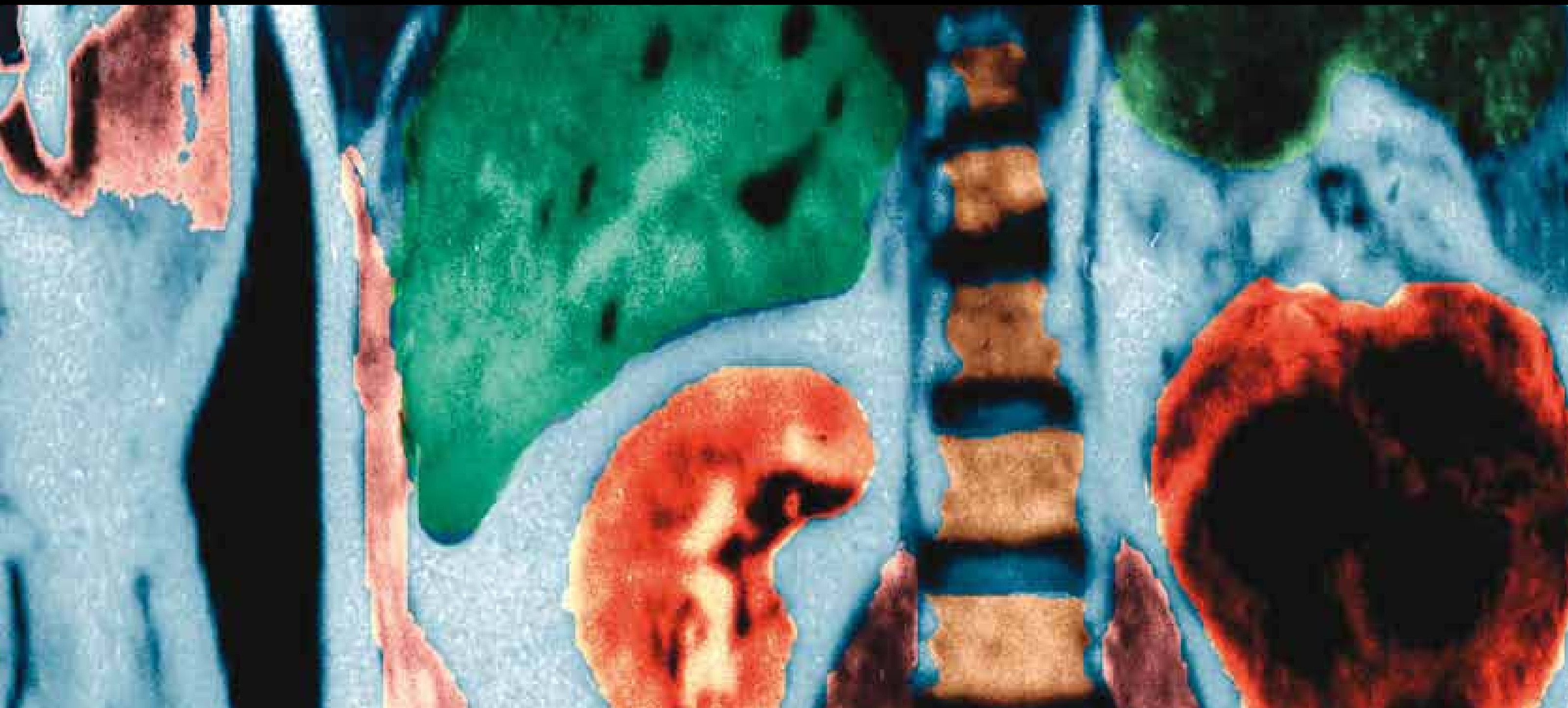
Anatomy Research International

The Human Knee: Gross, Microscopic, Surgical, and Radiological Anatomy

Guest Editors: Konstantinos Natsis, Nikolaos Anastasopoulos, Eleftherios Kellis, Juergen Koebke, Antonia Sioga, and Ioannis Tsitouridis



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Editorial Board

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Editorial

The Human Knee: Gross, Microscopic, Surgical, and Radiological Anatomy

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During the last years imaging techniques have rapidly developed in anatomy since they were included in the study of the human body. Normal patterns have been revisited and lately, in the era of evidence-based medicine, anatomy has shifted towards evidence-based morphology. Endoscopic and minimally invasive techniques require a different view and a better understanding of anatomy. Individualized patient care requires understanding of the individualized anatomy especially with regard to surgery. Anatomy is more well timed than ever and the papers selected for this special issue reflect the modern era of anatomy. The papers included are descriptive studies aiming to describe anatomy but they somehow represent different study designs and all of them have been conducted under a clinically orientated perspective. Although the human knee has been extensively studied, it seems that there are still research questions that need to be addressed. We would like to thank the authors for their contributions to this special issue. The fundamental work of all the reviewers is also acknowledged.

