Annals of Anatomy 239 (2022) 151794

Contents lists available at ScienceDirect

Annals of Anatomy

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

RESEARCH ARTICLE

Morphological variability of the plantaris muscle origin in human fetuses

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ARTICLE INFO

Article history:
Received 22 April 2021
Received in revised form 10 June 2021
Accepted 10 June 2021
Available online 1 July 2021

Keywords:
Plantaris muscle
Fetuses
Classification
Morphometry

ABSTRACT

Introduction: The plantaris muscle (PM) is a small, fusiform muscle located between the gastrocnemius muscle (GM) and soleus muscle (SM). PM supports movements of the knee and ankle. This muscle presents a great variability, and also has a high clinical significance. Nevertheless, data concerns morphology and morphometry of the origin of PM in human fetuses are scarce.
Material and methods: Forty-seven spontaneously-aborted human fetuses (23 male, 24 female) aged 18–38 weeks of gestation were examined. The morphology and morphometry of the origin of PM were evaluated.
Results: PM was present in 74 lower limbs (78.7%), and absent on 20 limbs (21.3%). We distinguished VI types of the proximal attachment of PM. Belly width and thickness, as well as thickness of the tendon and MT junction differed significantly between types of PM origin.
Conclusions: We distinguished six (I–VI) types of origin of PM in human fetuses. The most common type was type Ia, characterized by an attachment to the lateral head of GM, lateral femoral condyle and to the knee joint capsule. Our results of PM anatomical variation in fetuses will pave the way for detailed comparisons with studies carried out on adult cadavers.

1. Introduction

The plantaris muscle (PM) is a slight muscle, which usually originates from the knee joint capsule, the lateral condyle and the popliteal surface of the femur. It often runs between the gastrocnemius (GM) and soleus muscles (SM) in the posterior compartment of the leg (Rohilla et al., 2013; Vlaic et al., 2019). The belly of PM is short and fusiform, and passes into thin and long tendon, which after crossing the space between GM and SM, attaches to the calcaneal tuberosity (Spina, 2007; Vlaic et al., 2019).

PM supports movements of the knee and ankle. If the foot is not fixed, PM contributes plantar flexion of the ankle, if the foot is fixed it contributes to flexion of the knee. PM is moderately active while walking at ground level or stair climbing (Kots and Dolev, 2013; Spang et al., 2016; Spina, 2007). Nevertheless, none of the above actions can be led by PM alone because of its small cross-sectional area (Spang et al., 2016).

Due to the size and small influences on movement, PM is often dismissed and classified as a kind of vestigial muscle (Rohilla et al., 2013; Spina, 2007). Nonetheless, PM has high clinical significance (Gonera et al., 2020, 2021; Kurtys et al., 2020a; Olewnik et al., 2018c, 2020a,b). An injury of PM always should be considered during differentiating of the painful calf (Spina, 2007). There is the possibility of rupture of PM's belly and tendon at the muscular-tendon junction, which may be classified as *tennis leg*, a term that may also describe rupture of the GM (Helms et al., 1995; Olewnik et al., 2018c; Spina, 2007). Rupture of PM may be confused with deep vein thrombosis, which is much more serious clinically and radiologically (Rohilla et al., 2013). The long tendon of PM is also used in tendon reconstruction or stabilization of the joints (Carlson et al., 1993; Yammine et al., 2019). Moreover, the tendon of PM should be released during the correction in all types of equinus (DeHeer, 2017; Gourdine-Shaw et al., 2010). Therefore, the PM muscle and its morphology do need to be taken into consideration in comparative anatomical and clinical studies, in particular because it presents a great variability. It might be absent in 4–20% of cases, while in some cases it might be double (Aragão et al., 2010; Kotian et al.,

Abbreviations: SM, soleus muscle; PM, plantaris muscle; GM, gastrocnemius muscle.

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https://doi.org/10.1016/j.aanat.2021.151794

2013; Olewnik et al., 2020b; Sinnataby, 1999; Standring, 2005; Yammine et al., 2019). Indeed, both its proximal and distal attachments are highly variable (Olewnik et al., 2020a,b; Spang et al., 2016), as attested by a number of case reports about these attachments (Gonera et al., 2020; Herzog, 2011; Kotian et al., 2013; Kurtys et al., 2020a,b; Olewnik et al., 2017a,b, 2018c, 2020c; Rohilla et al., 2013; Smędra et al., 2020).

However, most of the studies that have focused on this muscle were usually focused on adults, and specifically on the tendon, the type of insertion and the influence on midportion Achilles tendinopathy (Calder et al., 2016; Spang et al., 2016). Therefore, in this study we focus on the morphological variability of PM in human fetuses, using the classification proposed by Olewnik et al. (2020b). By doing this, our study will pave the way for future studies comparing our fetal results with the conditions found in adults.

