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In Vivo Three-dimensional Morphological Assessment of Adult Knee Menisci: A Computed Tomography-based Approach

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Abstract. *Aim: The present study aimed to examine meniscal morphology in an adult population in vivo through computed tomographic images, including research into morphological differences related to osteoarthritis, ageing and the meniscal location within the knee joint and a proposal for a supplementation of the current morphological classification. Materials and Methods: Computed tomographic images of the knee for 118 patients were retrieved from the picture archiving and communication system of our Institute and included in this retrospective study. Each meniscus was subject to manual segmentation and converted into three-dimensional surfaces. The degree of osteoarthritis was determined for both the medial and lateral compartments of the knee. Statistical analysis was performed to search for any morphological difference related to osteoarthritis, ageing or the meniscal location within the knee joint. Furthermore, additional subcategories of the current morphological classification were proposed and applied to each meniscal reconstruction. Results: We did not observe the presence of discoid or V-shaped menisci. No statistically significant difference was found related to osteoarthritis, ageing or the meniscal location within the knee joint. A prevalence of morphological subcategories indicating a symmetry of the width of the anterior and posterior horns, both with rounded shape, emerged. Conclusion: Taking advantage of non-invasive imaging, this research gives new insights into the morphology of knee menisci in an adult population in vivo. Discoid menisci were rare in our sample and the frequency of V-shaped menisci may have been overestimated in previous studies. Osteoarthritis and ageing may not influence meniscal morphology and no significant morphological differences between lateral and medial menisci were observed. The suggested classification integrates the currently used meniscal morphological classification, increasing the quantity of anatomical information on the menisci of the knee joint, thus improving diagnosis and patient treatment.*

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The menisci of the knee joint are important functional structures able to improve both joint congruence and load distribution, and in this way reduce the stress on joints, a function considered fundamental in protecting the articular cartilage and preventing osteoarthritis (1). Knowledge of the morphological variations of the normal meniscus may help to differentiate between normal and pathological menisci. Moreover, the different shapes of the meniscus might predispose to meniscal tear, as reported for discoid meniscus (2-4). Therefore, the study of the morphology and the morphometry of the menisci of the knee joint is invaluable in understanding meniscal anatomy, which is necessary for a clinical diagnosis and the planning of surgical procedures, including arthroscopy and meniscal transplant surgeries (5, 6). Several works have already focused on morphological and morphometric examination of the knee menisci of human cadavers, or *in vivo* through magnetic resonance imaging (6-11). The current morphological classification was developed in 2006 by Kale *et al*. through the direct observation of menisci from neonatal cadavers; the different shapes defined were: Incomplete and complete discoid (A and B types, respectively), and crescent- (C-type), sickle- (D-type), C- (E-type), U- (F-type) and V- (G-type) shaped (Figure 1) (9). The

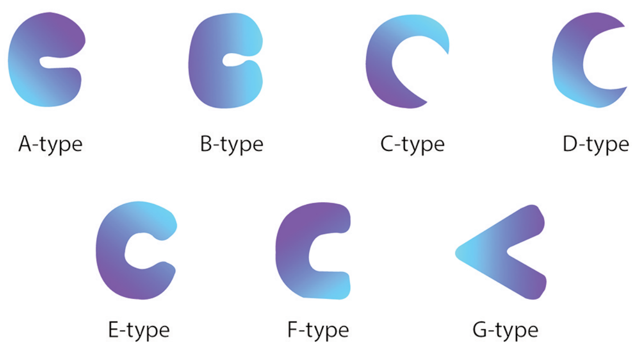

Figure 1. *Kale's morphological classification of the menisci. The shapes of the menisci in newborns according to Kale's classification (9) are illustrated. A-type: Incomplete discoid; B-type: complete discoid; C-type: crescentic-shaped; D-type: sickle-shaped; E type: C-shaped; F-type: sided U-shaped; G-type: V-shaped.*

Table I. *Computed tomography protocol. Standard protocols for computed tomography angiography (CTA) and (CT) of the knee and lower extremity. The reported parameters were customized to patients according to their build and CARE Dose 4D corrections (12).*

