ($n = 6$) (Horiuchi et al., 2020; Nakamura et al., 1996; Nakamura et al., 2001; Nakamura & Makita, 2000; Nakamura & Yabe, 2000; Saka et al., 2021), triangular fibrocartilage ($n = 4$) (Bednar et al., 1991; Mikic, 1978; Viegas & Ballantyne, 1987; Zhan, Li, et al., 2017), or central disk ($n = 1$) (Totterman & Miller, 1995). One study referred to the ulnar attachment fibers of the disc with the term “triangular ligament” (Zhan, Li, et al., 2017). The terms origin and insertion of the disc were used for varying attachment sites. The radial attachment was defined as origin by one study (Chidgey et al., 1991), while another study referred to the radial attachment as the insertion (Nakamura et al., 2001).

TABLE 2 An overview of the individual triangular fibrocartilage complex components according to studies specifically its composition

Study	Articular disc	Radioulnar ligaments	Ligamentum subcruentum	Meniscus homologue	Ulnolunate and ulnotriquetral ligaments	Extensor carpi ulnaris (sub) sheath	Ulnar collateral ligament
Toiterman and Miller (1995)	Central disk	Dorsal and volar radioulnar ligaments	Not stated	Meniscus homologue	Ulnolunate and ulnotriquetral ligaments	Extensor carpi ulnaris sheath	Not stated
Nakamura et al. (1996)	Disc proper	Proximal triangular ligament	Not stated	Meniscus homologue	Ulnolunate ligament and ulnotriquetral ligament	Floor of the sheath of the extensor carpi ulnaris (as part of the ulnar collateral ligament)	Ulnar collateral ligament
Ishii et al. (1998)	Articular disc	Palmar and dorsal distal radioulnar ligaments	Not stated	Meniscus homologue	Ulnotriquetral ligament and the ulnolunate ligament	Sheath of the extensor carpi ulnaris	ulnar capsule
Nakamura and Yabe (2000)	Disc proper	Radioulnar ligament	Not stated	Meniscus homologue	Ulnolunate and ulnotriquetral ligaments	Floor of extensor carpi ulnaris sheath (ecu subsheath)	Thickened joint capsule
Shigemitsu et al. (2007)	Articular disc proper	Radio-ulnar ligament	Internal portion	Meniscus homologue	Not stated	Dense part of ulnar collateral ligament	Loose part of ulnar collateral ligament
Rein et al. (2015)	Articular disc	Dorsal and volar radioulnar ligaments	Not stated	Ulnocarpal meniscoid	Ulnolunate and ulnotriquetral ligaments	Subsheath of the extensor carpi ulnaris	Not stated
Semisch et al. (2016)	Articular disc	Volar and dorsal radioulnar ligament	Not stated	Ulnocarpal meniscoid	Ulnotriquetral and ulnolunate ligament	Subsheath of the extensor carpi ulnaris	Not stated
Zhan, Li, et al. (2017)	Articular disc	Dorsal and volar distal radioulnar ligaments	Not stated	Meniscal homologue	Ulnotriquetral and ulnolunate ligament	Extensor carpi ulnaris tendon	Ulnar collateral ligament

4.1.2 | Anatomy

The articular disc appeared triangular shaped when viewed in the axial plane (Nakamura et al., 1996). Ekenstam and Hagert (1985) did not consider the articular disc as an individual component, yet rather as a part of the radio-ulnar ligament with reduced vascularization and cartilaginous metaplasia due to the central compression forces. A study by Nakamura et al. (1996), made a subdivision of the TFCC into three components: a proximal fan-shaped triangular ligament component, a distal hammock-like component and an ulnar collateral ligament component. The articular disc corresponded to the floor of the distal hammock-like structure (Nakamura et al., 1996).

Mikic (1978) aimed to assess regressive alterations of the articular disc by dissecting 180 wrist joints from all age ranges. Until the third decade of life, articular discs appeared as white and glistening with smooth ulnar and carpal surfaces (Mikic, 1978). From the age of 30, the discs became yellowish, matted, and less elastic with irregular surfaces, including some fibrillation, pitting, and shredding (Mikic, 1978). In some cases deep erosions, ulcerations, abnormal thinning, and even perforations could be observed (Mikic, 1978). From the age of 50, all discs showed abnormalities (Mikic, 1978).

The radial part of the disc was thin and the ulnar part was thick (Nakamura & Yabe, 2000). The disc was not discernable from the articular surface of the radius macroscopically (Benjamin et al., 1990; Totterman & Miller, 1995). Microscopically however, the difference between the radial part of the disc and the articular cartilage of the radius was clearly visualized (Nakamura et al., 2001). The radial attachment was located at the distal edge of the ulnar notch of the radius (Benjamin et al., 1990; Nakamura et al., 2001; Zhan, Li, et al., 2017). This anatomical location was also referred to as the sigmoid notch or incisura ulnaris radii (Nakamura et al., 2001). The radial attachment of the disc was to the hyaline cartilage of the distal radius (Zhan, Li, et al., 2017). No direct attachments to bone were observed (Benjamin et al., 1990).

Benjamin et al. (1990) and Zhan, Li, et al. (2017) described that the ulnar side of the disc split into two bands of collagen fibers, that had separate attachment sites. In the study by Zhan, Li, et al. (2017), the ulnar attachment was observed at the fovea (a slightly dorsally located depressed area between the ulnar head and the ulnar styloid process) by the most proximal fibers and at the ulnar styloid process by the most distal fibers. The two fiber bundles of the ulnar attachment of the disc were therefore named the proximal and the distal lamina (Zhan, Li, et al., 2017). The proximal lamina had a vertical orientation from the undersurface of the disc to the fovea and the distal lamina had a more horizontal orientation to the ulnar styloid process including its tip (Zhan, Li, et al., 2017).

Benjamin et al. (1990) also described two distinct fiber bundles, yet named them the upper and lower lamina. The upper lamina were bundles that extended to the ulnar head through to the radial side of the styloid process, where it had a conjoint, predominantly cartilaginous attachment with few direct bony attachments (Benjamin et al., 1990). According to the authors, the fibers at this ulnar attachment were a blend of fibers from the disc as well as the radioulnar

ligament (Benjamin et al., 1990). The lower lamina extended to and blended with the extensor carpi ulnaris (sub)sheath as well as the ulnar collateral ligament (Benjamin et al., 1990).

A study by Nakamura and Yabe (2000) described that the proximal part of the disc was surrounded by the radio-ulnar ligament and only several central fibers from this ligament fused with the proximal side of the articular disc. The distal part of the disc appeared to transit to the meniscus homologue (Nakamura & Yabe, 2000). A study by Totterman and Miller (1995) also observed some additional bands connecting the disc to the base and the tip of the styloid process. Similar to these authors, the majority of the studies considered the attachments to the ulna as (predominantly) being part of the radio-ulnar ligaments, instead of the disc itself (see subchapter radio-ulnar ligaments). Mikic (1978) as well as Viegas and Ballantyne (1987) found disc perforations. The study by Mikic (1978) found a total of 45 (36%) disc perforations in 162 healthy wrists of subjects aged between zero and 94 years. The study by Viegas and Ballantyne (1987) found an overall incidence of 21 (21%) disc perforations in 100 healthy wrists of subjects between 2 and 98 years. Both studies described a relation between age and disc perforations (Mikic, 1978; Viegas & Ballantyne, 1987).

In the study by Mikic (1978), no signs of disc perforation or degeneration were observed up until the age of 20 years, even though some discs showed almost translucent thinning at the center. The incidence of perforations increased progressively from the age of 40 years on (Mikic, 1978). An age related increase in perforations was observed by the author, ranging from in 7.6% of subjects aged 20 to 30 years, up to 53.1% of subjects aged 60 years and above (Mikic, 1978). In the study by Viegas and Ballantyne (1987), no perforations were observed under the age of 45 years and only one perforation was observed after the age of 50 years. The authors found an incidence of perforations in 27.6% of the wrists from subjects 60 years and older (Viegas & Ballantyne, 1987).

Of all wrists with a disc perforation in the study by Mikic (1978), there was one wrist, of a subject aged between 20 and 30 years, that showed no signs of degeneration. All other perforations were observed in discs with advanced degeneration in which the edge was consistently thin, irregular and shredded (Mikic, 1978). In 23 out of 45 (51.1%) the perforation appeared as a round, oval or irregular perforation at the center of the disc, whereas 18 (40%) perforations appeared as a fissure along the radial rim of the disc with ulceration and shredding of the proximal disc surface (Mikic, 1978). In three (6.6%) it imposed as a long, sagittal fissure through the central part of the disc, including one without any signs of degeneration in a 23 year old (Mikic, 1978). In one (2.2%) almost the entire disc surface was irregularly perforated (Mikic, 1978).

4.1.3 | Histology

According to four studies, the articular disc consisted of fibrocartilage (Nakamura et al., 1996; Nakamura et al., 2001; Ohmori & Azuma, 1998; Semisch et al., 2016). The study by Semisch et al. (2016)

found that the disc consisted of interlaced collagen bundles that were densely packed and became compact parallel oriented fibers at the ulnar limit. The study by Ohmori and Azuma (1998) found that the disc consisted of fibrocartilage, surrounded by a matrix of mostly collagen fibers and some elastic fibers. Fusiform fibroblasts were only observed in the periphery of the disc (Ohmori & Azuma, 1998).