In the paper "*The 'oblique popliteal ligament:' a macro- and microanalysis to determine if it is a ligament or a tendon*" B. Benninger and T. Delamarter challenge a well-known structure, the oblique popliteal ligament (OPL). Based on their observations the authors suggest that the OPL is indigenous to the distal semimembranosus muscle tendon unit. The microanalysis using an immunohistochemistry stain with PGP9.5 revealed a positive result for neuronal axons within both the semimembranosus tendon and OPL. Further microanalysis using an immunohistochemistry stain with β-tubulin revealed a positive stain for neuronal axons in the semimembranosus tendon, OPL, and lateral collateral ligament. Though the latter result leads the authors to question the validity of differentiating the tendon from ligament using this particular immunohistochemistry stain, the macroanalysis results are overwhelming, and the micro-analysis reveals striking similarities in the histology of both the OPL and semimembranosus tendon.

In the paper entitled "*The patellar arterial supply via the infrapatellar fat pad (of Hoffa): a combined anatomical and angiographical analysis*" G. Nemschak and M. L. Pretterklieber describe the rich patellar arterial supply provided via the infrapatellar fat pad (of Hoffa). Five human patellae, one was dissected under the operation microscope, a second was made translucent by Sihlers-solution, and three underwent angiography using a 3D X-ray unit, were studied. The results revealed that the patella to a considerable amount is supplied by arteries coursing through the surrounding parts of the infrapatellar fat pad. The latter were found to branch off from the medial and lateral superior and inferior genicular arteries. Within the infrapatellar fat pad, these arteries formed a dense network of anastomoses which are all contributing to the viability of the patellar bone. The authors conclude that due to the rich arterial supply reaching the patella via the infrapatellar fat pad, it seems advisable to preserve the fat pad during the surgery of the knee in order to reduce the risk of vascular impairment of the patella.

In the paper "*Meniscofibular ligament: morphology and functional significance of a relatively unknown anatomical structure*" K. Natsis et al. performed a gross and microscopic study on the meniscofibular ligament (MFL). Based on their observations the authors speculated that MFL could offer protection to the lateral meniscus from likely damage during the last stages of knee extension. Moreover, MFL seems to reinforce the posterolateral part of the lateral coronary ligament, a fact that could explain the relative low incidence of lateral coronary ligament rupture. This study formulated research questions for further research with regard to the exact biomechanical characteristics of the MFL, as well as the likely relation or not to lateral meniscus tears, protection of the coronary ligament, and function and traumatology of the proximal tibiofibular joint.

In the paper "*Application of soft tissue artifact compensation using displacement dependency between anatomical landmarks and skin markers*" T. Ryu presents a different view of anatomy applications with regard to joint analysis. Among many approaches to reduce errors in motion analysis, by means of stereophotogrammetry, is to estimate the position of anatomical landmarks during a motion with joint angle or displacement of skin markers, which is the so-called compensation method of anatomical landmarks. This study aimed to apply the compensation methods with joint angle and skin marker displacement to three lower extremity motions and to compare their reliability. Two sets of kinematic variables were calculated using two different marker clusters, and the difference was obtained. Results showed that the compensation method with skin marker displacement had less differences by 30–60% compared to without compensation. In addition, it had significantly less differences in some kinematic variables (7 of 18) by 25–40% compared to the compensation method with joint angle.

In the paper entitled "*Adequacy of semitendinosus tendon alone for anterior cruciate ligament reconstruction graft and prediction of hamstring graft size by evaluating simple anthropometric parameters*" Papastergiou G. S. et al. performed a retrospective study of a clinical population in order to determine whether the semitendinosus tendon length is adequate for a four-strand graft harvested by common technique and if there is a correlation of gracilis and semitendinosus grafts length and diameter with anthropometric parameters. According to the findings of the study the authors concluded that the length of semitendinosus tendon, harvested by the common technique, is usually inadequate in order to be used alone as a four-strand graft especially in females. Height and weight are considered to be moderate predictors of the adequacy of the semitendinosus tendon length when using alone the semitendinosus four-strand graft or of the four-strand semitendinosus and gracilis graft diameter for anterior cruciate ligament single-bundle reconstruction harvested by common technique (without bone plug). The most reliable predictor seems to be patients' height in males. In female patients, there is no such statistically important predictor.

In the paper "*Gender and side-to-side differences of femoral condyles morphology: osteometric data from 360 caucasian dried femori*" I. Terzidis et al. performed a population-based morphometric study of the femoral condyles.

It is still a controversial issue whether a new implant design might rather take into account interindividual variations in the knee joint anatomy instead of gender-specific variations. The authors highlighted differences in anatomy between genders that might add to the design of new prostheses. Based on the results of this study, the contralateral healthy side can be used safely for preoperative templating in total knee reconstruction surgery since no side-to-side differences were found.