Scan parameters	Lower extremity CTA	Knee CT
Scan mode	Helical	Helical
Field of view, mm	463	268
Helical pitch	0.6	0.8
Tube potential, kV	120	120
Tube current×rotation time, mAs	85	200
Slice thickness, mm	1	1
Slice increment, mm	0.7	0.8
Reconstruction filter	B26f medium smooth ASA	B30s medium smooth
Window	CT-Angio	Mediastinum

Table II. *Morphological comparison of meniscal shapes between groups according to osteoarthritis, age, and meniscal location. No significant differences were found.*

		Meniscal shape			
Factor		Crescent (C-type)	Sickle-shaped (D-type)	C-Shaped (E-type)	U-Shaped (F-type)
Osteoarthritis*	U	69.5	71	65	53
	p-Value	0.92716	0.96596	0.69854	0.27303
Age group**	X^2	0.004505	0.5544	4.262	3.045
	p-Value	0.9972	0.755	0.0998	0.1745
Laterality*	U	68	51.5	65	53
	p-Value	0.82986	0.24522	0.70061	0.27183

*Mann-Whitney *U*-test. **Kruskal-Wallis H-test.

present study aimed to examine meniscal morphology in the adult population *in vivo* through computed tomography (CT) images, including research of differences related to osteoarthritis, ageing or the meniscal location within the knee joint and proposal of a supplementation of the current morphological classification.

Materials and Methods

Study subjects. Inclusion criteria: A total of 340 CT images, including 254 CT angiographies (CTAs) of the lower extremities and 86 CTs of the knee, were retrieved from the Picture Archiving and Communication System of our Institute for potential inclusion in this retrospective study. Patients undergoing CTA had been examined for the suspicion of vascular diseases without any clinical report of articular complaint; CTs of the knee had been performed for both traumatic and non-traumatic articular pathology. Of these CT examinations, only those in which there were intact menisci, and an adequate CT protocol were included in the study, as described in the next section.

Exclusion criteria: Exclusion criteria were a non-compliant CT protocol, any artefact degrading the quality of the image, any previous knee surgery, osteoarthritis too severe to allow adequate visualization of the meniscus, meniscal tears and intra-articular fractures; moreover, for patients undergoing multiple CT scans, we only examined the qualitatively best examination excluding the others; lastly, patients over 75 years of age were excluded due to the probability of joint degenerations too serious to be analyzed. In conclusion, a total of 222 CT scans were excluded (Figure 2).

Final study population: A total of 118 patients (98 male and 20 females, between 15 and 72 years) met the inclusion criteria and constituted the final study population (mean age±SD=52±19). The total number of menisci evaluated was 418 (102 right lateral, 102 right medial, 107 left medial and 107 left lateral).

CT protocols. Patients were scanned on a Siemens Somatom Definition AS 128-slice CT scanner or on Siemens Somatom Definition 64-slice CT scanner. The standard CTA and CT protocols of the knee and lower extremities are described in Table I; however, the reported parameters were customized for

