Radiography 27 (2021) 108–114

Contents lists available at ScienceDirect

Radiography

journal homepage: www.elsevier.com/locate/radi

Application of knee MRI in forensic age estimation: A retrospective cohort

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ARTICLE INFO

Article history:
Received 30 March 2020
Received in revised form
23 June 2020
Accepted 24 June 2020
Available online 14 July 2020

Keywords:
Forensics
MRI
Knee
Diagnostics
Epiphysis

ABSTRACT

Introduction: Forensic age estimation is performed via clinical examination and utilizing various imaging modalities. Currently, radiography and CT are used. In this study we aim to evaluate if magnetic resonance imaging (MRI) can be used to determine stages of fusion in the epiphysis of the tibia and femur, and if these stages are significantly different regarding the mean age of subjects classified in each one.
Methods: A total of 193 subjects were included in the study. Knee MR imaging was performed on all of the patients, and the patients were categorized based on imaging findings of the tibial and femoral epiphysis. Tukey multiple comparison test and analysis of variance were used to assess if the difference in the mean age of the groups were significantly different.
Results: Analysis of variance revealed that the mean of the five groups, both in tibia and femur imaging were significantly different. Analysis of variance showed that in most of the cases, the groups mean age significantly differed from the other groups. Tukey multiple comparison tests showed that although the differences between stages I–III could not be regarded as significant, MR imaging was suitable in distinguishing stages IV–V from stages I–III.
Conclusion: MR imaging of the knee may be a suitable imaging modality to assess an individual's age, does not involve ionizing radiation, and that with imaging a single anatomical location, at least two epiphyses could be used to determine the age.
Implications for practice: Utilization of knee MRI by clinicians as a safe and practical age estimation method.

Introduction

Forensic age diagnostics is an ever-growing field in forensic medicine and diagnostic radiology sciences, which is involved with estimating an individual's age utilizing anatomical landmarks that undergo stepwise changes during the process of ageing. Age estimation is routinely used for legal purposes, as individuals gain criminal liability at a specific age.[1] In many countries, individuals are subject to other laws which have different age limits compared to criminal law, such as criminal responsibility laws, family law and social law in European countries, marriage law, inheritance law and family law in Muslim majority countries and other examples in penal systems worldwide.[2]

More so, the increase in immigration has led to individuals with no documentation in need of specialized legal, medicinal and human services, which some countries are obligated to provide for individuals under a certain age. Because of this, studies are undertaking new diagnostic methods to improve age detection.

The Study Group on Forensic Age Diagnostics for age estimation in living individuals in criminal proceedings has suggested that forensic age estimation should include the following: a physical examination with determination of height, weight, signs of sexual maturation and developmental disorders in children, X-ray of the

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https://doi.org/10.1016/j.radi.2020.06.019
1078-8174/

left hand, dental examination both by X-rays and physical examination (Orthopantomogram) and finally, an X-ray or computed tomography scan of the clavicle in individuals with completed skeletal development.[3] Although the use of the methods mentioned above has been widely accepted, limitations remain regarding the radiation doses acquired because of these procedures. Because of this, strict indications exist for obtaining imaging for non-medical purposes.[4] Another possible limitation of using X-ray images may be the existence of various models of estimation based on different atlases of previous imaging, which could be confusing.[5]