In the paper "*Anterior and posterior meniscofemoral ligaments: MRI evaluation*" A. Bintoudi et al. provide an overview of the MRI appearance of the anterior meniscofemoral and posterior meniscofemoral ligaments. The authors have used a large sample size to describe the imaging anatomy of these structures which aids in better conceptualization of the anatomy and averts misdiagnosis of the anterior meniscofemoral and posterior meniscofemoral ligaments as loose bodies or posterior cruciate ligament pathology.

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Research Article

Anterior and Posterior Meniscofemoral Ligaments: MRI Evaluation

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Although meniscofemoral ligaments are distinct anatomic units, their anatomy and function are controversial from an anatomic and radiologic point of view. Five hundred knee MR examinations were retrospectively studied in an effort to demonstrate the incidence and variations regarding sex and age distribution, as well as the anatomy of the meniscofemoral ligament at magnetic resonance imaging. Patients were mostly men, three hundred and twelve, in contrast with women who were fewer, one hundred eighty-eight patients. The mean age of the patients who were included in this study was 46 years. More than half of them were between 20 and 40 years old; one hundred thirty-three patients among 20 to 30 years old and one hundred and one patients among 31 and 40 years old, in total two hundred thirty-four patients.

1. Introduction

An imaging breakthrough had led us to pay more attention in small anatomic structures such as the meniscofemoral ligaments. Meniscofemoral ligaments are straight bands of collagen that attach to the posterior horn of lateral meniscus and lateral part of medial femoral condyle [1]. For some authors, the meniscofemoral ligament is one ligament with two distinct bands, whereas for others are two distinct ligaments. The anterior meniscofemoral ligament (aMFL) which is leaning anterior to the posterior cruciate ligament (PCL) is also known as ligament of Humphrey, and the posterior meniscofemoral ligament (pMFL) leaning posterior to PCL is known as ligament of Wrisberg [1–6]. The incidence of the aMFL and pMFL ranges in the literature, although most of the studies are anatomic studies [2–7]. There are not many reports in the literature regarding magnetic imaging examination of the respective ligaments.The purpose of the present study is to elucidate the incidence of ligaments concerning the distribution among males and females and among patients with different ages.

2. Materials and Methods

Six hundred and three knee MRI examinations performed at our hospital during the period 2010-2011. Exclusion criteria include the patients with limitation on diagnosis due to motion artifacts and with imaging findings of PCL and lateral meniscus (LM) pathology. The remaining five hundred knee MRI exams were included in this retrospective study. The age of the patients ranged from 29 to 73 years (mean age 46 years). The patients were admitted for MRI exam either for chronic knee pain or after trauma.

All patients underwent MRI exams that were performed at 1 Tesla scanner (*Siemens Expert Plus)* using a phased-array knee coil. Each patient was positioned supine with the knee in a 10° flexion and 15° external rotation. The examination protocol included coronal and sagittal turbospin echo PD-WI and T2-WI, axial T2*-WI, and coronal STIR MR sequences, all with a slice thickness of 4 mm. No intravenous media contrast was administered.

For the interpretation of MRI examination we paid special attention to coronal and sagittal PD-WI sequence and

Table 1: Incidence of appearance of ligament of Wrisberg and ligament of Humphrey in male and female patients.

	aMFL	pMFL	aMFL + pMFL
Male	40	240	44
Female	19	82	37

sagittal T2-WI sequence. The two ligaments, Humphrey and Wrisberg, were observed as a thin, linear band, with low MR signal intensity on coronal images anteriorly or posteriorly to PCL, respectively. On the sagittal images aMFL had a low MR signal, dot-like appearance located anterior to PCL and pMFL with the same appearance leaning posterior to PCL.

The incidence of appearance, the different proportions in males and females, the MR sign and the occurrence were recorded.

Ethical approval for this study was not obtained due to the fact that this is a retrospective study and was not needed.

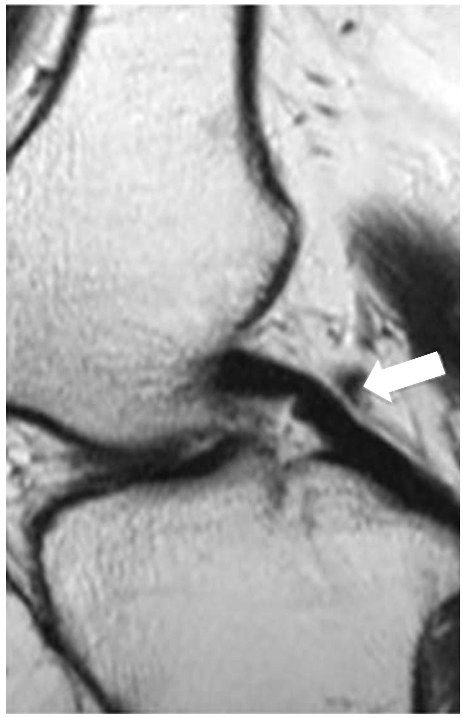
3. Results

From 603 knee MR examinations, 103 were excluded. The incidence of MFLs was evaluated in the remaining 500 knee MRIs. The pMFL or Wrisberg ligament was present in a very high percentage, 322 patients (64,4%), (Figure 1). Most of them in whom the pMFL was present were males, 240 patients (74,6%), and fewer, 82 patients (25,4%), were females. The visualization of the pMFL was easier and more frequently observed at the coronal sections (172/322/53%) rather than at the sagittal sections (150/322/47%). Although the incidence of appearance of Wrisberg ligament was high, it was usually thin and attached to PCL making the interpretation difficult.