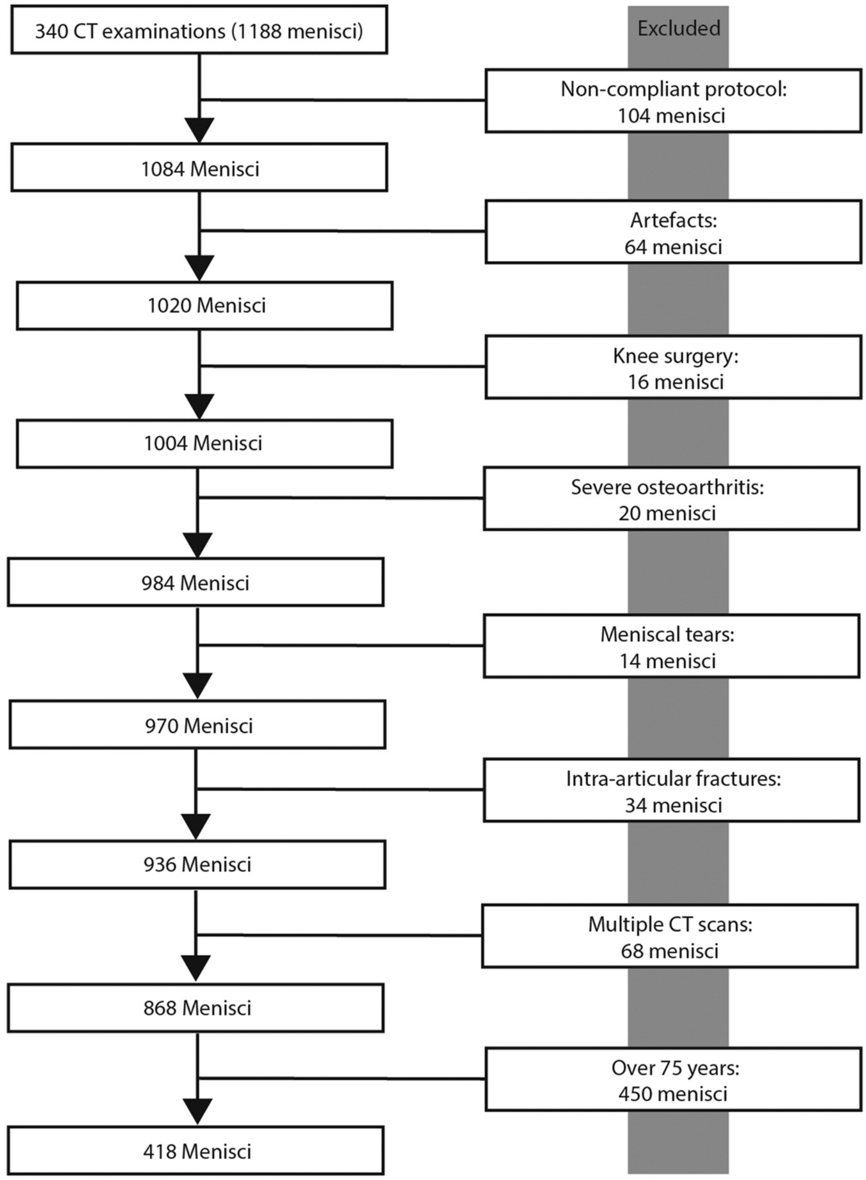

Figure 2. *Study flowchart criteria. For patients undergoing multiple Computed tomography (CT) scans, we only examined the qualitatively best examination excluding the others. Patients over 75 years of age were excluded due to the probability of serious joint degeneration.*

individual patients according to their constitution and CARE Dose 4D corrections (12).

Data gathering. A fourth-year radiology resident (Reader 1) performed manual segmentation of each meniscus using the open-source medical image computing platform 3DSlicer 4.8 (slicer.org) (13). For each meniscus, segmented contours were automatically converted to three-dimensional surfaces with subsequent smoothing, using the tools "Show 3D", "joint smoothing" and "closing (fill holes)" with a 0.50 smoothing factor and a 3.00 mm kernel size respectively (Figure 3).

To evaluate morphological variation related to osteoarthritis, Reader 1 and Reader 2 were asked to independently assign an

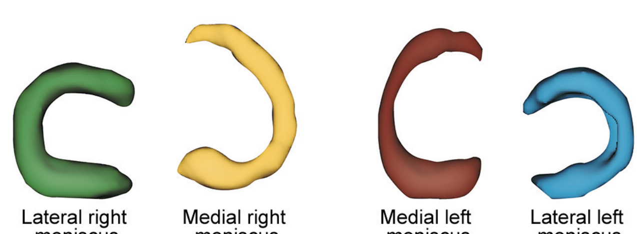

Figure 3. *Three-dimensional reconstruction of menisci. An example is shown of the three-dimensional reconstruction of the menisci automatically obtained from the manually segmented contours through the open-source medical image computing platform 3DSlicer (13).*