A slightly different cellular distribution was observed by Nakamura and Yabe (2000) who found the distal part of the disc to contain plenty of chondrocytes in a collagen matrix, while the proximal part contained radio-ulnar oriented fibers. Another variation was found by a study from Chidgey et al. (1991) that made a distinction between two superficial layers and one interposed deep part of the disc. The bundles in the central part appeared short, banded, randomly oriented, and formed a wavelike pattern, arranged in sheets with three-dimensionally angled layers up to 90° (Chidgey et al., 1991). The superficial layers were more distinctly oriented in an arched pattern (Chidgey et al., 1991).

The wavy pattern at the central part of the disc was more pronounced in immature wrists than in adults (Chidgey et al., 1991). In addition, the difference between the two layers was more evident in this age group, where it was more distinct at the radiocarpal surface than at the distal radioulnar surface (Chidgey et al., 1991). Evidence of early fibrillation in the superficial layer was observed in young adults (Chidgey et al., 1991).

At the radial attachment, the radial 1–2 mm of the disc consisted of collagen bundles that were thicker compared with remaining part of the disc (Chidgey et al., 1991). The ratio of collagen fibers to ground substance was found to be higher in the disc than in the distal radial cartilage and the arrangement of collagen fibers was more randomly oriented compared with the longitudinally orientation in the hyaline cartilage of the distal radius (Chidgey et al., 1991).

Several authors found small numbers of elastic fibers in the disc (Chidgey et al., 1991; Ohmori & Azuma, 1998). From the age of 20 years, the young fibroblasts were found to be replaced by chondrocytes and gradually the discs became much less cellular and the number of elastic fibers decreased which finally fragmented (Mikic, 1978). Then, fibrillation occurred and areas of mucoid degeneration with chondrocyte proliferation or calcification of ground substance could be observed (Mikic, 1978). These degenerative changes were observed first and most severely at the proximal surface of the disc, while the distal surface remained normal for a longer time; the thicker peripheral areas of the disc mostly remained normal, while thinner central parts became affected (Mikic, 1978).

The latter study also observed macroscopic calcifications in one 70 year old wrist with a disc perforation (Mikic, 1978). Similar calcium pyrophosphate dihydrate crystals depositions were found by Viegas and Ballantyne (1987) in four wrists with disc perforations of two cadavers of 72 years old.

4.1.4 | Vascularization and innervation

Several studies noticed that the central 80% and the radial attachment of the disc was avascular (Bednar et al., 1991; Ohmori &

Azuma, 1998; Semisch et al., 2016). The articular radial cartilage appeared to prevent the vascularity penetrating the disc from the radial side (Bednar et al., 1991). The remaining peripheral 15–25%, being the dorsal, volar, and ulnar parts, of the disc did, however, show sparse vascularization in various studies (Chidgey et al., 1991; Ohmori & Azuma, 1998; Semisch et al., 2016). According to one study, significantly less blood vessels per cm² were present in the articular disc compared with all other TFCC components, except for the ulnolunate ligament (Rein et al., 2015).

One study stated that the central disc area did not show any nervous tissue (Shigemitsu et al., 2007). In two other studies however, free nerve endings in the ulnar part disc were found (Ohmori & Azuma, 1998; Rein et al., 2015). The free nerve endings were without myelin sheaths and the location was further specified as only the peripheral part of the ulnar side of the disc (Ohmori & Azuma, 1998).

4.2 | Radioulnar ligaments

4.2.1 | Terminology

The terminology used for the ligaments showed some variety with the most commonly used terms being: (distal) dorsal and volar/palmar radioulnar ligaments ($n = 8$) (Chidgey et al., 1991; Ekenstam & Hagert, 1985; Ishii et al., 1998; Kleinman & Graham, 1998; Rein et al., 2015; Semisch et al., 2016; Totterman & Miller, 1995; Zhan, Li, et al., 2017), (distal) radioulnar ligaments ($n = 8$) (Benjamin et al., 1990; Horiuchi et al., 2020; Maniglio et al., 2020; Nakamura et al., 2001; Nakamura & Yabe, 2000; Saka et al., 2021; Shigemitsu et al., 2007; Shin et al., 2017), triangular ligament ($n = 1$) (Nakamura et al., 1996) or proximal ligamentous complex ($n = 1$) (Nakamura & Makita, 2000). The origin was defined by some studies at the radial attachment and the insertion at the ulnar attachment (Chidgey et al., 1991; Ekenstam & Hagert, 1985; Maniglio et al., 2020; Totterman & Miller, 1995). While other studies defined the origin at the ulnar attachment and the insertion at the radial attachment (Nakamura et al., 1996; Nakamura et al., 2001; Nakamura & Makita, 2000; Nakamura & Yabe, 2000).

4.2.2 | Anatomy

The study by Ekenstam and Hagert (1985) considered the radioulnar ligament to consist of a centrally located cartilaginous disc with two surrounding fibrous bands. These dorsal and volar fibrous bands were measured to be two millimeters thick (Ekenstam & Hagert, 1985). Nakamura et al. (1996) and Nakamura and Makita (2000) acknowledged various forms of a central portion of this ligament. However, most studies considered the radioulnar ligaments as the ligaments that are located on the dorsal and volar side of the disc and connect the radius with the ulna (Chidgey et al., 1991; Ishii et al., 1998; Nakamura et al., 2001; Nakamura & Yabe, 2000; Semisch et al., 2016; Totterman & Miller, 1995; Zhan, Li, et al., 2017). The difference between the articular disc and radioulnar ligaments was difficult to

distinguish visually through gross anatomy (Chidgey et al., 1991). However, the difference between structures was clearly palpable (Totterman & Miller, 1995). The radioulnar ligaments were found to blend with the wrist capsule peripherally by one study (Kleinman & Graham, 1998).

The radial attachment was wide and located at the dorsal and volar edges of the sigmoid notch (Chidgey et al., 1991; Nakamura et al., 1996; Nakamura & Makita, 2000; Zhan, Li, et al., 2017). The radial attachments were directly to the bony distal radius in contrast to the cartilaginous attachment of the articular disc to the radius (Benjamin et al., 1990; Nakamura et al., 2001; Zhan, Li, et al., 2017). Shigemitsu et al. (2007) referred to the radioulnar ligament as a strong fiber bundle attaching to the proximal part of the articular disc instead, without a direct attachment to the radius.

Regarding the ulnar attachment of the radioulnar ligament, a large variation in anatomical descriptions was found. Three studies found that, in addition to the radioulnar ligaments, fibers from the articular disc also had an ulnar attachment (Benjamin et al., 1990; Totterman & Miller, 1995; Zhan, Li, et al., 2017). Benjamin et al. (1990) found that the ulnar attachment of the radioulnar ligaments was located as one attachment, reaching from the ulnar head through to the radial side of the styloid process. In addition, these authors observed that the dorsal radioulnar ligament additionally extended beyond the ulna and blended with the extensor carpi ulnaris tendon (sub)sheath together with the lower lamina of the articular disc (Benjamin et al., 1990). Zhan, Li, et al. (2017) located the ulnar attachment of the radioulnar ligament at the ulnar styloid process base. Yet, Totterman and Miller (1995) observed two separate attachments at the base and the tip of the styloid process. From a proximal axial view, the bands appeared as folds with the dorsal fold being more prominent than the volar fold (Totterman & Miller, 1995).

Similar to Totterman and Miller (1995), both Chidgey et al. (1991) and Ekenstam and Hagert (1985) considered the ulnar attachments as solely fibers from the radioulnar ligaments and also defined the ulnar attachment as two separate attachments. Ekenstam and Hagert (1985) observed an attachment of converged fibers from the dorsal and volar radioulnar ligaments to the styloid base as well as along the styloid process. Chidgey et al. (1991) described that the more proximal collagen fiber bundles attached to the ulnar side of the ulnar head and that the more distal bundle attachment completely surrounded the styloid process and partly continued to merge with the extensor carpi ulnaris tendon (sub)sheath.

A slightly different view was stated by three authors, who found that one of those two ulnar attachment sites was located at the fovea and the other was located at the styloid base (Nakamura et al., 2001; Nakamura & Yabe, 2000; Shigemitsu et al., 2007). Radially from the ulnar attachments, the two fiber bundles first merged together and then split again into a dorsal and volar bundle that surrounded only the proximal side of the disc (Nakamura et al., 2001; Nakamura & Yabe, 2000). Only several central fibers of the radioulnar ligaments fused with this proximal side of the articular disc (Nakamura et al., 2001; Nakamura & Yabe, 2000).

In studies by Ishii et al. (1998), Shin et al. (2017) and Maniglio et al. (2020), a superficial and deep portion of the radioulnar ligaments were identified. Halfway between the radial attachments and the ulnar attachment, the dorsal and volar radioulnar ligaments split into a superficial and deep part and reached toward the ulnar attachment (Ishii et al., 1998). According to the study by Ishii et al. (1998), the deep ligament coursed toward the ulnar styloid base and the superficial ligament coursed toward the distal ulnar capsule. Therefore, the attachment to the fovea consisted of the deep dorsal and volar radioulnar ligaments while the superficial ligaments enclosed the most ulnar part of the disc without attaching to the ulnar styloid (Ishii et al., 1998). According to the study by Shin et al. (2017), the attachment of the deep portion was located at the fovea and the attachment of the superficial limb was located at the radial side of the styloid process. Maniglio et al. (2020) found that the superficial portion was attached around the distal 13% of the styloid process and therefore covering the tip. The deep portion was found to attach to the fovea, extending to the proximal 81% styloid process (Maniglio et al., 2020).