2. Material and methods

Forty-seven spontaneously-aborted human fetuses (23 male, 24 female) aged 18–38 weeks of gestation were examined. The fetuses were obtained from spontaneous abortion after parental consent and came from the Department of Anatomical Dissection and Donation collection. All aspects of this research were in accordance with the current legal procedures in Poland and in accordance with the program 'Donation Corpse', both concerning adults and fetuses. The ages were determined on the basis of cranio-sacral and head measurements. The Local Bioethics Commission at Medical University of Łódź gave consent for the study (agreement no. RNN/218/20/KE).

A dissection of the leg and foot was performed by traditional techniques (Karauda et al., 2020, 2021; Olewnik et al., 2018a). Firstly, GM was exposed by removing the subcutaneous tissue. Secondly GM was separated from the SM. The next step was to clean the anatomical structures around PM.

Upon dissection, the following features of PM were recorded:

1. Type of PM origin
2. PM morphometric measurements

The thickness and width of PM was measured at its thickest and widest place. Length of the belly was measured from its insert to the muscle-tendon junction. Measurements were carried out with an electronic digital caliper (Mitutoyo Corporation, Kawasaki-shi, Kanagawa, Japan). Each measurement was performed twice with an accuracy of up to 0.01 mm.

2.1. Statistical analysis

The collected measurements of muscle and muscle-tendon junction were compared using the Statistica 13.1 software package (StatSoft, Cracow, Poland). An analysis of variance (one-way ANOVA or Kruskal–Wallis test) followed by post-hoc tests (HSD Tukey) was used to calculate morphological differences. Shapiro–Wilk's W test was used to test the distribution of the studied variables. Comparisons between groups were performed using the Student's t-test (or nonparametric Mann–Whitney U-test) and chi2 test. A value of $p < 0.05$ was considered statistically significant.

3. Results

3.1. Frequency of occurrence of PM

PM was present in 74 lower limbs (78.7%), and absent on 20 limbs (21.3%). PM was absent in eleven males and nine females (ten limbs left and ten right). No significant difference in frequency of absence was observed between sexes ($p = 0.5409$) nor between body sides ($p = 1$) (Table1).

Table 1
Differences in data types with regard to sex and body sides.

Type	Sex		Body side	
	Male	Female	Right	Left
Ia	23 31.1%	15 20.3%	20 27.0%	18 24.3%
Ib	5 6.8%	5 6.8%	4 5.4%	6 8.1%
II	0 0.0%	3 4.1%	1 1.4%	2 2.7%
III	6 8.1%	11 14.9%	9 12.2%	8 10.9%
IV	0 0.0%	2 2.7%	1 1.4%	1 1.4%
V	1 1.4%	0 0.0%	1 1.4%	0 0.0%
VI	0 0.0%	3 4.1%	1 1.4%	2 2.7%
All	35 47.3% p = 0.06256	39 52.7%	37 50.0% p = 0.89730	37 50.0%

3.2. Evaluation of origin of PM

Six key types were distinguished based on the morphology of PM. The type classification was based on the classification of Olewnik et al. (2020b)

1. Type Ia — characterized by an attachment to the lateral head of GM, lateral femoral condyle and to the knee joint capsule. This type was present in 38 lower limbs (51.4%) — Fig. 1.
2. Type Ib — an origin was placed on the lateral head of the GM, lateral femoral condyle, knee joint capsule and the popliteal surface of the femur. This type was present in 10 lower limbs (13.5%) — Fig. 2.
3. Type II — this type was characterized by attachment on the knee joint capsule and to the lateral head of the GM and indirectly to the lateral femoral condyle through the lateral head of the GM. This type was present in three lower limbs (4.1%) — Fig. 3.
4. Type III — origin was located on the lateral femoral condyle and the knee joint capsule. This type was present on 17 limbs (23%) — Fig. 4.
5. Type IV — the origin was located on the lateral femoral condyle, the knee joint capsule and the iliotibial band. This type was observed on two lower limbs (2.7%) — Fig. 5.
6. Type V — the origin was located only on the lateral condyle of the femur. This type was observed on one lower limb (1.4%). — Fig. 6.
7. Type VI — the origin was located on the lateral femoral condyle and the iliotibial band. This type was present on three lower limbs (4.1%). — Fig. 7.

Belly width and thickness and also thickness of the tendon and MT junction differed significantly between types of PM origin. All morphometric measurements of the leg and plantaris muscle are compared according to type of origin in Table 2.

4. Discussion

The key value of the present work is that our investigation is the first study to analyze the morphological variability of PM in numerous human fetuses.

With the purpose of understanding the anatomical variations of such a complex muscle, it is crucial to take into account PM's

Table 2
Mean measurements depending on type of PM with the standard deviation (SD).