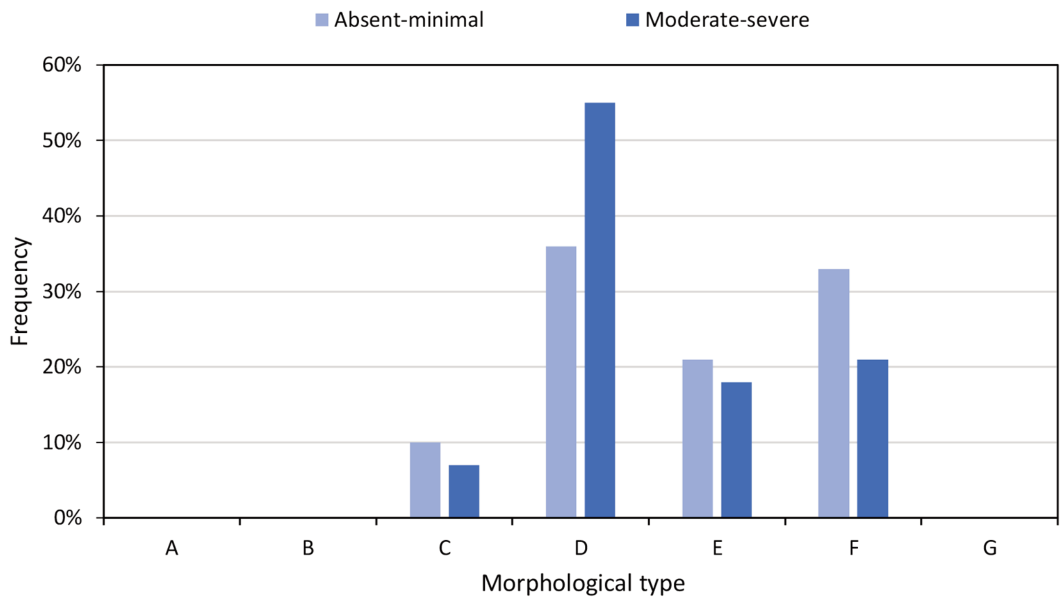

Figure 4. *Distribution of meniscal morphology according to Kale's classification in individuals with absent-minimal and moderate-severe osteoarthritis.*

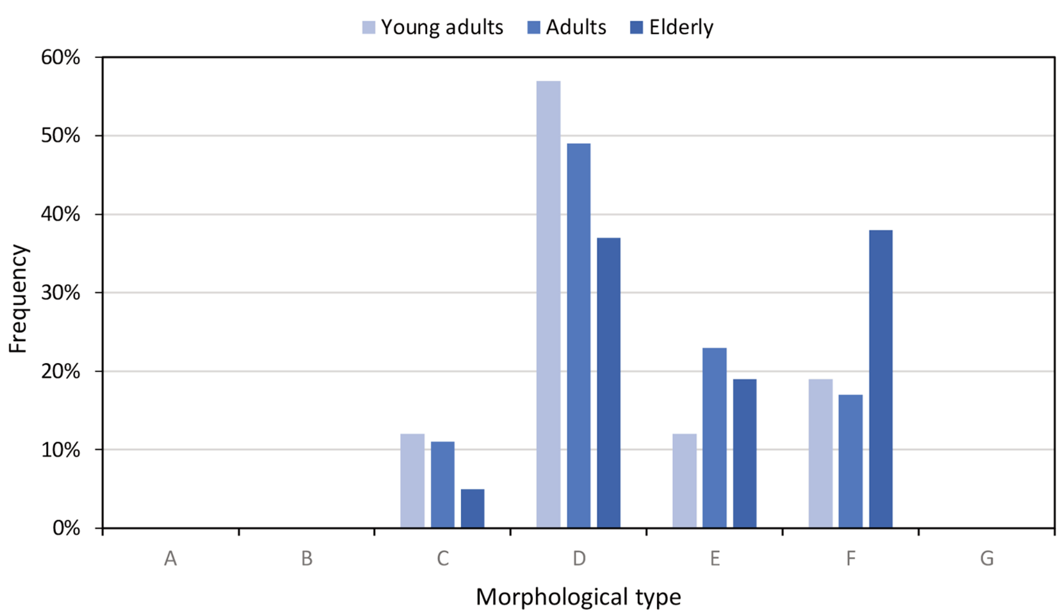

Figure 5. *Distribution of meniscal morphology according to Kale's classification in young adults (15-44 years of age), adults (45-64 years of age), and the elderly (>64 years of age).*