The attachment area at the ulnar styloid process was found narrower than at the fovea (Maniglio et al., 2020; Nakamura et al., 2001; Shin et al., 2017). When comparing the areas of attachment, the footprint of the superficial portion to the ulnar styloid tip was about three times smaller than the footprint of the deep portion to the fovea and ulnar base (Maniglio et al., 2020). The footprint of this deep portion however, showed asymmetry with a more prominent dorsal than volar portion and in 47% this dorsal portion even showed an accessory footprint (Maniglio et al., 2020).

Most recently, a completely different conception of the superficial part of the radioulnar ligament was stated by Horiuchi et al. (2020). The authors observed a difference in dorsal and volar orientation when comparing the deepest and the most superficial part of the superficial radioulnar ligaments, which is somewhat analogous to the cruciate ligaments of the knee. At the most deep side of the ligament at the level of the attachment to the middle third of the styloid process, the radioulnar ligament was attached to the volar side of the articular disc and to the dorsal part of the styloid process. At the most superficial part of the ligament, at the level of the distal third of the styloid process, the radioulnar ligament was attached to the dorsal side of the articular disc and to the volar side of the styloid process and even reached to the volar joint capsule. In between those two points, the attachments gradually transited toward another (Horiuchi et al., 2020).

A later study by Saka et al. (2021) also showed fibers attaching to the sigmoid notch, which was located at the ulnar protrusion of the volar ulnar rim of the radius, connected with the dorsal side of the ulnar styloid process. Those authors also showed that the attachment at the sigmoid notch could not be separated into a separate radioulnar- and short radiolunate ligament and therefore was termed the volar ulnar capsule (Saka et al., 2021).

Nakamura and Makita (2000) and Nakamura et al. (1996) explicitly described that they did not consider the ligamentous structures

surrounding the articular disc dorsally and volarly to be the radioulnar ligaments since they did not connect the radius with the ulna but rather reinforced the distal hammock structure. According to the authors' view, the true radioulnar ligament was embodied by a triangular ligament, accounting for the proximal ligamentous part of the TFCC (Nakamura et al., 1996; Nakamura & Makita, 2000). The dorsal and volar portions of this ligament reached from the fovea to the sigmoid notch (Nakamura et al., 1996; Nakamura & Makita, 2000). However, the central portion of this ligament did not show distinct fibers and at the radial part, a nearly fibrocartilaginous nature in the central portion of varying size was observed that seemed to merge with the proximal surface of the articular disc (Nakamura et al., 1996; Nakamura & Makita, 2000). The variation in the shape of this central fibrocartilaginous tissue induced a fan-like ligament shape if it was completely absent, a V-like ligament shape if it progressively disappeared from the fovea to the sigmoid notch, and a funnel-like ligament shape if it extended from the fovea to the sigmoid notch (Nakamura & Makita, 2000).

4.2.3 | Histology

The difference between the articular disc and radioulnar ligaments was difficult to distinguish through hematoxylin with eosin stained cross-sections (Chidgey et al., 1991). Yet, polarized light microscopy showed distinctive longitudinal collagen fibers of the radioulnar ligaments, with a much less wavy pattern and a twice as large distance between wave tops than those of the articular disc (Chidgey et al., 1991). A mean ratio between collagen I and III fibers of 1.27 ($SD \pm 0.56$) was found for the radioulnar ligaments (Shin et al., 2017). The ratio was significantly lower in the deep portion compared with the superficial portion, which indicated difference in mechanical properties (Shin et al., 2017).

Both dorsal and volar ligaments had a similar morphological structure that slightly varied between subjects with interlaced or parallel fiber bundles that were either densely packed or a mix of loose and densely packed parallel fibers, all oriented in a radioulnar direction (Semisch et al., 2016). Within these fiber bundles, the layer of loose connective tissue surrounding the fascicles appeared thicker and with more vascularization at the dorsal and volar margins of the dorsal and volar radioulnar ligaments respectively, compared to the margins enclosing the disc (Semisch et al., 2016).

The radial attachment was histologically found to consist of calcified as well as non-calcified fibrocartilaginous attachments (Benjamin et al., 1990; Saka et al., 2021). At the most dorsal and palmar sides calcified cartilaginous attachments to the radius with Sharpey's fibers were found with increasing amounts of cartilage cells and decreasing fibers toward the interposed attachment of the articular disc (Nakamura et al., 2001). Sharpey's fibers are considered perforating fibers extending from the periosteum ensuring adhesion of tendons and ligaments to cortex (Aaron, 2012).

The study by Benjamin et al. (1990) found that the fibers at the ulnar attachments consisted of intermingled fibers from the upper lamina coming from the articular disc, as well as both dorsal and volar radioulnar ligaments coming from the radius. These authors found that the radioulnar ligaments attached to the ulna through direct bony, but mostly fibrocartilaginous attachment zones (Benjamin et al., 1990). Contrarily, several other studies found that the ulnar attachments were strong with direct chondral-apophyseal attachments to the bone (Horiuchi et al., 2020; Nakamura et al., 1996; Nakamura et al., 2001; Nakamura & Yabe, 2000). Yet, these studies did have a different interpretation on the location of the ulnar attachment than Benjamin et al. (1990).

These authors also described that when viewed in the coronal plane some fibers were attached at the fovea, oriented in an almost vertical direction, and some fibers were attached to the ulnar styloid base, oriented in a horizontal orientation (Horiuchi et al., 2020; Nakamura et al., 1996; Nakamura et al., 2001; Nakamura & Yabe, 2000). The fibers were loose at the dorsal edge, became denser and vertically oriented in 2 to 4 mm from the dorsal edge, and were firm vertical Sharpey's fibers with direct bony attachments in 5 to 9 mm from the dorsal edge (Nakamura et al., 2001).

4.2.4 | Vascularization and innervation

The dorsal and volar radioulnar ligaments were found to be well vascularized (Chidgey et al., 1991; Rein et al., 2015). A higher number of blood vessels was observed in the volar radioulnar ligament (median, 363.62; range, 117.8–871.17/cm²) compared to the dorsal radioulnar ligament (median, 116.15; range, 53.91–185.1/cm²; difference of medians, 247.47; $p = 0.001$) (Rein et al., 2015). Although, Semisch et al. (2016) described a thicker and better vascularized epifascicular loose connective tissue layer at the dorsal and volar margins of the dorsal and volar radioulnar ligaments respectively, compared to the margins enclosing the disc. These authors also described that the middle parts of the ligaments never showed tight interstitial septa with blood vessels, which were occasionally shown at the insertion parts only (Semisch et al., 2016).

Free nerve endings were found in both radioulnar ligaments (Ohmori & Azuma, 1998; Rein et al., 2015; Shigemitsu et al., 2007). It mostly concerned common sensory nerve endings, with a mean density of 3.1 per mm² ($SE \pm 1.1$) (Rein et al., 2015; Shigemitsu et al., 2007). A mean total density of 6.0 per mm² ($SE \pm 2.4$) for all neural elements was found, which was comparable to the density found in the meniscus homologue (Shigemitsu et al., 2007). Single nerve fibers were found with a mean density of 1.6 per mm² ($SE \pm 0.8$), nerve fascicles with a density in 1.1 per mm² ($SE \pm 0.7$) and perivascular neural nets with a density of 0.1 per mm² ($SE \pm 0.1$) (Shigemitsu et al., 2007). In addition, sensory corpuscles as Ruffini, Vater-Pacini, Golgi-Mazoni, and unclassifiable corpuscles were found (Shigemitsu et al., 2007).

4.3 | Ligamentum Subcruentum

4.3.1 | Terminology

Almost every study that described the ligamentum subcruentum used the same terminology: ligamentum subcruentum ($n = 3$) (Chidgey et al., 1991; Ishii et al., 1998; Nakamura & Yabe, 2000). One study explicitly referred to the ligamentum subcruentum as the internal portion of the TFCC ($n = 1$) (Shigemitsu et al., 2007). This study was also the sole anatomical study to include this structure as a TFCC component (Shigemitsu et al., 2007).

4.3.2 | Anatomy

Two studies by Chidgey et al. (1991) and Zhan, Li, et al. (2017) found that the structure was located between the two ulnar attachment sites of the TFCC. The study by Zhan, Li, et al. (2017) further described the ligamentum subcruentum to even separate the proximal and distal lamina and to extend into the articular disc creating a typical triangular shape with a broad foveal base.

A study by Ishii et al. (1998) however, found that the ligamentum subcruentum was located between the deep part of the radioulnar ligament and the meniscus homologue instead of between the deep and superficial part of the radioulnar ligament. In wrists with a communication between the prestyloid recess and the distal radioulnar joint space instead of the ulnocarpal joint space, a ligamentum subcruentum was not observed by these authors (Ishii et al., 1998).

Yet, Sasao et al. (2003) described the ligamentum subcruentum rather as a structure surrounding the ulnar attachment sites as opposed to intervening them. A similar passing of the ligaments through a vascularized loose connective tissue to their ulnar attachments was also described by Benjamin et al. (1990), although these authors only found this for the fiber bundle that attached to the ulnar head and base of the styloid process, called the upper lamina.