	Ia	Ib	II	III	IV	V	VI	p
Leg length [mm]	48.0	47.8	35.8	53.5	45.0	47.7	38.9	0.27359
SD	12.5	6.8	3.6	16.7	5.4		0.7	
Belly length [mm]	12.0	11.3	7.1	11.9	14.0	6.5	9.3	0.22477
SD	4.5	2.4	1.2	3.1	0.5		2.2	
Belly width [mm]	4.3	5.9	2.8	4.8	4.5	1.5	2.4	0.00102
SD	1.3	2.4	0.7	1.3	0.4		0.5	
Belly thickness [mm]	0.9	1.0	0.7	1.2	1.9	0.9	1.3	0.00723
SD	0.3	0.3	0.6	0.5	0.1		0.2	
Width of the tendon and MT junction [mm]	1.1	1.0	0.7	1.0	1.4	0.5	0.6	0.32514
SD	0.4	0.4	0.3	0.6	0.2		0.2	
Thickness of the tendon and MT junction [mm]	0.2	0.3	0.2	0.2	0.5	1.2	0.2	<0.001
SD	0.1	0.1	0.1	0.1	0.1		0.2	

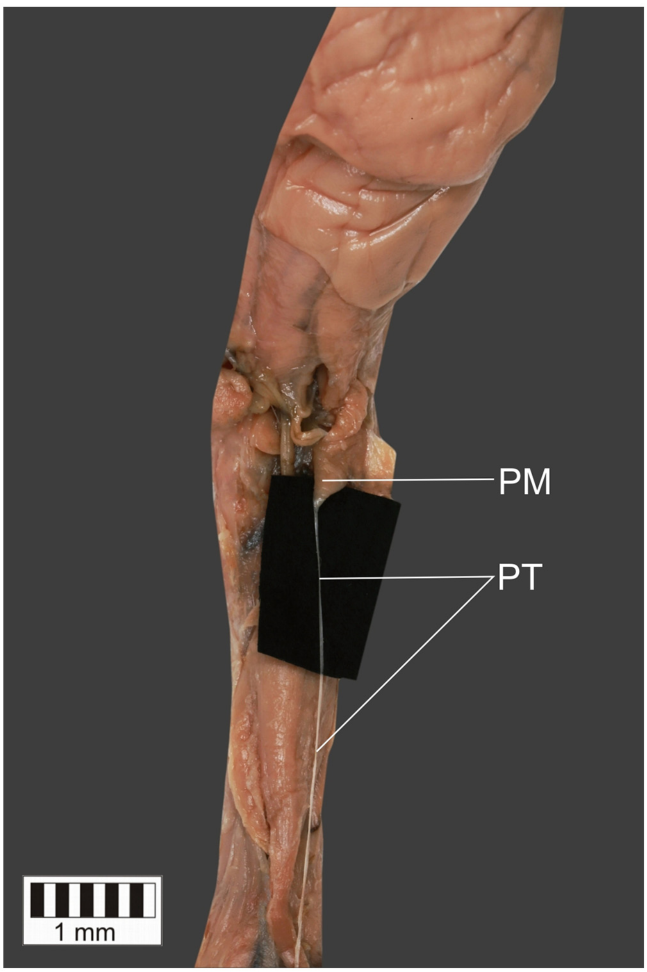

Fig. 1. Type Ia of PM origin.
GM — gastrocnemius muscle, PM — plantaris muscle, PT — plantaris tendon, SM — soleus muscle, TN — tibial nerve.