absent-to-minimal or moderate-to-severe degree of osteoarthritis for both the medial and lateral femorotibial compartments of each knee joint by observing the coronal reconstruction of each CT scan, following the criteria defined by the Kellgren and Lawrence system to classify osteoarthritis on radiographic examination (14). In fact, the absent-minimal degree includes Kellgren and Lawrence grades 0-2, while the moderate-severe degree includes grades 3-4. The few menisci in which a discrepancy emerged on the degree of the assigned osteoarthritis were reassessed by the two readers together to find a consensus view.

To examine morphological differences related to ageing, patients were divided into three age groups: Young adults (15-44 years of age), adults (45-64 years of age), and the elderly (>64 years of age) (15).

To allow the comparison between the meniscal shapes according

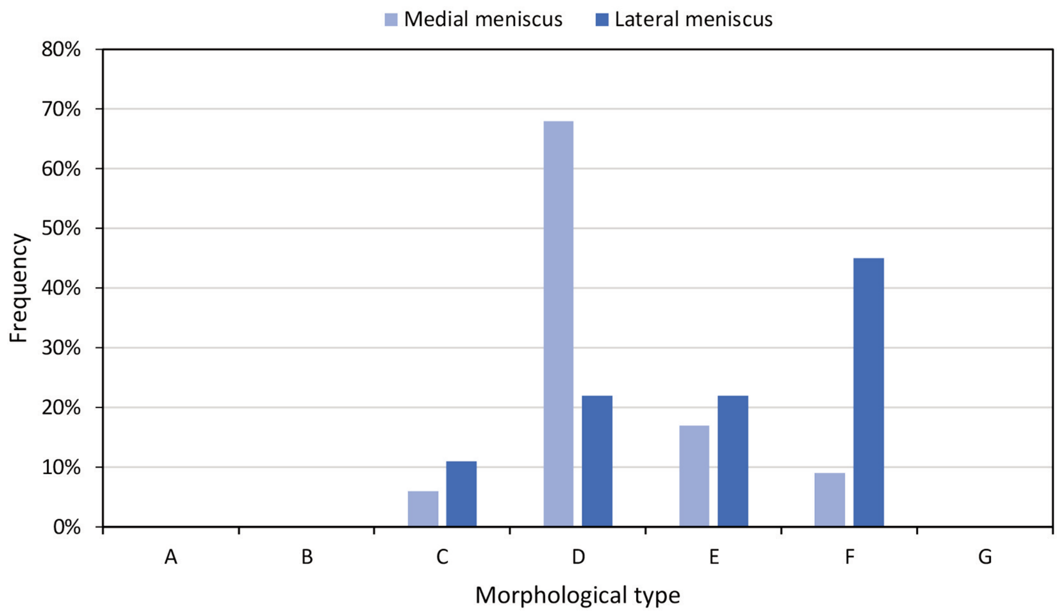

Figure 6. *Distribution of meniscal morphology in medial and lateral menisci according to Kale's classification.*

to the location within the knee joint, the menisci were divided into medial and lateral meniscal groups.

Finally, a revision of the current morphological classification, based on the anatomical variations described by Kale *et al*. (9), was finally proposed by an expert musculoskeletal radiologist (more than 10 years of experience in musculoskeletal imaging) observing the three-dimensional meniscal images. To examine the incidence of each meniscal morphological type in the adult population, Reader 1 and a second-year radiology resident (Reader 2) independently classified the shape of the three-dimensional meniscal reconstructions, according to the modified classification. The few menisci in which a discrepancy emerged for the assigned meniscal shape were reassessed by the two Readers together to find a consensus view.