Nakamura and Yabe (2000) further defined the location of the ligamentum subcruentum as the TFCC's internal portion that is surrounded by the articular disc, radioulnar ligament, meniscus homologue and a thickened part of the wrist joint capsule. This view was adapted by Shigemitsu et al. (2007) by referring to the ligamentum subcruentum as the internal portion.

Additionally, Shigemitsu et al. (2007) reported the internal portion to be situated deeply in the prestyloid recess. Yet, the study by (Totterman & Miller, 1995) that did not name the ligamentum subcruentum, described that the loose tissue that was observed in between the two bands connecting the articular disc to the tip and base of the ulnar styloid, specifically did not connect with the prestyloid recess.

4.3.3 | Histology

As opposed to what its terminology might suggest, the ligamentum subcruentum was found not to consist of ligamentous tissue (Chidgey

et al., 1991; Ishii et al., 1998; Shigemitsu et al., 2007). Chidgey et al. (1991) and Ishii et al. (1998) found it to consist of loose connective tissue. Shigemitsu et al. (2007) defined the ligamentum subcruentum as a mixture of not only loose but also dense connective tissue.

4.3.4 | Vascularization and innervation

The loose connective tissue was found to be very well-vascularized, by vessels coming through the bone at the foveal area (Chidgey et al., 1991; Ishii et al., 1998; Nakamura & Yabe, 2000; Shigemitsu et al., 2007). Several neural elements such as free nerve endings (mean density of 7.1 per mm^2 , $SE \pm 1.6$), single nerve fibers (mean density of 5.9 per mm^2 , $SE \pm 1.2$), nerve fascicles (mean density of 10.5 per mm^2 , $SE \pm 1.5$) and perivascular neural nets (mean density of 1.4 per mm^2 , $SE \pm 0.3$) were found in the ligamentum subcruentum (Shigemitsu et al., 2007). The mean density of all these elements was 24.9 per mm^2 ($SE \pm 2.9$), which was significantly higher compared to the articular disc, the meniscus homologue, the radioulnar ligaments and the ulnar collateral ligament (Shigemitsu et al., 2007).

4.4 | Meniscus homologue

4.4.1 | Terminology

The meniscus homologue was generally referred to as such ($n = 8$) (Benjamin et al., 1990; Ishii et al., 1998; Nakamura et al., 1996; Nakamura et al., 2001; Nakamura & Makita, 2000; Nakamura & Yabe, 2000; Ohmori & Azuma, 1998; Totterman & Miller, 1995) or meniscus homologue ($n = 1$) (Shigemitsu et al., 2007), but also as (ulno)meniscal homologue ($n = 2$) (Nishikawa & Toh, 2002; Zhan, Li, et al., 2017) or ulnocarpal meniscoid ($n = 2$) (Rein et al., 2015; Semisch et al., 2016).

4.4.2 | Anatomy

The study by Ishii et al. (1998) defined the meniscus homologue as the structure located between the ulnar border of the superficial part of the radioulnar ligaments and the ulnar part of the wrist capsule. In a coronal view, the meniscus homologue imposed as a meniscus (Nakamura & Yabe, 2000). The meniscus homologue was defined as a smooth, membranous, synovial fold, functioning as the ulnar internal wall of the distal part of the TFCC (Nakamura & Yabe, 2000; Nishikawa & Toh, 2002). This structure always contained some fibers of the radioulnar ligament and was observed in all wrists (Ishii et al., 1998). The meniscus completely surrounded the prestyloid recess in the majority of the wrists, although slight variation within wrists could be observed (Nakamura & Yabe, 2000).

The studies by Nishikawa and Toh (2002), Totterman and Miller (1995) and Zhan, Li, et al. (2017) found the meniscus to continue across the ulnar styloid and to attach to the triquetrum in almost

all wrists. The attachment to the triquetrum was observed at the ulnar articular side of the triquetrum by Nishikawa and Toh (2002). According to Zhan, Li, et al. (2017), this attachment was rather located at the dorsal side of the triquetrum. An additional attachment site was found at the fifth metacarpal by Nishikawa and Toh (2002) and Zhan, Li, et al. (2017). Nishikawa and Toh (2002) found this attachment to the fifth metacarpal in 90% of the wrists and extended either partially or completely to the lunotriquetral ligament in 10%. Furthermore, Zhan, Li, et al. (2017) found that the meniscus homologue additionally stretched to the hamate bone.

According to Ishii et al. (1998), the structure was intimately related to the ulnar border of the superficial part of the radioulnar ligaments and the ulnar part of the wrist joint capsule. These authors also found attachment sites to the ulnar styloid, which pattern differed between wrists leading to different opening patterns of the prestyloid recess (Ishii et al., 1998). The most common pattern (74%) was the narrow opening type with an attachment to the radial, dorsal and volar part of the ulnar styloid and to the entire styloid tip, creating a central narrow opening connecting the ulnar styloid to the prestyloid recess (Ishii et al., 1998). In 15% of the meniscus attached to the ulnar instead of the radial part of the ulnar styloid and did not attach to the styloid tip, creating no opening for the prestyloid recess (Ishii et al., 1998). In 11% the attachments were similar to the narrow opening type, without the attachment to the styloid tip, creating a wide opening for the prestyloid recess (Ishii et al., 1998).

A proximal attachment to the radius was found by Totterman and Miller (1995), where it was undistinguishable from the dorsal radioulnar ligament. In contrast to that study, five other studies found the meniscus not to attach to the radius (Nakamura et al., 2001; Nakamura & Yabe, 2000; Nishikawa & Toh, 2002; Shigemitsu et al., 2007; Zhan, Li, et al., 2017). Four of those studies reported that the structure extended from (the distal part of) the articular disc (Nakamura et al., 2001; Nakamura & Yabe, 2000; Nishikawa & Toh, 2002; Shigemitsu et al., 2007). According to two of those studies by Nakamura and Yabe (2000) and Nakamura et al. (2001), the more proximal part of the meniscus homologue attached to the radioulnar ligament in addition. According to Zhan, Li, et al. (2017), the meniscus homologue only stretched distally from the ulnar styloid.

In addition to the intimate relationship with the ulnar part of the wrist capsule described by Ishii et al. (1998), Shigemitsu et al. (2007) found distal attachments of the meniscus to the ulnar wrist joint capsule in addition to the carpal bones. In addition, Nakamura et al. (2001) found that the meniscus homologue appeared to confluent with fibers from a thickening in the ulnar wrist joint capsule. The study by Totterman and Miller (1995) rather found that the meniscus was inseparable from the extensor carpi ulnaris (sub)sheath. Benjamin et al. (1990) stated that the meniscus blended with the extensor carpi ulnaris tendon (sub)sheath as well as the ulnar collateral ligament, imposing as an integral part of the lower lamina that covered the styloid process' tip. Zhan, Li, et al. (2017) found that the meniscus homologue was rather marked by the extensor carpi ulnaris tendon and the ulnar collateral ligament, the sole fusion was with the ulnotriquetral ligament on the volar side of the meniscus.

4.5 | Histology

The meniscus was irregular shaped and composed of loose connective tissue (Nakamura & Yabe, 2000; Semisch et al., 2016). The study by Benjamin et al. (1990) defined the meniscus as an undefined structure consisting of dense fibrous connective tissue without an independent histological identity. The study by Shigemitsu et al. (2007) found a somewhat contradictory definition, stating that it was composed of synovial covered fibrocartilage. The meniscus homologue contained tight bundles of collagen fibers with an abundance of interposed loose connective tissue (Semisch et al., 2016). In nine out of 11 wrists, the meniscus homologue showed loose parallel as well as mixed tight collagen fibers and in 2 out of 11, it generally showed an interlaced pattern of mixed tight and loose collagen fibers (Semisch et al., 2016).

4.6 | Vascularization and innervation

The loose connective tissue of the meniscus homologue was well-vascularized (Semisch et al., 2016). Free nerve endings without myelin sheaths were observed in the meniscus homologue of all cases (Ohmori & Azuma, 1998). A density was reported of 1.9 ($SE \pm 0.4$) free nerve endings per mm^2 , of 3.1 ($SE \pm 1.0$) single nerve fibers per mm^2 , of 1.5 ($SE \pm 0.9$) nerve fascicles per mm^2 and of 0.3 ($SE \pm 0.3$) perivascular neural nets per mm^2 (Shigemitsu et al., 2007). Bulb endings enabling position, movement, and vibration sensation, such as Meissner's corpuscles and Krause's corpuscles (articular corpuscles) were also observed in this area and the axons were enclosed with Schwann cells (Ohmori & Azuma, 1998). Free nerve endings, Golgi-like, Pacini, Ruffini, and unclassifiable corpuscles were found as sensory corpuscles in the meniscus homologue (Rein et al., 2015). The density of all neural elements was 6.8 ($SE \pm 1.9$) per mm^2 and this did not differ from the radioulnar ligaments (Shigemitsu et al., 2007).