Introduction of new imaging modalities has led physicians to consider safer imaging techniques for forensic age estimation. Magnetic resonance imaging (MRI) is perhaps the most promising method currently being considered, not only for forensic age estimation but for other forensic medicine applications, such as post-mortem imaging.[6] The ankle, the wrists, the clavicle and finally, the knee joint have all been candidates for MRI imaging.[7] The knee joint has shown exceptional promise in this regard. The distal femur and proximal tibia contain epiphyseal growth plates, which undergo physiological changes during young adult years. These stepwise physiological changes are documented and classified into five categories by O, Connor et al.[8] Cross sectional studies have shown that each of these stages, termed union stages, happen at certain ages.[9] Early studies used X-rays to study the epiphysis and were able to obtain promising results, but limitations remained regarding the sensitivity of X-ray studies incorrectly detecting union stages. Because of this MRI was chosen as a possible alternative. Previous studies had shown that MRI was indeed useful in the study of evolving epiphysis, and pathologic insults to the epiphyseal plate.[10] Studies were also able to apply the 5 stage model presented for epiphyseal maturation to MRI imaging.[11] Initial studies performed on populations from France, Germany,[12] Egypt[13] and China[14] have shown promise. However, questions remain regarding the technical aspects of imaging, the effect of race and sex on MR findings and the generalizability of findings. More so, limited evidence exists regarding the use of MRI for forensic purposes, compared to X-rays and CT-scans.[15] Our aim in the present study is to examine if knee MRI could be used in age estimation, especially in teen years, covering critical age limits such as 16 and 18 years.

Methods

Population

The present study was performed on an Iranian population, who were of Caucasoid race and Iranid type, between April 2016 and April 2019. All of the cases had been referred to a tertiary hospital-outpatient clinics complex for imaging of the knee for legal purposes, and with an indication for imaging determined by legal representatives. Inclusion criteria consisted of age between 15 and 40 years old, and consented to participate in the study. Exclusion criteria consisted of pathologies in the femur and tibia bones, such as epiphyseal tumours, skeletal trauma, infections (septic arthritis or osteomyelitis), congenital dysplasia of the region, patients with a history of chemotherapy, or currently under chemotherapy and the history of prolonged corticosteroid use.

A total of 193 patients were included in the study. The mean age of all of the participants was 26.32 ± 1.1 years old.

MRI examination

MR imaging was performed with a 1.5-T whole-body scanner (Avanto, Siemens, Germany). Technical specifications were as the following: proton density fat sat: TR 2500 MS, TE 39 MS, slice thickness 4 mm, time for each acquisition: 2 min and 20 s and T2 sagittal: TR 4000 MS, TE 71 MS, slice thickness 4 mm, time for each acquisition: 2 min and 10 s. Images were taken in sagittal and coronal planes.

Image analysis

All of the obtained images underwent analysis after the deletion of information such as age, sex and name. Two different radiologists with at least ten years of experience each reviewed the images simultaneously, but separately. Intra-observer variability was determined, with a second interpretation after 30 days. Sagittal and coronal series of all of the cases were studied, and a staging system containing five distinct entities was used to classify the cases.[11] Schmeling et al. first introduced this staging., and later further sub-classifications were added by other scholars.[16,17] We did not use the sub-classifications, as our goal was to study the difference between the mean ages of the original groups introduced by Schmeling et al.[3,18] This classification is presented in Table 1. The images were interpreted based on a pre-determined checklist, which puts the focus on anatomical landmarks, epiphysis characteristics, epiphysis vessels, and the articular cartilage (see Table 2).

In cases of hesitation and disagreement, the mean staging was accepted and included in the analysis.

Statistical analysis

SPSS version 16 was used for statistical analysis. Cohen's kappa non-parametric test was used to evaluate the variabilities of the image analysis. Analysis of variance (ANOVA) was used to evaluate the significance of the difference between the mean ages of the five stages. Tukey multiple comparison tests were used to compare different groups.

Ethical considerations

The regional ethics board of the medical-educational center in which the study was performed approved the present study (96.5.1). All participants had written informed consent notes. This study complied with the Helsinki declaration.

Table 1
Staging system used to categorize epiphyseal change during the maturation process.