Statistical analysis. Normality of the data distribution was tested *via* Shapiro-Wilk test. Because of the nonparametric data, the comparison of the meniscal shape between osteoarthritic and non-osteoarthritic knee joints and between lateral and medial menisci was performed through the Mann-Whitney *U*-test, while among the three age groups was performed with the Kruskal-Wallis *H*-test. A value of $p \leq 0.05$ was considered statistically significant.

Statistical analyses were performed using the open-source statistical analysis software Past 4.03 (https://folk.universitetetioslo.no/ohammer/past) (16).

Results

Incidence and comparisons. In our study, we did not observe the presence of the meniscal shapes classified by Kale *et al*. as incomplete discoid (A-type), complete discoid (B-type), or V-shaped (G-type). The distribution of the other meniscal shapes is reported in Figure 4, Figure 5 and Figure 6 according to osteoarthritis, age group, and meniscal location, respectively. No statistically significant difference was found according to osteoarthritis, age or meniscal location, as reported in Table II.

Modified Kale's classification. The current morphological classification by Kale *et al*. divides the shapes of the menisci into incomplete and complete discoid (A and B types, respectively), and crescent- (C-type), sickle- (D-type), C- (E-type), U- (F-type) and V- (G-type) shaped menisci, as depicted in Figure 1 (9). Our proposed classification consists of its subcategorization with two letters and two numbers. The first letter corresponds to the original Kale's classification, *i.e*. A: incomplete discoid; B: complete discoid; C: crescent-shaped; D: sickle-shaped; E: C-shaped; F: U-shaped; G: V-shaped (9). Regarding the second letter, 'A' was assigned to menisci in which the anterior third was visually wider than the posterior one, 'P' to menisci in which the posterior third was visually wider than the anterior one, and 'S' to menisci in which there were no visually appreciable differences in width between the anterior and posterior thirds. In addition, for both the anterior and posterior horns, a number was assigned in accordance with their shape: 1 for a pointed shape, and 2 for a rounded shape; the first number always referring to the anterior horn, while the second to the posterior horn (Figure 7). Table III reports the distribution of these subcategorizations for our dataset, where a prevalence of subcategories indicating a symmetry of the width of the anterior and posterior horns, both with rounded shape, emerged.

Table III. *Distribution of meniscal morphological variations according to the modified Kale classification. The table displays the incidence in our dataset of each subcategory of meniscal morphology according to our modification of Kale's classification with subcategorization using two letters and two numbers. The first letter corresponds to the original Kale classification, i.e. A: incomplete discoid; B: complete discoid; C: crescent-shaped; D: sickle-shaped; E: C-shaped; F: U-shaped; G: V-shaped (9). Regarding the second letter, A: anterior third visually wider than the posterior; P: posterior third visually wider than the anterior; S: no visually appreciable difference in width between anterior and posterior thirds. In addition, a number was assigned for both horns (anterior followed by posterior): 1 pointed shape; 2: rounded shape; the first number always referring to the horn, while the second to the horn. The predominance of subcategories indicating symmetry of the width of the anterior and posterior horns, both with rounded shape, is apparent (shown in bold).*

Kale class	Modified Kale classification	Absolute number	Percentage distribution (%)
A		0	–
B		0	–
C	CA (1-1)	3	9%
	CA (1-2)	0	–
	CA (2-2)	4	11%
	CA (2-1)	3	9%
	CP (1-1)	0	–
	CP (1-2)	3	9%
	CP (2-2)	0	–
	CP (2-1)	0	–
	CS (1-1)	3	9%
	CS (1-2)	1	–
	CS (2-2)	**16**	**46%**
	CS (2-1)	2	6%
D	DA (1-1)	3	2%
	DA (1-2)	1	–
	DA (2-2)	3	2%
	DA (2-1)	7	4%
	DP (1-1)	9	5%
	DP (1-2)	43	23%
	DP (2-2)	19	10%
	DP (2-1)	3	2%
	DS (1-1)	25	13%
	DS (1-2)	20	11%
	DS (2-2)	**47**	**25%**
	DS (2-1)	9	5%
E	EA (1-1)	1	1%
	EA (1-2)	2	2%
	EA (2-2)	3	4%
	EA (2-1)	5	6%
	EP (1-1)	1	1%
	EP (1-2)	8	10%
	EP (2-2)	3	4%
	EP (2-1)	0	–
	ES (1-1)	4	5%
	ES (1-2)	16	20%
	ES (2-2)	**35**	**44%**
	ES (2-1)	2	2%
F	FA (1-1)	4	3%
	FA (1-2)	0	–
	FA (2-2)	9	8%
	FA (2-1)	5	4%
	FP (1-1)	0	–
	FP (1-2)	9	8%
	FP (2-2)	1	1%
	FP (2-1)	0	–
	FS (1-1)	1	1%
	FS (1-2)	17	15%
	FS (2-2)	**59**	**52%**
	FS (2-1)	9	8%
G		0	–