4.7 | Ulnolunate and ulnotriquetral ligament

4.7.1 | Terminology

The ulnolunate and ulnotriquetral ligaments were referred to as such in most papers ($n = 8$) (Ishii et al., 1998; Nakamura et al., 1996; Nakamura et al., 2001; Nakamura & Makita, 2000; Nakamura & Yabe, 2000; Rein et al., 2015; Semisch et al., 2016; Totterman & Miller, 1995; Zhan, Li, et al., 2017). In one paper the ligaments were combined and referred to as the ulnocarpal ligaments ($n = 1$) (Chidgey et al., 1991) or only the ulnolunate ligament was mentioned ($n = 1$) (Hagert et al., 2007). The term origin was used for the attachment at the volar side of the articular disc (Ishii et al., 1998; Totterman & Miller, 1995; Zhan, Li, et al., 2017) and insertion was used for the distal insertion at the lunate or triquetrum bone (Ishii et al., 1998; Zhan, Li, et al., 2017).

4.7.2 | Anatomy

Three studies found that the ulnocarpal ligament was composed of two individual ligaments, the ulnolunate attaching to the volar part of the lunate and the ulnotriquetral ligament attaching to the volar part of the triquetrum (Ishii et al., 1998; Nakamura & Yabe, 2000; Zhan, Li, et al., 2017). Only one study by Totterman and Miller (1995) did not qualify the ulnolunate and ulnotriquetral ligaments as a strong, distinct ligament, but described the ligaments as simple thickenings in the wrist joint capsule. The ulnolunate and ulnotriquetral ligaments were found to attach in a fan-shaped form to the lunate as well as the triquetrum (Zhan, Li, et al., 2017). The ulnotriquetral ligament had a more oblique direction than the ulnolunate ligament (Ishii et al., 1998). The ulnolunate ligament seemed strongly entangled with the volar radioulnar ligament (Ishii et al., 1998).

Ishii et al. (1998) found that both ligaments showed individual proximal attachments sites. The proximal attachment of the ulnolunate ligament was found on the volar side of the articular disc with some fibers attaching to the volar part of the distal radius as well (Ishii et al., 1998). The proximal attachment of the ulnotriquetral ligament was found on the volar-radial part of the ulnar styloid base, the volar part of the meniscus homologue and the volar part of the articular disc (Ishii et al., 1998). By contrast, two other studies by Nakamura and Yabe (2000) and Nakamura et al. (2001) found a proximal attachment at the volar part of the disc. Three different studies however, described both the ulnolunate and the ulnotriquetral ligament being attached to the volar radioulnar ligament, rather than to the peripheral part of the articular disc, where only several fibers attached (Chidgey et al., 1991; Totterman & Miller, 1995; Zhan, Li, et al., 2017).

4.7.3 | Histology

The ulnocarpal ligaments were composed of collagen fibers with parallel orientation that were densely packed (Hagert et al., 2007). In the ulnotriquetral ligament, these fibers were mixed in tight and loose structures with interposed loose connective tissue and became more interlaced near the distal attachment (Semisch et al., 2016). The fibers from the ulnolunate ligament were more tightly packed compared to the ulnotriquetral ligament and had less interposed loose connective tissue (Semisch et al., 2016).

4.7.4 | Vascularization and innervation

Vascularity was observed epifascicular and fascicular, yet the ulnolunate ligament was less well vascularized than the ulnotriquetral ligament (Semisch et al., 2016). The innervation of the ulnolunate was qualified as limited in the amount of nerves as well as mechanoreceptors, which indicated a more mechanically than sensory function of the ligament (Hagert et al., 2007). A different study found sparse distribution of free nerve endings, Golgi-like endings and unclassifiable corpuscles in the ulnolunate ligament, yet did not contain Ruffini or

Pacini corpuscles (Rein et al., 2015). The ulnotriquetral ligament however, did contain all types of sensory corpuscles (Rein et al., 2015).

4.8 | Extensor carpi ulnaris (sub)sheath

4.8.1 | Terminology

This component of the TFCC was generally referred to as the extensor carpi ulnaris (sub)sheath ($n = 10$) (Benjamin et al., 1990; Chidgey et al., 1991; Ishii et al., 1998; Kleinman & Graham, 1998; Nakamura et al., 1996; Nakamura et al., 2001; Nakamura & Yabe, 2000; Rein et al., 2015; Semisch et al., 2016; Totterman & Miller, 1995), yet slight variations such as extensor carpi ulnaris tendon ($n = 1$) (Zhan, Li, et al., 2017), ulnar carpal extensor ligament peritendineum ($n = 1$) (Ohmori & Azuma, 1998) or the dense part of the ulnar collateral ligament ($n = 1$) (Shigemitsu et al., 2007) were also encountered. The term origin was used for the attachment at the triquetrum and insertion for the attachment on the dorsal ulnar styloid (Ishii et al., 1998).

4.8.2 | Anatomy

The floor of the extensor carpi ulnaris tendon (sub)sheath was found to be attached to the dorsal-ulnar part of the ulnar styloid and its base (Ishii et al., 1998). The location of the attachment was further specified as at the dorsal part of the ulnar fovea (Nakamura et al., 2001; Nakamura & Yabe, 2000). The tendon (sub)sheath blended with the dorsal wrist joint capsule near the attachment to the ulna (Ishii et al., 1998; Kleinman & Graham, 1998). More distally, the tendon (sub)sheath attached to the dorsal side of the triquetrum (Ishii et al., 1998). There, the difference between the tendon (sub)sheath and the wrist joint capsule was distinct in form and density and the structures could easily be dissected from each other (Ishii et al., 1998; Kleinman & Graham, 1998). The study by Chidgey et al. (1991) found that the superficial fibers from the articular disc blended with the extensor carpi ulnaris tendon (sub)sheath, extending distally beyond the ulnar styloid.

4.8.3 | Histology

The tendon (sub)sheath collagen fibers were organized in parallel collagen bundles (Semisch et al., 2016). The bundles were generally composed of parallel fibers that were mixed loose and tight, yet some were mostly packed densely (Semisch et al., 2016). In 1 out of 11 wrists, the mixed loose and tight fibers were found interlaced instead of oriented parallel (Semisch et al., 2016). In between the extensor carpi ulnaris tendon and its (sub)sheath, fibrocartilage was observed by one study (Semisch et al., 2016). The attachment to the dorsal part of the ulnar fovea was found to consist of Sharpey's fibers with few chondrocytes ensuring a firm connection (Nakamura et al., 2001).

The extensor carpi ulnaris (sub)sheath was defined by Shigemitsu et al. (2007) as a thin layer dense connective tissue laying within loose connective tissue, which the authors defined as the ulnar collateral ligament. The authors therefore named the tendon (sub)sheath the dense part of the ulnar collateral ligament (Shigemitsu et al., 2007).

4.8.4 | Vascularization and innervation

Vascularization of the extensor carpi ulnaris (sub)sheath was found at the attachment sites and spread through to the central collagen bundle (Semisch et al., 2016). Innervation was rich with all types of sensory corpuscles (Rein et al., 2015). A median of 66.3 free nerve endings (range 34.9–267), no Ruffini corpuscles (range 0–0.6), no Pacini corpuscles (range 0–0.6), no Golgi-like corpuscles (range 0–1.7), and 0.4 unclassifiable corpuscles (range 0–1) were found per cm² (Rein et al., 2015).

4.9 | Ulnar collateral ligament

4.9.1 | Terminology

The terminology of this structure was fairly consistent as ulnar collateral ligament ($n = 5$) (Benjamin et al., 1990; Nakamura et al., 1996; Nakamura & Makita, 2000; Ohmori & Azuma, 1998; Zhan, Li, et al., 2017), although it was also referred to as the (thickened) ulnar joint capsule ($n = 2$) (Ishii et al., 1998; Nakamura et al., 2001) or the loose and dense part of the ulnar collateral ligament ($n = 1$) (Shigemitsu et al., 2007).

4.9.2 | Anatomy

Several studies did not identify the ulnar collateral ligament as a definite ligamentous structure (Benjamin et al., 1990; Ishii et al., 1998; Nakamura et al., 1996; Nakamura et al., 2001). Ishii et al. (1998) referred to it as the ulnar wrist joint capsule rather than the ulnar collateral ligament. The authors noted that the capsule blended with the extensor carpi ulnaris (sub)sheath on the ulnar styloid's dorsal side (Ishii et al., 1998).

The study by Nakamura et al. (2001) also no longer referred to the ulnar collateral ligament and reported a thickened ulnar wrist joint capsule reaching from the ulnar styloid tip to the triquetrum that was confluent with the meniscus homologue instead. The authors defined the proximal attachment of the capsule thickening as the cartilaginous middle to top part of the ulnar styloid (Nakamura et al., 2001). The distal insertion of the wrist joint capsule thickening showed a fusion with the hyaline cartilage on the ulnar side of the triquetrum (Nakamura et al., 2001).

An earlier study by Nakamura et al. (1996) found the ulnar collateral ligament to consist of both the extensor carpi ulnaris sheath floor and an ulnarly located loose ligamentous structure. Shigemitsu

et al. (2007) referred to this tendon sheath floor as the dense part of the ulnar collateral ligament and to this loose ligamentous structure as the loose part of the ulnar collateral ligament.

Zhan, Li, et al. (2017) was the only study that clearly identified the ulnar collateral ligament, closely linking to the meniscus homologue radially and to the extensor carpi ulnaris on the ulnar side. Benjamin et al. (1990) described a fairly poor defined, loose structure. Yet, these authors specified the location of the proximal attachment to be at the ulnar side of the ulnar styloid base, distal from the prestyloid recess.