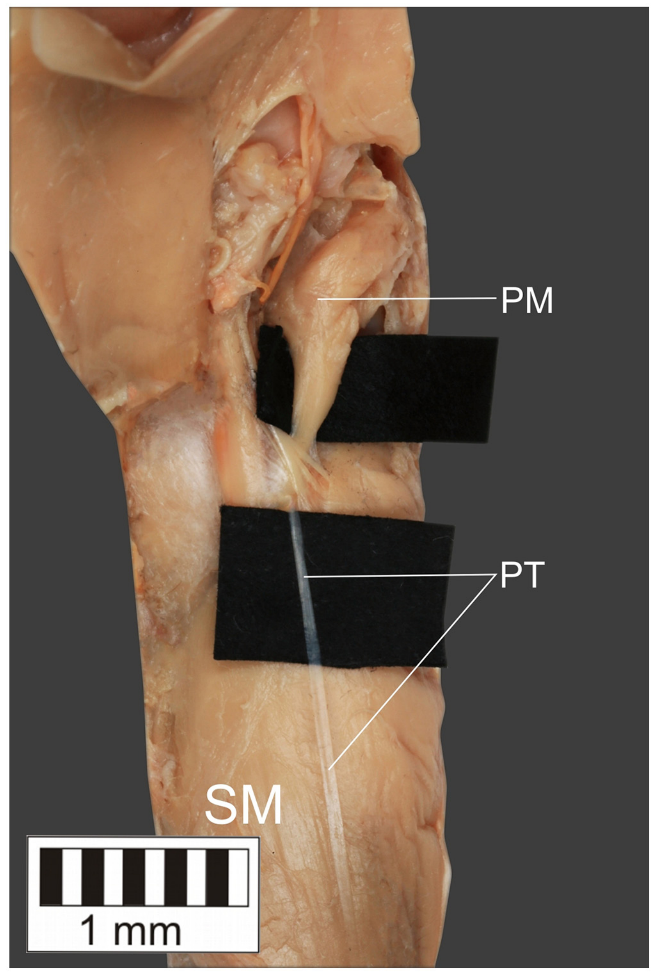

Fig. 2. Type Ib of PM origin.
GM — gastrocnemius muscle, PM — plantaris muscle, PT — plantaris tendon.

embryonic development (Daseler and Anson, 1943). The differentiation of the common flexor mass into the muscle rudiments begins in 11 mm embryos (Boyle et al., 2020; Diogo et al., 2019). The two, separate muscle groups may be visible in an 14 mm embryo: a first, superficial, more lateral group for SM, PM and GM, and a second, deeper and more medial group for the flexor digitorum longus, flexor hallucis longus, popliteus and tibialis posterior muscles (Boyle et al., 2020; Diogo et al., 2019). The gastrocnemius-soleus group connects to the blastema of the calcaneal bone and the two flexor muscles with an aponeurotic “foot-plate” (Boyle et al., 2020; Diogo et al., 2019), The “foot-plate” tendons extend to the blastema for the digitis. The gastrocnemius-soleus group progressively moves from the lateral position to the medial side to attain the tibial attachment. During the second month the two heads of the GM develop. After that, PM splits off from the lateral head of the GM (Marchi et al., 2018). According to Jin et al. in midterm fetuses, the thickness of PM is similar to the thickness of the lateral head of the GM; then the lateral head grows faster than PM and probably takes over the fabella from PM (Jin et al., 2017). Interestingly, Okamoto et al., analyzed PM’s innervation, and suggested that this muscle develops from the deep – not the superficial – posterior crural muscles (Okamoto et al., 2013).

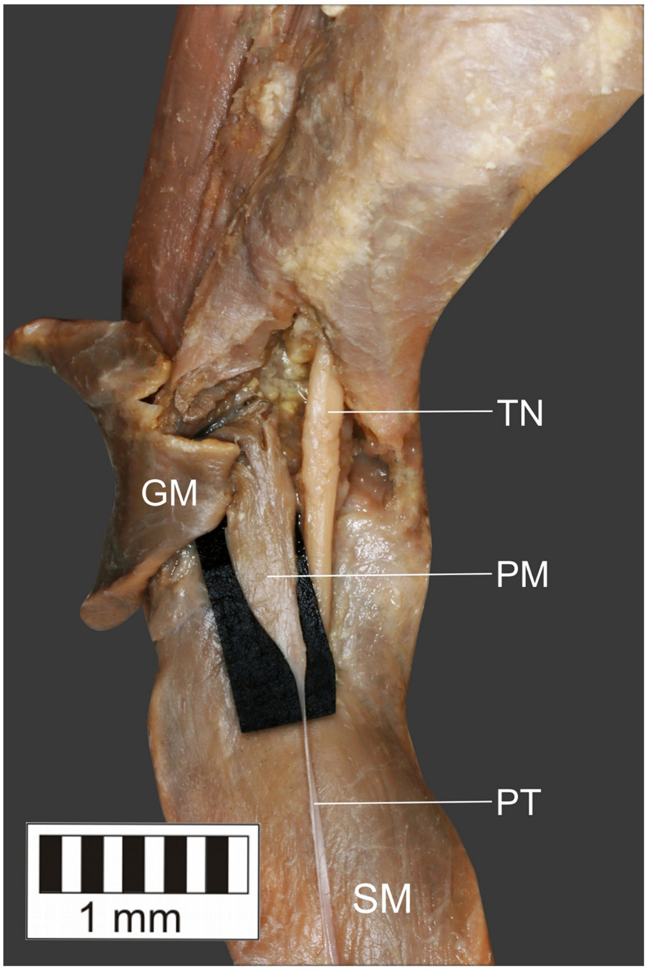

Fig. 3. Type II of PM origin.
LhGM — left head of gastrocnemius muscle, PM — plantaris muscle, PT — plantaris tendon, SM — soleus muscle.