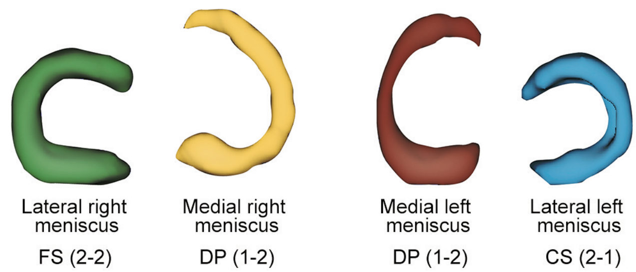

Figure 7. *Modified Kale's morphological classification of the menisci. An example of the modified Kale's classification applied to three-dimensional meniscal reconstruction. This classification uses a two-letter two-number system. In the example here, the lateral right meniscus has a U-shape and is assigned F as the first letter according to Kale's classification. There were no visually appreciable differences in width between the anterior and posterior meniscal thirds, therefore S is assigned as the second letter. Since both anterior and posterior horns are rounded, both are assigned the number 2. The medial right and left menisci have a sickle-shape (corresponding to D), a visually wider posterior third (corresponding to P), a pointed anterior horn (assigned 1) and a rounded posterior horn (assigned 2). The lateral left meniscus has a crescent shape (corresponding to C), no visually appreciable differences in width between the anterior and posterior meniscal thirds (assigned S), a rounded anterior horn (assigned 2) and a pointed posterior horn (assigned 1).*

Discussion

Knowledge of the anatomy of the human body is a fundamental component of medical science and practice and undergoes constant growth linked to the development of methods. In this research, indirect observation of the menisci through the manual segmentation of CT images was the key to highlighting the feasibility of supplementing the standard Kale's classification with additional findings *in vivo*.

Compared to previous articles, which examined meniscal morphology in adult cadavers, we observed a comparable incidence of A and B types (Table IV) (8, 11, 17, 18). In accordance with other recent studies, our results confirm the large variability of incidence of the other meniscal morphologies (C-F types) (8, 11, 17, 18). Interestingly, we did not observe any G-type meniscal shape. The possible explanation for this finding is twofold. Firstly, it is a rare variant, as was also shown in other studies, where the frequency found was between 0 and 38% (Table IV) (8, 11, 17, 18). Secondly, morphological assessment is not an objective measurement. In fact, according to Kale's classification, the G-type is overall characterized by a V shape (9). Moreover, in the example figure reported by Kale *et al.*, a V shape can be traced for both the inner and outer meniscal edges (9). However, in the menisci classified as a G-type by other authors, the V shape can only be traced for the inner border (7, 11, 17). For these reasons, we speculated

Table IV. *Comparison of current results with previous studies. The table displays the incidence of the morphological variations of the medial and lateral menisci reported in our and previous studies. The meniscal shapes were classified according to Kale et al. as follows: A: Incomplete discoid; B: complete discoid; C: crescent; D: sickle-shaped; E: C-shaped; F: U-shaped; G: V-shaped (9).*