On the contrary, aMFL was present in a smaller number of patients, 59 patients (11,8%) (Figure 2). In this case the incidence of appearance in males was disproportional higher, 40 patients (67,8%), than in females, 19 patients (32,2%). Interpretation of the Humphrey ligament was easier at the sagittal images (34/59/57,6%) than in coronal (15/59/25,4%).

Both anterior and posterior meniscofemoral ligaments were present in 81 patients (37%) (Figure 3). Both ligaments were also more frequently observed in males, 44 patients (54,3%), than in females 37 (45,6%). The results are summarized in Table 1. Meniscofemoral ligaments were absent in 38 patients (7,6%). Finally, we separated our patients according to ages. Five different groups were formed. The first group included patients between 20 and 30 years old, the second 31 to 40 and go on until the last group in which patients older than 60 years old were included. First group consisted of 174 (34,8%) patients 98 (56,3%) males and 76 (43,6%) females, the second group 101 (20,2%) patients, 46 (45,5%) males (Figure 4) and 41 (44,5%) females, third group 111 (22,2%) patients, 69 (62,1%) males and 42 (37,8%) females, 59 patients between 50 and 60 years old 35 (71,1%) males and 24 (40,6%) females. Finally, the last group comprised of patients, 55 (11%) males and 20 (21%) females (Figure 5), respectively. Table 2 summarizes the incidence of one or both ligaments and the number of patients with no ligament present with regard to age.

(a)



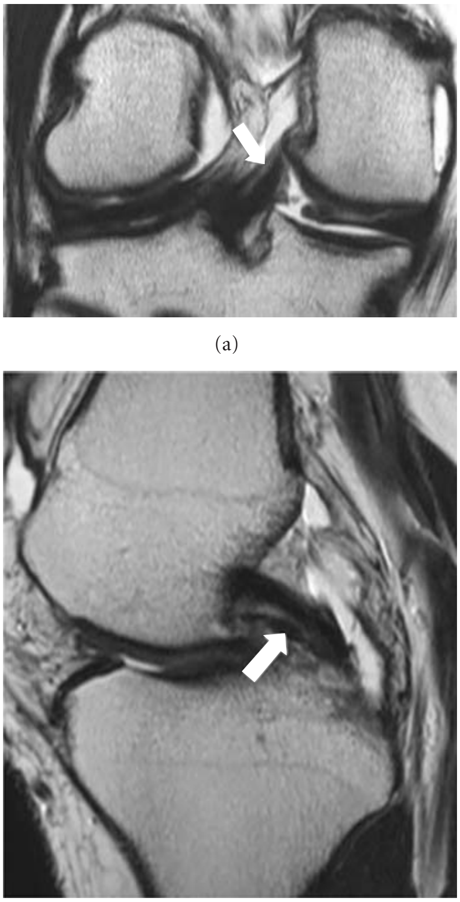
(b)

Figure 1: Coronal (a) PD-W image in which pMFL is demonstrating as a thick band and sagittal (b) PD-W image as a dot-like with low signal intensity posteriorly to posterior cruciate ligament (PCL) (white arrow).

The Wrisberg ligament was thicker than the Humphrey ligament. It was depicted with clarity at the coronal sections. On the other hand, Humphrey ligament was thinner and better visualized on sagittal images.

4. Discussion

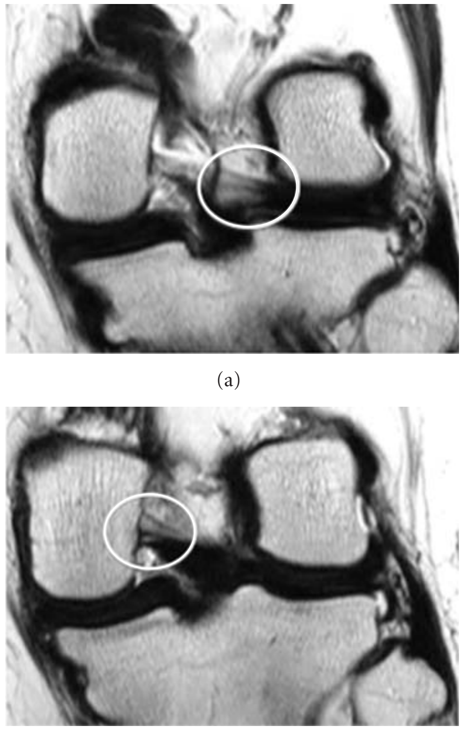
The anatomy, the function, and the imaging of the MFLs are a major issue among anatomists, orthopedics, and radiologists. The meniscofemoral ligaments connect the posterior horn of lateral meniscus with the lateral part of medial femoral condyle [1]. There are bands of collagen that