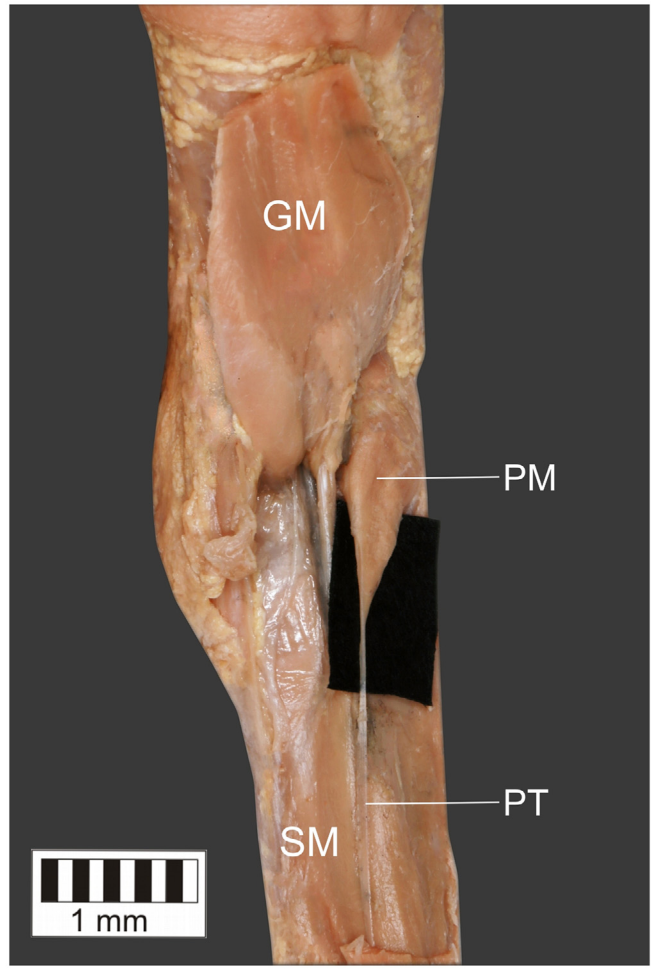

Fig. 4. Type III of PM origin.
PM — plantaris muscle, PT — plantaris tendon, SM — soleus muscle.

Although in human ontogeny PM is the last muscle within the flexor compartment of the leg to differentiate, during evolutionary history this muscle evolved before the flexor hallucis longus and SM (Diogo et al., 2019). In several mammalian species, such as American brown bears or primates, PM is well developed, its insertion to the plantar aponeurosis often helping in the foot grasp (Vlaic et al., 2019). According to Sichting et al., it is likely that in the last common ancestor of all primates there was a PM that was continuous with the plantar aponeurosis (Sichting et al., 2020). Nevertheless, most of present catarhines have the PM bounded to the periosteal structure of the calcaneus. Related to the changes in human evolution, from a quadrupedal to bipedal position, the function of the foot also changed (Ferrero et al., 2012; Sichting et al., 2020), for instance in quadrupedal primates the foot is often used to grasp while in a bipedal posture it is predominantly a support structure, being mainly prependicular to the leg (Vlaic et al., 2019). With these changes, the muscular part of the plantar aponeurosis regressed and inserted onto the lower side of the calcaneus. According to Henle, the evolution of the calcaneal tuberosity was related to PM's insertion moving from the plantar aponeurosis to this tuberosity (Henle, 1871). In some chimpanzees and gorillas a PM might be absent while the plantar aponeurosis is present. In other species of primates, such as capuchin monkeys and red slender lorises, PM is present while the plantar aponeurosis is missing. In humans PM might be missing, while the plantar aponeurosis is consistently present. De-coulping of PM and plantar aponeurosis probably allowed the aponeurosis to stiffen the midfoot, which enhanced propulsive power production during locomotion (Sichting et al., 2020).

According to the literature, PM is absent in 4–20% of adult cases, and in some cases it was present in all investigated adult cadavers (Aragão et al., 2010; Kotian et al., 2013; Sinnataby, 1999; Standring, 2005; Yammine et al., 2019). Also previous studies carried out in our department revealed the absence of PM in 4–10.8% of adult cases (Olewnik et al., 2017a; 2018b; 2020b). Regarding PM in fetuses, the absence of this muscle varies from 9.5%–31.4%: in our study it was 21.3% (Desdicioglu et al., 2015; Szaro et al., 2020; Yıldız et al., 2011). Sometimes the fact that the muscle is so often absent in human adults leads some authors to consider it as a vestigial muscle (Menton, 2000), particularly because biomechanically, it has only small influence on the movements at the knee and ankle joints. According to Menton, PM is more a sensory organ than a typically functioning muscle (Menton, 2000). This assumption is based on a possible effect of PM on the central nervous system by sending afferent information about the foot's position (Menton, 2000).