Stage	Description
I	Ossification centers have not been ossified, and no fusion exists
II	Ossification centers have ossified, the epiphyseal cartilage has not ossified
III	Partial ossification of epiphyseal cartilage
IV	The epiphyseal scar is seen
V	The epiphyseal scar is not seen

Table 2
Mean age (in years) of achieving fusion in epiphysis based on studies utilizing X-ray images of the knee as the diagnostic method.[9,24]

	Femoral epiphysis		Tibial epiphysis	
	Male	Female	Male	Female
Stage 1	13.8 ± .76	12.9 ± .7	13.9 ± .86	13.2 ± .9
Stage II	16.4 ± 1.8	14.0 ± .9	16.1 ± 2.28	14 ± 1.5
Stage III	18.0 ± 2.7	17.3 ± 2.5	18.0 ± 3.65	17.3 ± 4.5
Stage IV	23 ± 4.45	21.1 ± 3.4	22.1 ± 5.97	21.6 ± 6.0
Stage V	27 ± 3.8	23.8 ± 3.8	27.8 ± 3.3	24.8 ± 3.9

Results

Patients were classified to 5 subgroups based on MRI findings. Fig. 1 and Fig. 2 demonstrate the number of subjects included from each age and sex, and the mean age documented in each fusion stage. Mean age of each of the groups is presented in Table 3. Of all of the patients included, 54 were female, and 139 were male. One-way analysis of variance was performed to assess if the means of the groups were significantly different. The results are summarized in Table 4. As can be seen, in both assessing the femur and tibial epiphysis, the means are significantly different. Tukey HSD analysis was performed to assess if the difference between the means of each group was significant. The results are summarized in Table 5. As it can be seen the difference between the groups is significantly different, except when the group I is compared to group II, Group II to groups I and III, and group III to group II. Tukey HSD was also performed to assess the differences between the five sub-groups of femoral and tibia imaging. The results are summarized in Tables 5 and 6. As it can be seen, the results are consistent with analysis of femoral imaging, except that the difference between group III and group I was not significant.

The interrater reliability rate was assessed via Cohen's κ statistical test. It was shown that Kappa equalled .83 ± .072, which is regarded as excellent agreement. Intra-observer agreement was also assessed. Kappa was .89 ± .037 and .861 ± .021 for the two radiologists ($P < 0.001$). Figs. 3 and 4 are examples of imaging outputs. Fig. 5 is a schematic presentation of the stages of fusion.

Discussion

In the present study, we evaluated tibia and femoral epiphysis in 193 patients. We classified the subjects to 5 groups based on MRI findings and then compared the mean age in each group to the others. The difference was significant in most cases, except in instances of comparing patients in groups I, II and III, where the mean in each group was not statistically significant compared to the next group. Our results show that knee MRI could not sufficiently differentiate a critical limit of 16–18 years, as a wide overlap existed among patients manifesting fusion stages III and IV in femoral and tibial epiphyses. Furthermore, our results failed to show a significant difference between the mean age of stages II and III. The transition between these two stages happens at a critical age (16–20 years), and lack of a significant difference in our results suggests a limited application for MRI of the knee joint in forensic age estimation.