(a)

(b)

Figure 2: Coronal (a) PD-W image in which aMFL is depicted as a thick band and in sagittal (b) PD-W image as a dot-like with low signal intensity anteriorly to PCL (white arrow).



(a)

(b)

Figure 3: 39 years old female who admitted to our hospital for chronic pain. Consecutive (a) (b) coronal PD-W image evaluate both aMFL and pMFL as thick bands with low signal intensity anteriorly and posteriorly, respectively, to PCL (white cycle).

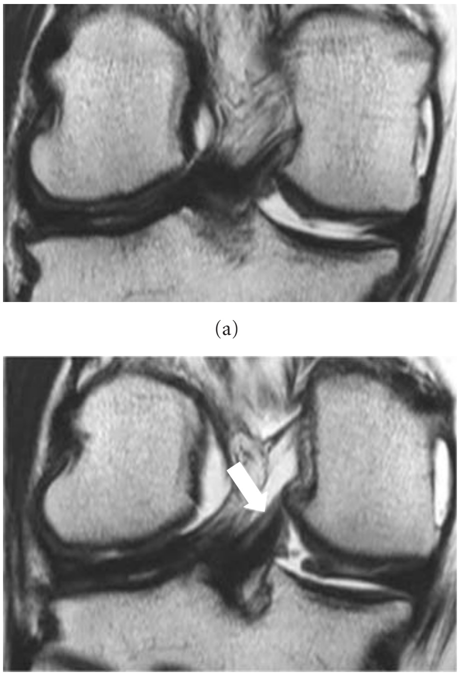
Table 2: Incidence of appearance in different age groups.

Age group	aMFL	pMFL	aMFL + pMFL	Absent
20–30 y	17	132	24	1
31–40 y	13	57	29	2
41–50 y	16	77	16	2
51–60 y	8	33	8	10
>60 y	5	23	4	23

attach firmly the posterior portion of the lateral meniscus during knee flexion [5, 8]. Poirier and Charpy first described it in 1892 [3]. The name of the third cruciate ligament was mistakenly used [9]. The name of ligament is also not correctly used because meniscofemoral ligament is not extended from a bone to another bone but from a fibrocartilage anatomic structure is the meniscus to a bone [9].

Embryological studies in human and animal knees proposed that MFL starts from posterior horn of lateral meniscus as a single band. The appearance of single or double MFL is due to the position of the PCL. Based on this evidence, different hypothesis was made for the variants which could present a meniscofemoral ligament [8]. Anatomically there have been described numerous variations of the scheme, proximal or distal insertions of the ligaments [6, 8, 10]. Anterior meniscofemoral ligament passes anterior to posterior cruciate ligament and there were described anatomic variants of the respective ligament. In the least frequent variant, the ligament consists of two or even three different bands with different origins from posterior horn of the lateral meniscus and different insertions at the femoral condyle. Most of the times variants are according to the size of the ligament, which could be small or large [8]. On the other hand posterior, meniscofemoral ligament, which passes posteriorly to posterior cruciate ligament, displays also anatomic variants.PMFL has described that could consist of two distinct bands having or not a hour-glass shape. Although is a thin ligament another anatomic variant describes a thick ligament, thicker than PCL. Of course all these variants are anatomically demonstrated and it might be difficult to observed them at knee MRI examinations [8].

Anterior meniscofemoral ligament extents between the posterior portion of the posterior horn of the lateral meniscus and the femur, in the 10 o'clock position in a left knee, adjacent to the articular cartilage. Posterior meniscofemoral ligament leaning also between the anterior portion of the posterior horn on the lateral meniscus but at the femur it inserts at the medial part of the intercondylar notch near to insertion of the posteromedial band of the posterior cruciate



(a)

(b)

Figure 4: 31 years old weekend football player, male, admitted to our hospital for medial meniscus tear. Consecutive (a) (b) coronal T2-W image demonstrating only the pMFL as a thick band with low signal intensity posteriorly to PCL. No fluid was present. MR examination was negative for meniscal tear (white arrow).