Multiple studies have focused on the insertion of the tendon of PM in adults, but fewer studies have studied its origin in detail (Desdicioglu et al., 2015; Freeman et al., 2008; Nayak et al., 2010; Olewnik et al., 2020b; Szaro et al., 2020; Yıldız et al., 2011). Our classification is based on a study presented by Olewnik et al. Type Ia, characterized by an attachment to the lateral head of the GM, lateral femoral condyle and to the knee joint capsule, and was present in 39.8% of cases, whereas in our study it was present in 51.4% of

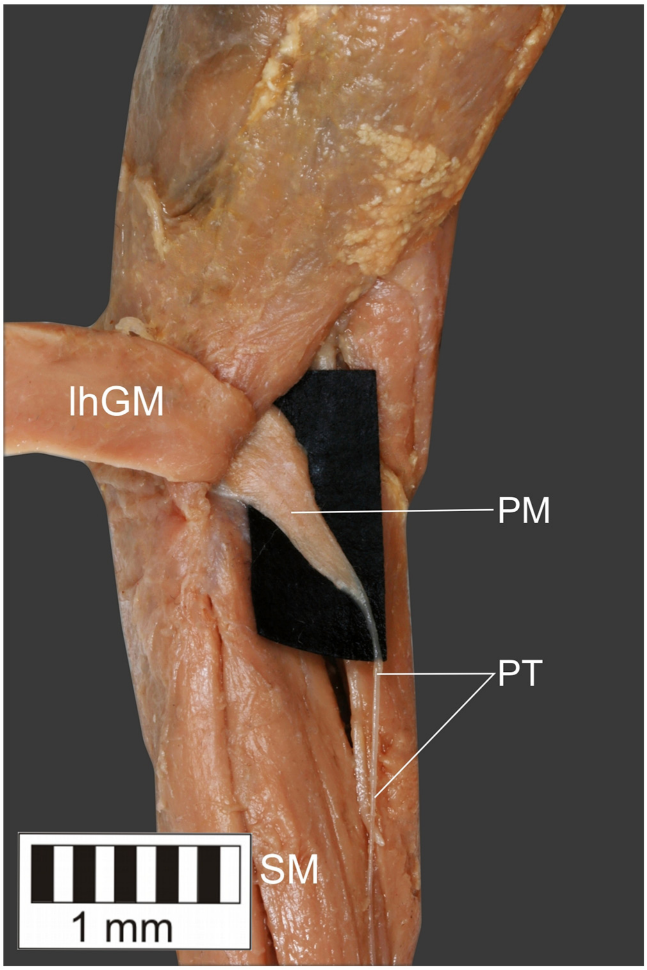

Fig. 5. Type IV of PM origin.
PM — plantaris muscle, PT— plantaris tendon, GM — gastrocnemius muscle.

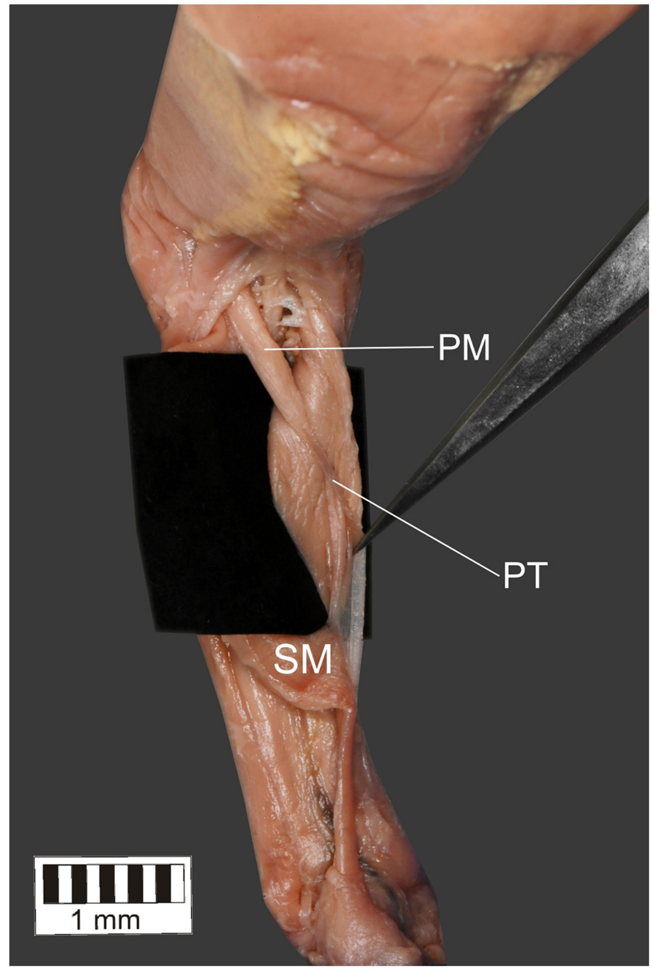

Fig. 6. Type V of PM origin.
PM — plantaris muscle, PT — plantaris tendon, SM — soleus muscle.