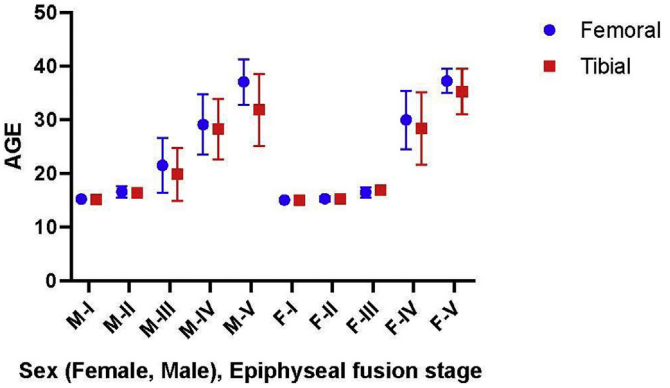
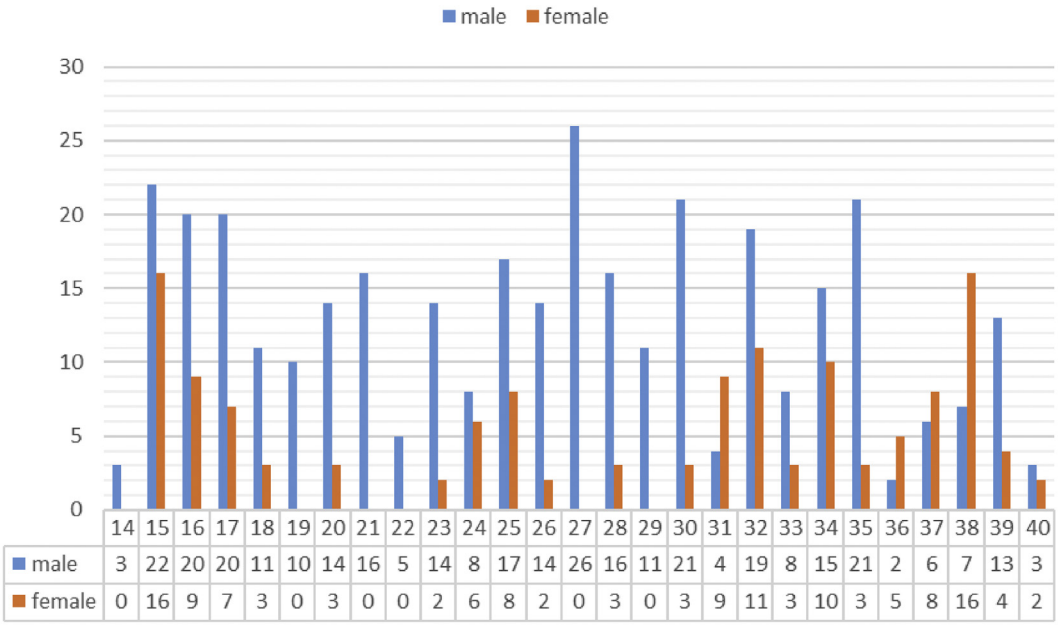


Figure 2. Mean age (in years) of subjects in each stage of fusion.

Hypothetically, using the knee joint to determine the legal age of an individual is possible, as three sets of epiphysis exist in the joints proximity (the femur, tibia and fibula). Early studies used X-rays to perform the necessary imaging. Dogaroiu et al.[9] studied anterior-posterior X-ray images of 173 subjects aged between 13 and 23 years. They used the five stages of union proposed by O′ Connor et al.[8] and classified the subjects to 5 groups. They used linear correlation to assess whether there was a relationship between age and grades of the union and found that there was indeed a strong correlation. O′ Connor et al. were also able to notice differences between the union patterns of the two sexes, as females had union initiate 1.11 years earlier, and the correlation was not as strong for females as it was for males ($r = .829$ and $r = .769$ for distal femur and tibia bones of male subjects, respectively, compared to $r = .816$ and $r = .700$ for distal femur and tibia bones of female subjects,



	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
male	3	22	20	20	11	10	14	16	5	14	8	17	14	26	16	11	21	4	19	8	15	21	2	6	7	13	3
female	0	16	9	7	3	0	3	0	0	2	6	8	2	0	3	0	3	9	11	3	10	3	5	8	16	4	2

Figure 1. Age (in years) of subjects being included in the study.

Table 3
Number of subjects in each of the staging groups, based on femoral and tibial imaging findings.

Sex	Type-Femur	Mean age	Std. Deviation	N	Type tibia	Mean	Std. Deviation	N
female	I	15.00	.000	3	I	15.00	.000	2
	II	15.25	.500	4	II	15.20	.447	5
	III	16.43	.976	7	III	16.80	.837	5
	IV	29.93	5.443	28	IV	28.37	6.710	24
	V	37.17	2.250	12	V	35.22	4.223	18
	Total	27.87	8.761	54	Total	27.87	8.761	54
male	I	15.18	.603	11	I	15.09	.701	11
	II	16.56	1.094	16	II	16.38	.768	13
	III	21.47	5.137	17	III	19.83	4.914	12
	IV	29.08	5.592	93	IV	28.19	5.603	88
	V	37.00	4.243	2	V	31.80	6.635	15
	Total	25.72	7.377	139	Total	25.72	7.377	139

Table 4
Analysis of variance test results of femoral and tibial staging, which shows that the mean age was significantly different between the five groups.