4.9.3 | Histology

Benjamin et al. (1990) observed that the ligament occasionally showed collagen fibers with a longitudinal orientation. In the majority of wrists, the ulnar collateral ligaments had a more loose texture that was not compatible with tendon nor tendon sheath tissue (Benjamin et al., 1990). Near the attachment to the triquetrum, the ulnar thickening of the wrist joint capsule consisted of collagen matrix that was less dense and more loosely oriented compared to the vertically oriented fibers more proximal (Nakamura et al., 2001).

4.9.4 | Vascularization and innervation

No information on vascularity of the ulnar collateral ligament could be identified. The innervation of the ulnar collateral ligament was found to be consistent with the meniscus homologue (Ohmori & Azuma, 1998). Free nerve endings without myelin sheaths, bulb endings enabling position, movement and vibration sensation, such as Meissner's corpuscles and Krause's corpuscles (articular corpuscles) and axons enclosed with Schwann cells were observed in all investigated cases (Ohmori & Azuma, 1998).

4.10 | Prestyloid recess

4.10.1 | Terminology

The prestyloid recess was never included as a component of the TFCC, yet it was frequently described due to the close relation with the TFCC. The terminology was completely uniform with prestyloid recess ($n = 6$) (Benjamin et al., 1990; Ishii et al., 1998; Nakamura et al., 1996; Nakamura & Yabe, 2000; Shigemitsu et al., 2007; Totterman & Miller, 1995).

4.10.2 | Anatomy and histology

The prestyloid recess was defined as a synovial space (Nakamura & Yabe, 2000; Shigemitsu et al., 2007; Zhan, Li, et al., 2017). The recess was triangularly shaped in the coronal plane (Nakamura et al., 1996).

Studies by Nakamura et al. (1996) and Zhan, Li, et al. (2017) located the recess between the articular disc and the meniscus homologue. Zhan, Li, et al. (2017) further specified this location as in between the attachments of those two structures to the ulnar styloid. Two other studies by Nakamura and Yabe (2000) and Shigemitsu et al. (2007) defined the recess as being located inside the meniscus homologue.

The prestyloid recess connected the radiocarpal joint space with the tip of the ulnar styloid (Nakamura & Yabe, 2000). According to Totterman and Miller (1995), the prestyloid recess did not communicate with the loose connective tissue in between the two bands of the radioulnar ligaments that separately attached to the ulnar styloid tip and base. Although, a study by Shigemitsu et al. (2007) identified the well vascularized ligamentum subcruentum to be located deeply in the prestyloid recess.

On the contrary, Ishii et al. observed that the communication of the prestyloid recess with different joint spaces depended on the type of opening (Ishii et al., 1998). The authors subdivided the opening of the prestyloid recess in a narrow, a wide or absent opening (Ishii et al., 1998). In wrists with a narrow and wide type opening, the prestyloid recess communicated with ulnocarpal joint space through a long slim tunnel from the palmar side of the ulnar styloid and through a short thick tunnel from the ulnar styloid tip, respectively (Ishii et al., 1998). In wrists with no opening, the prestyloid recess communicated with the distal radioulnar joint space instead of the ulnocarpal joint space (Ishii et al., 1998).

5 | DISCUSSION

5.1 | TFCC composition

In current anatomical literature that stated the composition of the TFCC, the articular disc, dorsal and volar radioulnar ligaments, meniscus homologue and extensor carpi ulnaris (sub)sheath were unanimously classified as TFCC components. Only one study did not include the ulnolunate and ulnotriquetral ligaments as a TFCC component (Shigemitsu et al., 2007) and therefore these ligaments also appear to be considered as a TFCC component. The ligamentum subcruentum was classified as a TFCC component in only one study (Shigemitsu et al., 2007) and therefore it does not appear to be considered as a TFCC component. Rather than the subdivision into specific individual components, only one study preferred the subdivision into a proximal fan-shaped triangular ligament component, a distal hammock-like component and an ulnar collateral ligament component (Nakamura et al., 1996).

The most profound disagreement existed regarding the inclusion of the ulnar collateral ligament as a TFCC component. Three studies did not include this ligament in their definitions (Rein et al., 2015; Semisch et al., 2016; Totterman & Miller, 1995). Two other studies even referred to the structure as a thickening of the ulnar wrist joint capsule rather than a ligament (Ishii et al., 1998; Nakamura & Yabe, 2000). Only three studies included the ulnar collateral ligament (Nakamura et al., 1996; Shigemitsu et al., 2007; Zhan, Li, et al., 2017).

However, four studies that were excluded, due to lack of disease information of the examined wrist, included the ulnar collateral ligament as a TFCC component (Lubowitz et al., 1993; Mikic, 1989; Palmer & Werner, 1981; Taleisnik, 1976). Therefore, inclusion of the ulnar collateral ligament as a TFCC component remains debatable.

Two other studies that were excluded due to the lack of disease information on the examined wrists specifically stated the short radiocarpal or the short radiolunate ligaments as a component of the TFCC (Corner, 1898; Sasao et al., 2003). Both ligaments had a similar proximal attachment to the distal radius and distal attachment to the lunate bone (Corner, 1898; Sasao et al., 2003). However, the short radiolunate ligament as described by Sasao et al. (2003), did not have an additional attachment to the volar rim of the articular disc as opposed to the short radiocarpal ligament described by Corner (1898) (Corner, 1898; Sasao et al., 2003). According to Sasao et al. (2003), the ligament might be assigned to the ulnolunate ligament in former studies since the ulnolunate ligament overlapped the short radioulnar ligament on the volar side (Sasao et al., 2003).

5.2 | Terminology

The term “triangular fibrocartilage complex” (TFCC) was consistent within anatomical studies. Only some earlier anatomical studies that were excluded in the present study, referred to the TFCC as the “ulnocarpal complex” or the “medial carpal ligament complex” instead (Lubowitz et al., 1993; Taleisnik et al., 1984). Regarding the central, fibrocartilaginous disc of the complex, the most commonly used term was the “articular disc.” Often, it was also referred to as the “triangular fibrocartilage” (TFC). However, in line with Lubowitz et al. (1993) we consider this term to be confusing with the term “triangular fibrocartilage complex” (TFCC) and therefore advise to use the term “articular disc.”

Regarding the ulnar attachment of the TFCC, frequently, a split into two separate bundles termed “laminae” with individual attachments was described. These bundles were referred to with a variety of terms. Some studies named them “proximal” and “distal” lamina, while other studies used the terms “upper” and “lower,” or “superficial” and “deep.” Even studies that used the same terms, had different anatomical definitions of the attachment sites of the laminae. Consensus regarding these terms should be established, especially, since different parts of the ulnar attachment appear to play different, yet important roles in stabilization of the distal radioulnar joint (Haugstvedt et al., 2006). Considering “upper and lower” or “superficial and deep” leave room for different interpretation in wrist anatomy, we advise to use the term “proximal and distal” lamina.

In the more older literature the term “the triangular ligament” was used to refer to the entire TFCC (Garcia-Elias & Domenech-Mateu, 1987). After individual components of different histological substances were distinguished within this complex, this terminology was considered as incorrect and has been disputed (Garcia-Elias & Domenech-Mateu, 1987). Later on, two studies in this review provided the term “the triangular ligament” for the fibers that were

actually connecting the radius with the ulna (Nakamura et al., 1996; Nakamura & Makita, 2000). In addition, one additional study used the term “triangular ligament” to refer to the ulnar attachment fibers from the disc specifically (Zhan, Li, et al., 2017). Therefore, in order to prevent confusion and based on the more frequently used term “radioulnar ligaments” we suggest to use this term instead and avoid the term “triangular ligament.”

The ligamentum subcruentum does not appear to be a ligamentous structure. Yet, the fiber bundles attaching to the fovea are frequently interpreted as identical to the ligamentum subcruentum (Atzei & Luchetti, 2011). We consider this interpretation to be incorrect and the “ligamentum” part of the definition proves to be a misnomer. The “subcruentum” part, which is derived from the Latin word for “somewhat bloody” (Lewis, 1907), proves to be accurate and a term as “subcruent tissue” would appear more precise. Considering the term “ligamentum subcruentum” is widely established we accept that changing this would create more confusion, nevertheless it is important to realize the ambiguity of this term.

5.3 | Anatomical definitions

The included studies did not find disc perforations under the age of 20–45 years old (Mikic, 1978; Viegas & Ballantyne, 1987). These studies have contributed to the general assumption that perforations are either traumatic or degenerative and not congenital (Palmer, 1989). Meanwhile, a study that was excluded based on missing disease information, found wrist perforations in all age ranges, from newborns to elderly (Weigl & Spira, 1969). In the absence of degenerative changes in subjects younger than 40 years, these apparently congenital perforations were always found to occur symmetrically and to be located on the border between the radial and middle third of the disc, at its thinnest point (Weigl & Spira, 1969). In a cadaveric study on fetal and infant wrists, 16 out of 60 (26%) showed slit, oval or circular disc perforations at the exact same location, of which 11 were bilateral (Tan et al., 1995). Additionally, when bilateral wrists were studied, perforations on both sides even can be reported in around 60% of subjects with a TFC perforation (Lee et al., 2004; Viegas et al., 1993). This suggests the potential occurrence of congenital perforations. If an additional category of congenital TFC perforations turns out to be prevalent in a younger population as well, this could have clinical consequences in deciding upon surgical treatment of Palmer 2A injury, indicating a traumatic central disc perforation (Palmer, 1989). A proper study on a large number of wrists of young individuals to settle this contradicting literature, would therefore be indicated.