cases (Olewnik et al., 2020b). In both studies type Ia was the most common type. Type Ib was characterized by an origin on the lateral head of the GM, lateral femoral condyle, knee joint capsule and the popliteal surface of the femur; in our study it was present in 13.5% of cases, whereas in Olewnik et al. it was present in 8.6% of cases (Olewnik et al., 2020b). The second, most common type in Olewnik et al.'s study was type II, its attachment being on the knee joint capsule and the lateral head of the GM and indirectly the lateral femoral condyle through the lateral head of the GM; this occurred in 4.1% of our cases, and 25% of cases in their study (Olewnik et al., 2020b). Types from Ia to II are represented by a partial connection of PM and GM, which may support the developmental origin of PM from the lateral head of the GM (Olewnik et al., 2020b). Type III was the second most common type in our study: the muscle originated from the lateral femoral condyle and the knee joint capsule in present study it 22.9% of the cases; in Olewnik et al.'s study it was found in 10.2% of cases. The attachment of PM, within type IV, was located on the knee joint capsule, the lateral femoral condyle and the iliotibial band. In our study, type IV was present on 2.7% of cases, whereas in Olewnik et al.'s study it was found in 6.6% of the cases (Olewnik et al., 2020b). The least common type within our study was type V; the origin in this type was located only on the lateral condyle of the femur. It was present in 1.4% of our cases, and 8.6% of Olewnik et al.'s cases. In our study, 4.1% cases had type VI, which was characterized in Olewnik et al.'s study to occur only in rare cases (Olewnik et al., 2020b).

The origin of PM is therefore characterized by a great variability, so it is probable that the numbers of types presented in previous studies were too low to reflect the true variability of the muscle. Regarding comparisons with studies conducted on PM on human fetuses, we only could find three previous studies (Desdicioglu et al., 2015; Szaro et al., 2020; Yıldız et al., 2011). Yıldız et al. analyzed 48 limbs, Szaro et al. 72 and Desdicioglu et al. 102 fetal limbs (Desdicioglu et al., 2015; Szaro et al., 2020; Yıldız et al., 2011). Our study is based on 94 fetal limbs. However, Yıldız et al. and Desdicioglu et al. focused only on the morphometry of PM, while Szaro et al. focused on its distal insertion and presence/absence, whereas our study investigated in more detail its variability and the origin of its belly, as well as its morphometry (Desdicioglu et al., 2015; Szaro et al., 2020; Yıldız et al., 2011) (Table 3).

The greatest absence of PM was observed in Desdicioglu et al.'s report, the least in Szaro et al. study (Desdicioglu et al., 2015; Szaro et al., 2020; Yıldız et al., 2011). Width, thickness and length of PM was similar in ours and Desdicioglu et al.'s reports, however there was a great difference between these two studies and Yıldız et al.'s study: this might be a result of the difference in number of the investigated fetuses in those studies because Desdicioglu et al. studied more individuals than Yıldız et al. (Desdicioglu et al., 2015; Szaro et al., 2020; Yıldız et al., 2011). Interestingly, Yıldız et al. described in their study bifurcated PM (Yıldız et al., 2011), as did Olewnik et al. in 1.6% of their cases (Olewnik et al., 2020b). This type had two separate bellies, which fused and had a common tendon, corresponding to Olewnik et al.'s type VI (Olewnik et al., 2020b).

Table 3
Comparison of the morphometry of PM origin between studies (Desdicioglu et al., 2015; Szaro et al., 2020; Yıldız et al., 2011). Data presented as mean ± standard deviation.

	Our study	Desdicioglu et al.	Yildiz et al.	Szaro et al.
Number of limbs	94	102	48	72
Absence of PM	21.3%	31.4%	12.4%	9.5%
II Trimester				
Width of the belly [mm]	4.2 ± 1.6	4.7 ± 1.1	3.0	
Thickness of the belly [mm]	0.9 ± 0.4	1.0 ± 0.4		
Length of the belly [mm]	10.4 ± 3.3	12.7 ± 2.6	7.5	
III Trimester				
Width of the belly [mm]	5.7 ± 1.0	6.0 ± 1.0	5.8	
Thickness of the belly [mm]	1.2 ± 0.3	1.2 ± 0.2		
Length of the belly [mm]	15.9 ± 2.7	16.0 ± 2.0	17.6	