Age					
	Sum of Squares	df	Mean Square	F	Sig.
Femur					
Between Groups	7410.454	4	1852.614	80.111	.000
Within Groups	4347.629	188	23.126		
Total	11,758.083	192			
Tibia					
Between Groups	6655.977	4	1663.994	61.314	.000
Within Groups	5102.106	188	27.139		
Total	11,758.083	192			

Table 5
Tukey test applied to each of the five stages in the femoral epiphysis.

Multiple Comparisons							
	(I) Type-Femur	(J) Type-Femur	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Tukey HSD	I	II	−1.157	1.676	.958	−5.77	3.46
		III	−4.857[a]	1.617	.025	−9.31	-.40
		IV	−14.130[a]	1.358	.000	−17.87	−10.39
		V	−22.000[a]	1.818	.000	−27.01	−16.99
	II	I	1.157	1.676	.958	−3.46	5.77
		III	−3.700	1.456	.086	−7.71	.31
		IV	−12.973[a]	1.161	.000	−16.17	−9.78
		V	−20.843[a]	1.676	.000	−25.46	−16.23
	III	I	4.857[a]	1.617	.025	.40	9.31
		II	3.700	1.456	.086	-.31	7.71
		IV	−9.273[a]	1.075	.000	−12.23	−6.31
		V	−17.143[a]	1.617	.000	−21.60	−12.69
	IV	I	14.130[a]	1.358	.000	10.39	17.87
		II	12.973[a]	1.161	.000	9.78	16.17
		III	9.273[a]	1.075	.000	6.31	12.23
		V	−7.870[a]	1.358	.000	−11.61	−4.13
	V	I	22.000[a]	1.818	.000	16.99	27.01
		II	20.843[a]	1.676	.000	16.23	25.46
		III	17.143[a]	1.617	.000	12.69	21.60
		IV	7.870[a]	1.358	.000	4.13	11.61

[a] The mean difference is significant at the .05 level.

respectively).[8] In this study, only patients between 13 and 23 years of age were included, and X-ray had limited sensitivity in detecting any further changes happening after that age. Another critical issue was the limitation of burdening subjects with radiation. All of the subjects included in the study done by O′ Connor et al. were those chosen by a legal order to undergo imaging, and legal authorization was obtained to perform the imaging. Compared to our study, the study by O' Connor et al. included more patients in the critical juncture of 16–20 years but did not include older patients. We were not able to show a significant difference in mean ages of fusion stages II–III, although this could have been caused by our studies innate limitations in design and implementation.

More recent studies have utilized MRI in knee imaging, as it is more sensitive to epiphyseal alterations during bone maturation. Alaa El-Din et al. studied 355 Egyptian patients aged between 8 and 28 years old, and classified them into the five subgroups above, and then compared male and female patients, based on the mean age of each sub-group. They also recorded the earliest age at which specific landmarks were seen in the MRI scans. They suggested that the difference was not significant in stages I–III, but was significant in

Table 6
Tukey test applied to each of the five stages in the tibial epiphysis.

Multiple Comparisons							
Dependent Variable: Age							
	(I) Type tibia	(J)Type tibia	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Tukey HSD	I	II	-.979	1.896	.986	−6.20	4.24
		III	−3.864	1.919	.264	−9.15	1.42
		IV	−13.155[a]	1.526	.000	−17.36	−8.95
		V	−18.590[a]	1.706	.000	−23.29	−13.89
	II	I	.979	1.896	.986	−4.24	6.20
		III	−2.886	1.762	.475	−7.74	1.97
		IV	−12.177[a]	1.323	.000	−15.82	−8.53
		V	−17.611[a]	1.526	.000	−21.82	−13.41
	III	I	3.864	1.919	.264	−1.42	9.15
		II	2.886	1.762	.475	−1.97	7.74
		IV	−9.291[a]	1.356	.000	−13.03	−5.56
		V	−14.725[a]	1.555	.000	−19.01	−10.44
	IV	I	13.155[a]	1.526	.000	8.95	17.36
		II	12.177[a]	1.323	.000	8.53	15.82
		III	9.291[a]	1.356	.000	5.56	13.03
		V	−5.435[a]	1.032	.000	−8.28	−2.59
	V	I	18.590[a]	1.706	.000	13.89	23.29
		II	17.611[a]	1.526	.000	13.41	21.82
		III	14.725[a]	1.555	.000	10.44	19.01
		IV	5.435[a]	1.032	.000	2.59	8.28