Meniscus	Meniscal shape	Our study	Murlimanju *et al*. (17)	Itagi *et al*. (8)	Shashidar and Sridevi (11)	El Aasar *et al*. (18)
Medial	A	0%	0%	5%	0%	0%
	B	0%	0%	0%	0%	0%
	C	26%	38.9	0%	46%	92%
	D	22%	0%	0%	0%	8%
	E	22%	61.1	88.33%	0%	0%
	F	45%	0%	6.66%	14%	0%
	G	0%	0%	0%	38%	0%
Lateral	A	0%	0%	0%	0%	0%
	B	0%	0%	0%	2%	0%
	C	6%	50%	96.6%	28%	84%
	D	68%	0%	1.66%	0%	0%
	E	17%	0%	0%	72%	0%
	F	19%	11.1%	0%	0%	16%
	G	0%	38.9%	1.66%	0%	0%

that the G-type morphology may have been overestimated in previous studies.

Regarding the incidence of different meniscal morphologies according to osteoarthritis, we observed a difference in the proportion of individual meniscal shapes between absent-minimal and moderate-severe osteoarthritis (Figure 4 and Table II). The D-type was the most frequent meniscal shape in both groups, with a higher incidence in those with moderate-severe osteoarthritis. The remaining C-, E- and F-morphological types had higher incidence in the group with no or only minimal osteoarthritis. However, these differences did not reach statistical significance, thus suggesting that knee osteoarthritis may not affect meniscal morphology.

Concerning the incidence of different morphologies according to age, the D-type variant was the most frequent shape in under 64-year-olds while D and F types were the most common shapes in the over 64-year-olds (Figure 5). No significant difference was shown among young adults, adults, and the elderly regarding meniscal morphology (Table II). These findings suggest that ageing may not influence meniscal morphology. Interestingly, no additional meniscal shapes emerged in our study, not even in the elderly population, in agreement with the work of Tsujii *et al*. work, which concluded that the aged meniscus is not deformed and visually appears almost normal (19).

We did not find any significant morphological difference related to meniscal location within the knee joint, suggesting that the distribution of meniscal shapes is similar in the medial and lateral femorotibial compartment of adults (Figure 6 and Table II).

Finally, we proposed a modification of Kale's classification by considering the variability of the width and shape (pointed or rounded) of the anterior and posterior horns. For each meniscal shape classified by Kale *et al.,* in our dataset we found subcategories indicating a symmetry of the width of the anterior and posterior horns, both with rounded shape to be most prevalent (Table III) (9). These results suggest a predominance of width symmetry and rounded shape of both meniscal horns.

To the best of our knowledge, our work appears to be the first to evaluate different meniscal shapes *in vivo* with diagnostic imaging in adult humans, which is essential in daily clinical practice to recognize pathological findings properly and possibly help surgical planning.

Our study has some limitations. Firstly, despite the relatively large sample size, it does not represent an ideal population. In fact, very severe osteoarthritis, and patients over 75 years of age were excluded due the limited usefulness of imaging, which would not have allowed a reliable segmentation of overly degenerated menisci. Secondly, our study was retrospective and based on CT and CTA scans. We are aware that our results need to be tested prospectively with other imaging methods, such as magnetic resonance imaging and possibly with a cadaveric comparison.

Conclusion

V-Shaped (G-type) meniscal morphology was not found in our *in vivo* dataset and may have been overestimated in the previous studies. Moreover, no discoid menisci (A and B types) were identified, confirming the very low incidence of this morphological type. A large variability of incidence was found for the other meniscal morphologies (C-F types).

Osteoarthritis, ageing and meniscal location do not affect meniscal morphology nor Kale's classification.

An awareness of both the variability of anterior and posterior horn width and shape (pointed or rounded) and the prevalence of width symmetry and rounded shape of the meniscal horns may provide new insights into the anatomy of knee menisci, thus improving the diagnosis and patient treatment.

Conflicts of Interest

The Authors declare that they have no conflicts of interest.

Authors' Contributions

All Authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Maria Grazia Chiarilli, Andrea Delli Pizzi, Piero Chiacchiaretta and Andrea Prattichizzo. The first draft of the article was written by Maria Grazia Chiarilli. All Authors commented on previous versions of the article and read and approved the final article.

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