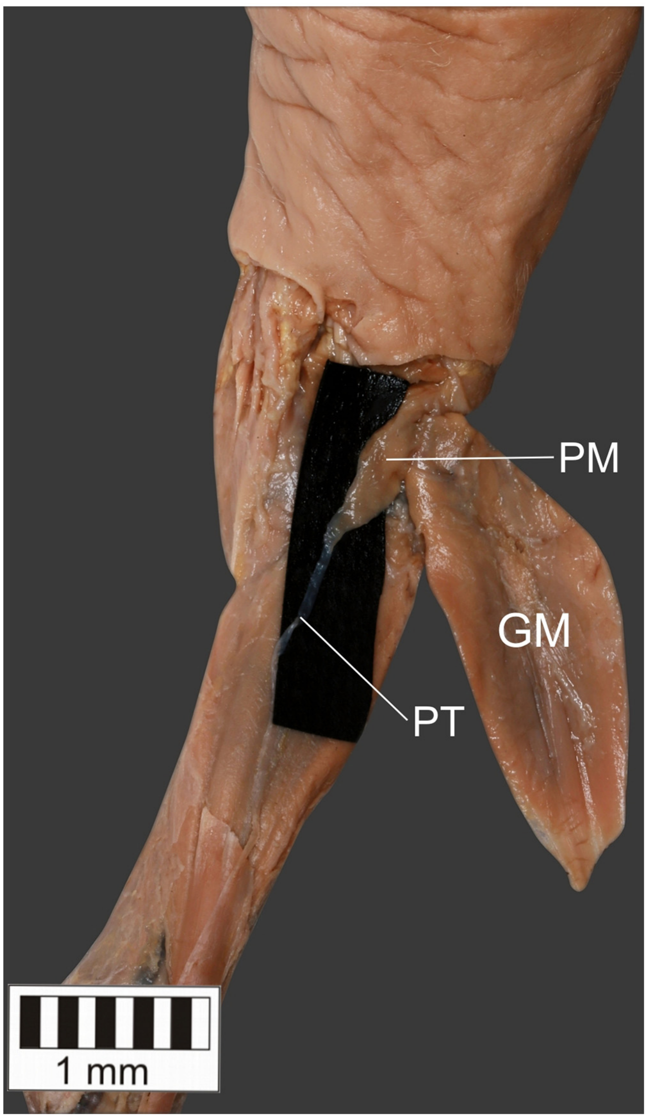

Fig. 7. Type VI of PM origin. PM — plantaris muscle, PT — plantaris tendon.

In Table 4 we compile information about the variability of the origin of PM in a number of published studies.

As we mentioned above, some clinicians believe that the rupture of the tendon or belly muscle of PM may be described as *tennis leg*, a term that previously was only used to for tears or ruptures of the medial head of the GM (Rohilla et al., 2013). This injury is commonly observed in athletes and sports amateurs as a result of excessive stretching of GM by strong dorsiflexion of the foot with simultaneous extension of the knee joint. According to Rohilla et al., patients with rupture of PM will suffer from less pain and will recover full mobility much faster than those with rupture of GM or SM (Rohilla et al., 2013). However, it is much more likely for patients to refer to the rupture of the medial head of the GM than to the rupture of PM (Rohilla et al., 2013).

Table 4
Variability of the origin of PM in multiple studies.

Type of the origin	Study
Bifurcated or double PM	Herzog (2011), Kotian et al. (2013), Kurtys et al. (2020a), Kwinter et al. (2010), Smędra et al. (2020)
The belly of PM ran posterior to the popliteal vessels and the tibial nerve	Olewnik et al. (2018c)
Three muscle bellies of PM	Olewnik et al. (2020c)

We should note that the present study has some limitations. Because PM is so variable, the proposed classification is heterogenous and depends on several morphological details such as the presence of an accessory band of origin and the place of origin of the PM. Nevertheless, our study provides an unique type of information about variability, anatomy, and fetal development of the muscle, which can be crucial to pave the way for further clinical, developmental and morphological studies, for instance concerning *tennis leg* and tendon reconstruction.

5. Conclusions

We distinguished six (I–VI) types of origin of PM in human fetuses. The most common was type Ia, characterized by an attachment to the lateral head of GM, lateral femoral condyle and to the knee joint capsule. The results of our study on PM anatomical variation in fetuses will hopefully important, in the future, for comparisons with other studies carried on adult cadavers as well as for clinical and developmental works.

Ethical approval and consent to participate

The cadavers belong to the Department of Anatomical Dissection and Donation, Medical University of Lodz.

Consent to publish

Not applicable.

Availability of data and materials

Please contact authors for data requests (Anna Waśniewska — email address: anna.wasniewska@umed.lodz.pl).

Funding

The authors have no financial or personal relationship with any third party whose interests could be positively or negatively influenced by the article's content. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Authors' contributions

Anna Waśniewska (MD) – Assistant – project development, data collection and management, data analysis and manuscript writing.

Rui Diogo (MD., PhD) – Professor –manuscript editing.

Łukasz Olewnik (D.P.T., PhD) – Associate Professor – data collection, data analysis and manuscript editing.

Michał Polguj (MD., PhD) – Professor – data analysis, manuscript editing.

All authors have read and approved the manuscript.

Ethical

The fetuses were obtained from spontaneous abortion after parental consent and were from Department of Anatomical Dissection and Donation collection. Everything was in accordance with the legal procedures in force in Poland and in accordance with the program Donation Corpse both adults and fetuses. The Local Bioethics Commission gave a consent for the study (agreement no. RNN/218/20/KE).

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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