[a] The mean difference is significant at the .05 level.

Figure 3. Femoral and Tibial epiphysis in a 16-year-old male subject. The patient was categorized as stage II.

Figure 4. Femoral and Tibial epiphysis of a 32-year male subject. The subject is categorized as stage IV.

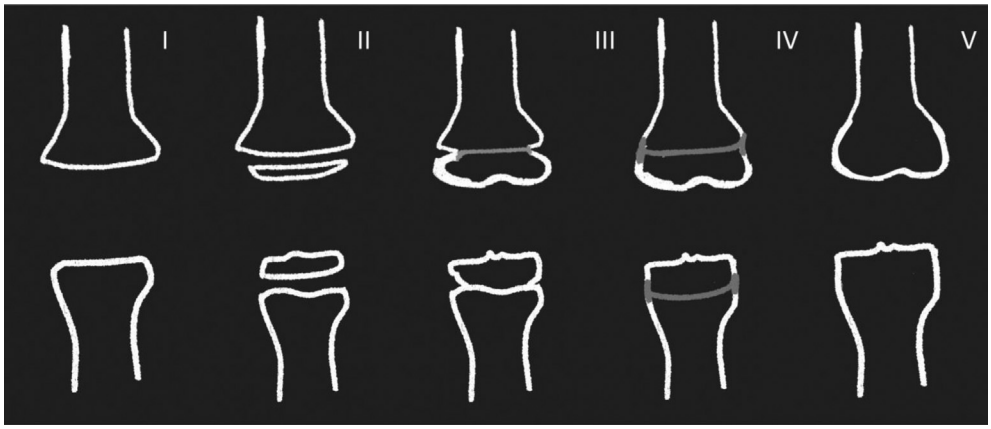


Figure 5. Schematic presentation of stages of fusion in the femur and tibia.

stages IV and V, which included the eldest patients (minimum age of 18 and maximum age of 28). They also agreed with previous studies, as skeletal landmarks were observed in females before males, with complete ossification and union happening in 21–27.8 years of age in females and 24–28 years males.[19] The results of this study are of critical importance, as the targeted population is classified in a similar anthropologic classification as to the Iranian population, and both nations have a similar age-gender pyramid.[20] We also failed to show a significant difference between stages II and III. Interpreting the results of two studies combined may suggest a limited application of MRI in specific racial profiles.

Ottow et al. also found that significant differences existed between the ossification patterns of males and females, as in their study females reached earlier landmarks after the age of 13 years old (the earliest time females reached stages 2c (based on the subclassification introduced by Kellinghaus et al.) was 12.11 years, for 3a 13.39, for 3b 14.73, while the same in males was 12.05, 13.68 and 17.77 respectively).[21] We also reported a similar observation, as females had an earlier onset of fusion compared to males, though no difference was witnessed regarding the significance of the difference in mean ages of stage II–III subjects among genders.