The origin of the ulnar attachment fibers showed ambiguity (Table 3). The majority of the included studies considered the attachment to the ulna as fibers deriving from the radioulnar ligaments (Chidgey et al., 1991; Ekenstam & Hagert, 1985; Horiuchi et al., 2020; Ishii et al., 1998; Maniglio et al., 2020; Nakamura et al., 2001; Nakamura & Yabe, 2000; Saka et al., 2021; Shigemitsu et al., 2007; Shin et al., 2017; Totterman & Miller, 1995). One of those studies found only several additional fibers directly connecting the ulnar part

of the disc with the ulna (Totterman & Miller, 1995), while two other studies considered the ulnar attachment of the TFCC as fibers extending from the disc, as well as the radioulnar ligament (Benjamin et al., 1990; Zhan, Li, et al., 2017). Two studies considered the attachment to the ulna to be part of neither the disc, nor of the ligaments enclosing the distal part of the disc (i.e., radioulnar ligaments), but rather to be part of the proximal ligamentous component or triangular ligament (Nakamura et al., 1996; Nakamura & Makita, 2000). Together with the prior mentioned consensus regarding the terminology, consensus on the derivative of the ulnar attachment is important in further understanding of the biomechanical properties of the complex and future studies should clarify this ambiguity.

Inconsistency within anatomical literature also appears to exist in the ulnar attachment location sites (Table 3). The majority of the studies described two individual ulnar attachments and these were located at slightly varying locations being (1) the ulnar styloid base, the fovea, or the ulnar side of the ulnar head and (2) along the styloid process, at the styloid base, the radial side of the ulnar styloid process with or without its tip, or the entire styloid process (Chidgey et al., 1991; Ekenstam & Hagert, 1985; Maniglio et al., 2020; Nakamura et al., 2001; Nakamura & Yabe, 2000; Shigemitsu et al., 2007; Shin et al., 2017; Totterman & Miller, 1995; Zhan, Li, et al., 2017). By contrast, one study found one conjoint attachment from the ulnar head through to the lateral side of the styloid process (Benjamin et al., 1990). Also, three other studies found just one ulnar attachment, located at the fovea (Ishii et al., 1998; Nakamura et al., 1996; Nakamura & Makita, 2000). While the two most recent studies specifically focused on the ulnar styloid attachments and reported a new concept of a dorsal to a volar shift from the proximal toward the distal ulnar styloid (Horiuchi et al., 2020; Saka et al., 2021). Especially since the current literature is proposing additional modifications on Palmer's initial injury classification with special focus on the ulnar attachments, it seems important to clarify its exact anatomy (Atzei & Luchetti, 2011; Zhan et al., 2020).

More distal extensions of the articular disc and radioulnar ligaments were described by few studies and the attachment sites varied from the extensor carpi ulnaris (sub)sheath to the meniscus homologue, ulnar capsule or ulnar collateral ligament (Benjamin et al., 1990; Chidgey et al., 1991; Ishii et al., 1998; Nakamura & Yabe, 2000). The attachment sites of the meniscus homologue, in turn, also widely varied between studies (Benjamin et al., 1990; Ishii et al., 1998; Nakamura et al., 2001; Nakamura & Yabe, 2000; Nishikawa & Toh, 2002; Shigemitsu et al., 2007; Totterman & Miller, 1995; Zhan, Li, et al., 2017). Therefore, the distal attachment sites of the articular disc and the radioulnar ligaments, as well as the anatomical substrates of the structures where the attachment sites are supposed to be located, remain unclear (Table 3).

From anatomical studies that were excluded from the present review due to missing disease data, early studies generally reported the ulnar collateral ligament as a true ligament (Kuhlmann et al., 1985; Lubowitz et al., 1993; Mayfield et al., 1976; Mikic, 1989; Pachucki & Meznik, 1988; Palmer & Werner, 1981). Only one recent anatomical study that was excluded supported the results from Zhan, Li, et al. (2017) and claimed that the ulnar collateral ligament was a true

TABLE 3 Remaining crucial ambiguity regarding the ulnar attachment of the radioulnar ligaments

Study	Ulnar attachment fiber origin	Two separate ulnar attachments			
		Proximal ulnar attachment	Distal ulnar attachment	One conjoint ulnar attachment	Additional distal attachment
Ekenstam & Hagert, 1985	RULs	Styloid base	Along the styloid process	No	No
Benjamin et al., 1990	Articular disc and RULs	No	No	ulnar head through to radial side of styloid process (by upper lamina)	ECU (sub)sheath (by dorsal RUL and lower lamina) and UCL (by lower lamina)
Chidgey et al., 1991	RULs	Ulnar side of the ulnar head	Surrounded ulnar styloid process	No	ECU (sub)sheath (partly extended into by distal bundle)
Totterman & Miller, 1995	RULs (some additional fibers from ulnar margin of the articular disc)	Base of styloid process	Tip of styloid process	No	No
Nakamura et al., 1996	Triangular ligament	Fovea	No	No	No
Ishii et al., 1998	RULs	Ulnar styloid base (by deep RUL)	No	No	Distal ulnar capsule (by superficial RUL)
Nakamura & Yabe, 2000	RULs	Fovea	Styloid base	No	MH (transited into by distal disc fibers)
Nakamura & Makita, 2000	Proximal ligamentous complex (formerly triangular ligament)	Fovea	No	No	No
Nakamura et al., 2001	RULs	Fovea	Styloid base	No	No
Shigemitsu et al., 2007	RULs	Fovea	Styloid base	No	No
Shin et al., 2017	RULs	Fovea (by deep RUL)	Radial side of styloid process (by superficial RUL)	No	No
H. L. Zhan et al., 2017	Articular disc and RULs	Fovea (by articular disc)	Styloid process including the tip (by articular disc)	Styloid process base (by RULs)	No
Maniglio et al., 2020	RULs	Fovea extending to or with accessory footprint at proximal 81% of styloid process (by deep RUL)	Distal 13% of styloid process (by superficial RUL)	No	No
Horiuchi et al., 2020	RULs	Not stated ^a	Dorsal part of middle 1/3 of styloid process transiting into the volar part of the distal 1/3 of styloid process (by superficial RUL)	No	No
Saka et al., 2021	RULs	Not stated ^a	Dorsal side of styloid process	No	No

Abbreviations: ECU, extensor carpi ulnaris; MH, meniscus homologue; RUL, radioulnar ligament, UCL, ulnar collateral ligament.

^aThese attachments were not assessed in the study and therefore not stated.

ligament (Turker et al., 2019). Nonetheless, this claim was based on gross anatomical dissections in 12 cadaver wrists and positive immunohistochemical staining for collagen type I in one cadaver wrist. Two excluded anatomical studies rather supported the observations from

Ishii et al. (1998) and Nakamura et al. (2001) by reporting that the structure consisted of a joint capsule thickening (Taleisnik, 1976; Taleisnik et al., 1984). Two other excluded anatomical studies considered it to consist of the extensor carpi ulnaris sheath floor and