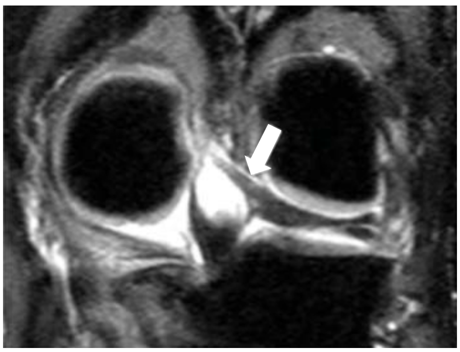


Figure 5: 45 years old aerobic dancer, female, admitted to our hospital for trauma. Coronal STIR image demonstrating a very thick band with low signal intensity posteriorly to PCL, a large pMFL which plays the role of PCL (white arrow).

ligament. This is the reason why fibers of the pMFL and PCL are sometimes intermingle [2, 8–11]. Meniscal insertion of the MFLs is possible to mimic the appearance of a tear. In our study, anatomic variations of MFLs were not evaluated. We try to describe specific details of MFLs, because as far as you concern, there have been very few studies with MRI at the respective issue.

The function of the aMFL and the pMFL is not clearly understood. We know that MFLs play an important role as stabilizers and protectors for the posterolateral femorotibial compartment. They try during knee motion to increase congruity between the mobile lateral meniscus and lateral femoral condyle. They also play a protective role for the posterior horn of the lateral meniscus. The MFL has a totally different function during knee extension and flexion due to the tension, which is applied on pMFL and aMFL, which is totally different. They have reciprocal and non-isometric tensioning pattern. The aMFL is taught during flexion and lax during extension that is in contrast to the function of the pMFL. It is taut during extension and lax during flexion. The aMFL has a supplementary role to the anterior band of posterior cruciate ligament in contrast with the pMFL which supplements the function of the posterior band of the PCL [2–4, 10, 12–15]. Studies had shown that MFLs have a principal role during internal rotation of the tibia with a fixed foot [10]. There are authors who have implied that MFLs have functional similarities with posterior band of posterior cruciate ligament. For these reasons, most of the studies negotiated the antagonistic role of MFLs after partial or total tear of posterior cruciate ligament [4]. MFLs could act as a splint during injuries of the PCL giving the proper time to the ligament for conservative healing. It is important to be aware of the presence, anatomy, and specific difficulties and variations on MFLs.

Imaging is adding important information regarding incidence of appearance. Several authors have shown, most through anatomic studies, the high prevalence of one of or both of MFLs. Anatomic studies, such as by Kusayama et al. and Amadi et al., demonstrate a very high incidence of 100%, thus other studies, such as Amis et al., a smaller incidence of 93% [2, 9, 15].There is no radiological study with such a high incidence as it is show in the study by Amis et al. [2]. In recent radiological studies which were performed by Hassine et al., Gupte et al., Choi et al., Erbagci et al., and Lee et al., incidences range from 87% to 78% for the presence of at least one MFL [4–6, 14, 16]. In our study, the incidence of at least one MFL was almost 65%, which is in accordance with the other studies. The different incidence between anatomic and radiologic studies is due to or a partial volume averaging effect either to a slight difficulty on evaluation the ligament of Humphrey.

Each meniscofemoral ligament was separately evaluated. The incidence of pMFL was higher than incidence of aMFL in all studies. Cho et al. visualized the ligament of Wrisberg in 84% of cases, Lee et al. 80%, and the smallest incidence was by Erbagci et al. 42% [5, 14, 16]. In our study pMFL was present in 322 patients (64,4%). The aMFL was present in a smaller incidence in all imaging studies. Cho et al., visualized the ligament of Humphrey in 15,8% of cases, Lee et al. 4%, and at the study of Erbagci et al. 12%. In our study aMFL was present in 59 patients (11,8%) [5, 14, 16]. Results in our research are smaller than in other studies maybe due to the large number of knee MRI examinations that were retrospectively studied.

We further divided the respective cohort regarding the sex of patients. The pMFL was present in 240 males, (74,6%) but fewer females, 82 patients (25,4%). Although Erbagci et al., visualized pMFL in a significant smaller cohort of 100 MRI knee examinations in 22 (52%) male patients and

20 (48%) females, the percentage of appearance is almost in accordance [15].

The aMFL was present in 40 males (67,8%), number disproportion higher than that of females 19 patients (32,2%). Amadi et al. visualized aMFL in 4 (33%) male patients and 8 (67%) females, which is in disagreement with our study [15]. Perhaps it is also due to the large number of knee MR images that are retrospectively studied.

Both MFLs were present at Moran et al. 28% and Lee et al. 1% [5, 13]. Erbagiet al. did not reveal any number [16]. In our study both MFLs were present in 81 patients (37%). Both MFLs were present in 44 males (54,3%) and 37 (45,6%) females. In the study by Erbagci et al., MFLs were present in 13 (46,4%) male patients and 15 (53,6%) females, which is in disagreement with our study [16]. Once more there is also a difference in findings at this group but is relative by smaller.