A prospective study conducted by Mauer et al. applied the Jopp staging method on 36 male patients. They conducted three MRI scans in intervals of one year and studied the alterations in imaging compared to the baseline imaging. They found that age 16 was correlated with stage 3 (complete ossification of the epiphysis) and that this staging could be used on all three bones (fibula, femur and tibia). Interestingly, Mauer et al. recorded body measurements such as weight, standing height and sitting height, and witnessed that there was no correlation between them and age, but the scoring of the epiphyses at the knee joint was significantly correlated with age.[12] Galic et al. also reported similar findings. Galic et al. also reported similar findings. These authors had suggested that cut-offs of score of maturation for the knee joint would be beneficial in determining individuals over 18 years old.[22]

Overall, studies performed recently show high potential for knee MRI in forensic age estimation, as it is convenient to interpret and does not burden the patient with radiation exposure. However, more studies are needed to establish if MRI of the Knee can be beneficial in distinguishing critical age limits, such as 16 and 18 years old.[23] Our study also showed that this method could also be used to differentiate the early 30s from the 40s (group IV and V), and also differentiate early teen years from late teen years (group I compared to group III). Noteworthy, skeletal changes accompanying average growth have different milestones in various races, and studies have found considerable differences between different nationalities regarding epiphyseal maturation.[8] However, our results failed to show a significant difference between the mean ages of subjects achieving stage II and III fusion in the femur and tibia. Our study was the first of its kind being performed on the Iranian population, which is located in the middle east and is included in the Caucasian race (the Iranid sub-race). Although we were able to show that the presence of specific radiological findings correlates with specific ages, our findings could not be generalized because of the limited number of subjects included in the study.

Furthermore, our imaging protocols differed from the previously performed studies, which could again limit generalizability. In this study, we included those patients who were referred to obtain forensic imaging, based on legal indications determined by the judiciary or other legal authorities, and we did not include subjects from the general public. Most of our referred subjects were males, and because of the legal framework of forensic age estimation in our setting, a rather limited number of subjects between 14 and 18 years were referred in the first place.

Our findings, however, do show potential to use MRI in forensic investigations. Nevertheless, it is essential to note that MRI was not able to differentiate between stages I–III, making its utilization limited, especially in teen years. Our study was limited by its small sample size, and that it was performed in only one center. Furthermore, we did were not able to sufficiently include patients in critical legal ages, limiting the application of our results to the clinical context.

Large scale prospective multi-center studies will be needed to determine the details mentioned above. Large cohorts targeting specific racial profiles, which include subjects from various ages, especially those between 16 and 20 years, will be needed to make optimal clinical decision making possible.

In conclusion, in this study, a total of 193 patients ageing between 15 and 40 years were included. All of the patients underwent knee MRI and were classified to 5 groups based on epiphyseal findings. The mean age of each group was determined and was compared to other groups mean using Tukey HSD. Our results failed to show a significant difference in the mean age of subjects in fusion stages II–III, corresponding to the critical age of 16–20 years. We did, however, notice that there was a significant difference between the mean ages of stages I–III compared to stages IV–V. More evidence is needed to justify the routine use of MRI of the knee joint in forensic age estimation.

Conflict of interest statement

The authors have no conflicts to declare.

Ethics approval

The study was approved by the local ethics committee of Tabriz University of Medical Sciences (CODE: 3341).

Consent to participate

Written informed consent was obtained from all of the patients.

Consent for publication

Consent was obtained.

Availability of data and material

Data will be available with reasonable reason and request.

Code availability

N/A.

Authors' contributions

Mohammad hossein Daghighi: Study conception, patient selection, overall supervision, Reporting imaging findings.

Masoud Pourisa: Study conception, patient selection, overall supervision, Reporting imaging findings.

Hannaneh Javanpour-Heravi: Reporting imaging findings, Systemic search of the literature, patient selection.

Morteza Ghojazadeh: statistical analysis, manuscript preparation.

Mohammad Mirza-Aghazadeh-Attari: manuscript preparation, study conception, final edit.

Shadi Daghighi: patient selection, final edit, systemic search of literature.

Hossein Jabbari: Statistical analysis. Final edit, drafting of manuscript.

Armin Zarrintan: manuscript preparation, study conception, final edit, reporting of imaging findings.

Acknowledgements

The authors would like to thank the deputy of research of Tabriz University of Medical Sciences. This study and it's results are a part of thesis for obtaining a specialty degree in Diagnostic Radiology, by Dr. Javanpour. Funding was done by Tabriz University of Medical Sciences.

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