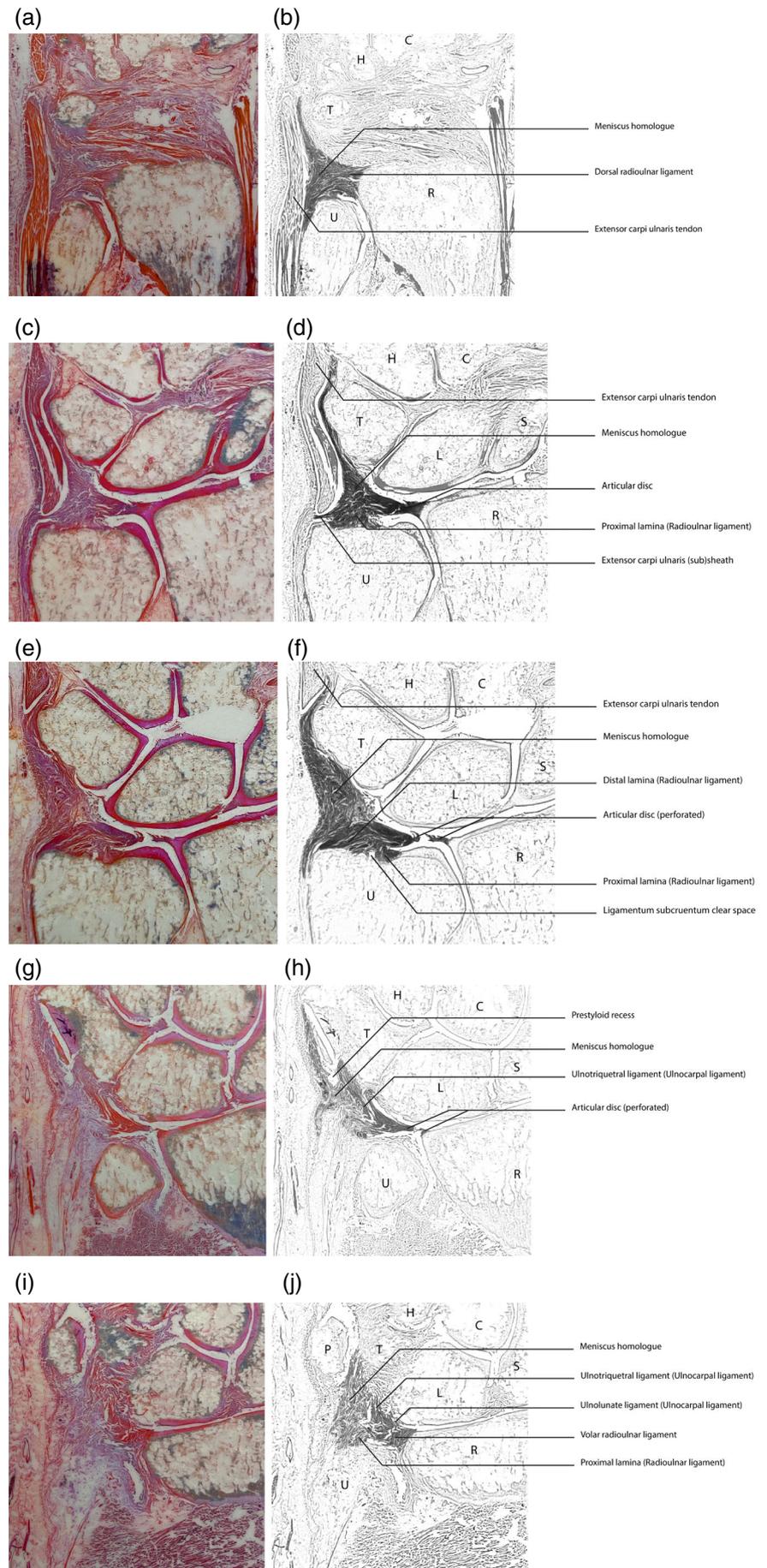
TABLE 4 Proposition of TFCC composition with recommended terminology and morphological definitions

TFCC component	Anatomical definition		
	Morphology	Attachments	Histology
Articular disc	A structure that macroscopically appears continuous with the distal radius cartilage, has a triangular shape in the axial plane, is thinner radially while thicker ulnarly and at the radial attachment in the coronal plane and occasionally can be perforated	A broad cartilaginous radial attachment to the sigmoid notch of the radius, with no or only some fibers attaching to the ulna	Fibrocartilage with densely packed, interlaced collagen fibers and some elastic fibers, with an avascular central part (80%) and radial attachment
Radioulnar ligaments	Two ligaments that connect the radius with the ulna, located dorsally and volarly from and enclosing the disc, of which they are macroscopically distinguishable by palpation only	Broad bony radial attachments to the dorsal and volar borders of the sigmoid notch of the radius and two ulnar attachments being one by the proximal lamina to the fovea and one by the distal lamina to the ulnar styloid with a proximal to distal transition from dorsal to volar, separated by highly vascularized and innervated loose connective tissue called the ligamentum subcrurum	Radioulnar oriented parallel collagen fibers, being collagen I and III, with a lower collagen I:III ratio in the proximal lamina than in the distal lamina, both well vascularized and innervated
Meniscus homologue	A structure extending from the distal part of the articular disc with a meniscus-like appearance in the coronal view and close relation to the distal radioulnar ligament	A distal attachment at the triquetrum, the ulnar wrist joint capsule and sometimes even the fifth metacarpal base and the hamate bone, a proximal attachment of varying shape to the styloid process	Irregular shaped tissue formed by loose connective tissue with loose parallel as well as mixed tight collagen fibers which is well vascularized and innervated
Ulnolunate ligament	Volar ligament connecting the distal ulna to the lunate bone	A proximal attachment to the volar radioulnar ligament with varying additional fibers attaching to the articular disc/distal radius and a distal attachment to the volar part of lunate bone in a fan-shaped form	Parallel oriented densely packed collagen fibers with less interposed loose connective tissue, less vascularized and limited innervation
Ulnotriquetral ligament	Volar ligament connecting the distal ulna to the triquetral bone	A proximal attachment to the volar radioulnar ligament with varying additional fibers attaching to the articular disc/ulnar styloid base/meniscus homologue and a distal attachment to the volar part of the triquetral bone in fan-shaped form with a more oblique direction	Parallel oriented less densely packed collagen fibers with more interposed loose connective tissue, well vascularized and innervated
Extensor carpi ulnaris (sub)sheath	The sheath surrounding the extensor carpi ulnaris tendon	The floor of the sheath blends with the ulnar wrist joint capsule, has a bony attachment to dorsal-ulnar part of the ulnar styloid process through to its base and an attachment to the dorsal side of the triquetrum	Mixed loose and tight parallel collagen fiber bundles that are vascularized and richly innervated

therefore supported the view of Nakamura et al. (1996) and Shigemitsu et al. (2007) (Mizuseki & Ikuta, 1989; Sasao et al., 2003). In conclusion, it appears quite likely that the ulnar collateral ligament is not a

distinct structure and therefore we suggest not to use the term “ulnar collateral ligament” nor to consider it as a component of the TFCC in further research.

FIGURE 2 Coronal sections through the TFCC of a human cadaver wrist without reported wrist pain or history of wrist injury (50 um slice thickness and Mallory/Cason staining) from dorsal to volar indicating (A, B) the dorsal radioulnar ligament, (C, D) a small part of the extensor carpi ulnaris tendon sheath, (E, F) the centrally perforated articular disc, the proximal and distal lamina with the clear space in which the vascular tissue of the ligamentum subcruentum is situated in between the lamina, the meniscus homologue, (G, H) the prestyloid recess, the ulnotriquetral ligament and (I, J) the ulnolunate ligament and volar radioulnar ligament



Even though the prestyloid recess was not considered a component of the TFCC, it was frequently described in the anatomical studies on the complex (Benjamin et al., 1990; Ishii et al., 1998; Nakamura et al., 1996; Nakamura & Yabe, 2000; Shigemitsu et al., 2007; Totterman & Miller, 1995). Nakamura and Yabe (2000) found that the prestyloid recess connected radiocarpal joint space with the tip of the ulnar styloid, while Ishii et al. (1998) found that the prestyloid recess communicated with the ulnocarpal joint space or the distal radioulnar joint space, depending on the type of opening (Ishii et al., 1998; Nakamura & Yabe, 2000). Several excluded anatomical studies also described different shapes and opening types of the prestyloid recess within wrists, which have been acknowledged as pitfalls in diagnostic magnetic resonance imaging (Buck et al., 2009; Burns et al., 2011; Lewis et al., 1970; Mikic, 1989). However, communications between the prestyloid recess and the distal radioulnar joint space are currently interpreted as TFCC perforations (Yoshioka & Burns, 2012). It therefore seems important to recognize that these communications could, in fact, be based on anatomical variance.

5.4 | Study quality and limitations

The major complicating factor of this review was the lack of information on the specimen's disease status included in the anatomical studies. We decided to initially exclude all studies that did not provide any information on the disease status since this is a major risk for bias when assessing anatomical structures (Henry et al., 2016). The studies that were included however, showed divergent disease statements (Table 1). Some studies excluded wrists with degeneration and/or articular disc perforation, while other studies only excluded wrists with a history of disease or trauma. For future morphological studies, we therefore emphasize the importance of elaborately reporting disease status and inclusion criteria of the examined cadavers.

The major methodological limitation of this scoping review was the fact that data extraction was performed by one reviewer. Due to the comprehensiveness of the descriptive data included in the present review, it was unachievable to have data extracted by two reviewers independently and have the data merged in a later stage. The results of the present study, therefore may have been subjected to personal interpretation of descriptive data. Yet, the entire review team has been closely involved in reporting of the results and raw anatomical data were collected as much as possible.

We realize that for descriptive anatomy to be useful in medical settings, it should be focused on clinical relevance. By including specialists with high levels of expertise from different sub-specialisms (i.e., anatomy, radiology, and hand surgery) in the review team, we have attempted to provide an anatomical review that is clinically relevant. In order to reach consensus on clinically relevant anatomy however, the terminology should be unequivocal and undisputed (Chmielewski, 2020). Consensus regarding clinically relevant anatomy is generally established by the Delphi approach (Henry et al., 2017). Therefore, the present study can only provide recommendations as the first step in the process of reaching clinically relevant definitions.

5.5 | Proposition of TFCC composition with definitions

The results of this review indicate that the TFCC is a structure without clear anatomical demarcations of its individual components. For unequivocal and uniform interpretation and communication of pathology however, clear anatomical demarcation is a prerequisite. Defining the individual components of this complex appears to be in the eye of the beholder and has previously been subjected to arbitrariness. Based on the current review, we have to conclude that crucial ambiguity still exists on several definitions (Table 3). Nonetheless, we can propose a concise and clear definition of the healthy TFCC by stating the individual components with uniform terminology and morphological definitions, to be used as a starting point for future studies and clinical practice (Table 4). Illustrative histological sections through the TFCC of an adult human cadaver wrist without reported wrist pain or history of wrist injury indicating these individual components are depicted in Figure 2. It should be kept in mind that this proposition has required making concessions in reaching uniformity. Future anatomical research of the TFCC should focus on resolving these ambiguities.

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