We observed that the Wrisberg ligament was thicker than Humphrey ligament. It was depicted with clarity at the coronal sections. On the other hand, Humphrey ligament was thinner and better visualized on sagittal images. Lee et al. reached the same conclusion [5].

In this study the incidence and appearance of meniscofemoral ligaments has been presented for different age groups. Gupte et al. and Cho et al. have proposed that the incidence is higher in younger patients, which is in totally agreement with our series [3, 4, 14].

The present study has limitations. The retrospective nature in the study design does not allow any arthroscopic or surgical correlations.

5. Conclusions

The purpose of the present study was to give an overview of the radiologic prospective of the aMFL and pMFL. Degenerative cause might be able to explain the higher incidence in younger patients. The relatively large cohort of patients can contribute to the better knowledge of radiologic anatomy of meniscofemoral ligament and avert misdiagnosis of the aMFL and pMFL as loose bodies or PCL pathology.

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Research Article

Gender and Side-to-Side Differences of Femoral Condyles Morphology: Osteometric Data from 360 Caucasian Dried Femori

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The purpose of the present study was to conduct direct measurements in a large sample of dried femori in order to record certain morphometric parameters of the femoral condyles and determine whether there are gender and side differences. Three hundred sixty (Greek) Caucasian dried femori (180 left and 180 right), from 192 males and 168 females, were measured using a digital caliper. The mean age was 67.52 years. The mean bicondylar width of the femur was 8.86 cm ± 0.42 cm in men and 7.85 cm ± 0.30 cm in women ($P < 0.01$). The relative values for the medial condylar depth were 6.11 cm ± 0.34 cm and 5.59 cm ± 0.29 cm ($P < 0.05$); for the lateral condylar depth were 6.11 cm ± 0.33 cm and 5.54 cm ± 0.21 cm ($P < 0.01$); for the intercondylar width were 2.20 cm ± 0.18 cm and 1.87 cm ± 0.10 cm ($P < 0.001$); for the intercondylar depth were 2.78 cm ± 0.16 cm and 2.37 cm ± 0.12 cm ($P < 0.001$). No significant side-to-side difference was observed in any parameter. The femoral condyles differences in anatomy between genders might be useful to the design of total knee prostheses. The contralateral healthy side can be safely used for preoperative templating since there were no significant side differences.

1. Introduction

Quantitative anatomy of the distal femur is important for the design of total joint replacement and internal fixation material. Recent studies emphasize on differences between genders and among ethnic groups [1–5]. Preoperative templating for a total knee arthroplasty usually involves the contralateral, healthy side, based on the assumption that there are no side-to-side differences [6]. Furthermore, it has been found that certain osteometric parameters of the femur, such as the femoral intercondylar notch width, differ between genders and are associated with both the volume and the incidence of anterior cruciate ligament (ACL) rupture [7–9]. However, this association has been questioned by other researchers [10, 11].

Most morphometric large sample size studies of the distal femur include measurements on radiographs, computerized tomography or magnetic resonance imaging [1, 9, 11, 12]. A study on 1207 dried femora was published recently, where authors performed measurements using a microscribe digitizer for 3D analysis [13]. In the present study, certain osteometric parameters of the femoral condyles were recorded and the existence of gender and side-to-side difference was examined in 360 Caucasian dried femori.

2. Materials and Methods

The sample consisted of 360 paired dried femori (180 left and 180 right) from 192 males and 168 females. The mean age was 67.52 years (range 40–94 years). Femori that belonged to individuals other than Greeks were excluded. Femori that on gross inspection had evidence of fracture, postmortem damage or arthritis were excluded from the study, as well. All measurements were performed with a digital sliding caliper. The osteometric parameters were defined as follows: (1) bicondylar width: the maximum distance across the femoral condyles in the transverse plane (Figure 1);

Figure 1: Measurement of the femur bicondylar width.

Figure 2: Measurement of the femur medial condylar depth. Similarly the lateral condylar depth was measured.

Figure 3: Measurement of the femur intercondylar width.

Figure 4: Measurement of the femur intercondylar depth.

(2) medial condylar depth: the maximum anteroposterior diameter of the medial femoral condyle (Figure 2); (3) lateral condylar depth: the maximum anteroposterior diameter of the lateral femoral condyle; (4) intercondylar notch width: the distance between 1/2 the anteroposterior diameter of the lateral surface of the medial femoral condyle and 1/2 the anteroposterior diameter of the medial surface of the lateral femoral condyle (Figure 3); (5) intercondylar notch depth: the vertical distance between the most anterior point of the inferior border of the intercondylar notch and the tangent to the posterior surface of the femoral condyles (Figure 4).

Data analysis was conducted using SPSS for Windows version 18.0. One way ANOVA was used to test for significant differences between genders and sides of the body. A P-value less than 0.05 was considered statistically significant. A single author performed all measurements for consistency. Each measurement was repeated three times and the mean value was recorded. Measurement error was assessed for every anatomical parameter according to the method described by White and Folkens for osteometric studies [14]. All measurements were rounded to two decimal places.

3. Results

The mean bicondylar width of the femur was 8.39 cm ± 0.63 cm (range, 7.15 cm–9.42 cm). It was 8.86 cm ± 0.42 cm (range, 7.83 cm–9.42 cm) in men and 7.85 cm ± 0.30 cm (range, 7.15 cm–8.20 cm) in women ($P < 0.01$). The mean medial condylar depth was 5.87 cm ± 0.41 cm (range, 5.12cm–6.60 cm). The relative values for the medial condylar depth in men were 6.11 cm ± 0.34 (range, 5.23 cm–6.60 cm) and in women were 5.59 cm ± 0.29 cm (range, 5.12 cm–6.01 cm) ($P < 0.05$). The average lateral condylar depth was 5.85 ± 0.40 (range, 5.11 cm–6.60 cm). It was 6.11 cm ± 0.33 cm (range, 5.32 cm–6.60 cm) in men and 5.54 cm ± 0.21 cm (range, 5.11 cm-5.98 cm) in women ($P < 0.01$). The mean intercondylar width was found 2.05 cm ± 0.22 cm (range, 1.60 cm–2.64 cm). In male femora average value was 2.20 cm ± 0.18 cm (range, 1.89 cm–2.64 cm) and in female femora was 1.87 cm ± 0.10 cm (range, 1.60 cm–2.12 cm) ($P < 0.001$). The intercondylar depth was 2.59 cm ± 0.20 cm on average (range, 2.32 cm–3.10 cm). It was 2.78 cm ± 0.16 cm (range, 2.47 cm–3.10 cm) and 2.37 cm ± 0.12 cm (range, 2.32 cm–2.76 cm) ($P < 0.001$). Data, as well as measurements error values, are summarized in Tables 1, 2, 3, 4, and 5.

Table 1: Gender and side distribution of distal femur bicondylar width values (measurement error 1.6%).

	Bicondylar width (CM)				
	Specimens	Mean value	Minimum value	Maximum value	Standard deviation
Gender					
Male	192	8.86	7.83	9.42	0.42
Female	168	7.85	7.15	8.20	0.30
Total	360	8.39	7.15	9.42	0.63
Side					
Left	180	8.37	7.15	9.38	0.63
Right	180	8.41	7.15	9.42	0.62
Total	360	8.39	7.15	9.42	0.63

Table 2: Gender and side distribution of femur medial condylar depth values (measurement error 1.1%).

	Medial condylar depth (CM)				
	Specimens	Mean value	Minimum value	Maximum value	Standard deviation
Gender					
Male	192	6.11	5.23	6.60	0.34
Female	168	5.59	5.12	6.01	0.29
Total	360	5.87	5.12	6.60	0.41
Side					
Left	180	5.87	5.12	6.56	0.41
Right	180	5.86	5.12	6.60	0.41
Total	360	5.87	5.12	6.60	0.41

Table 3: Gender and side distribution of femur lateral-condylar-depth values (measurement error 1.0%).

	Lateral condylar depth (CM)				
	Specimens	Mean value	Minimum value	Maximum value	Standard deviation
Gender					
Male	192	6.11	5.32	6.60	0.33
Female	168	5.54	5.11	5.98	0.21
Total	360	5.85	5.11	6.60	0.40
Side					
Left	180	5.85	5.11	6.60	0.40
Right	180	5.84	5.12	6.60	0.40
Total	360	5.85	5.10	6.60	0.40

Table 4: Gender and side distribution of femur intercondylar width values (measurement error 1.8%).

	Intercondylar width (CM)				
	Specimens	Mean value	Minimum value	Maximum value	Standard deviation
Gender					
Male	192	2.20	1.89	2.64	0.18
Female	168	1.87	1.60	2.12	0.10
Total	360	2.05	1.60	2.64	0.22
Side					
Left	180	2.05	1.62	2.53	0.22
Right	180	2.05	1.60	2.64	0.23
Total	360	2.05	1.60	2.64	0.22

Table 5: Gender and side distribution of femur intercondylar depth values (measurement error 1.1%).

	Intercondylar depth (CM)				
	Specimens	Mean value	Minimum value	Maximum value	Standard deviation
Gender					
Men	192	2.78	2.47	3.10	0.16
Female	168	2.37	2.32	2.76	0.12
Total	360	2.59	2.32	3.10	0.20
Side					
Left	180	2.65	2.34	3.10	0.21
Right	180	2.53	2.32	3.02	0.18
Total	360	2.59	2.32	3.10	0.20

4. Discussion

In the present study, five morphometric parameters were recorded in dried bones with a direct method using digital sliding caliper. In the literature most anatomic morphometric studies have been conducted with indirect methods including radiography, computerized tomography, magnetic resonance imaging, and 3D modelling. Given the fact that cadaveric material is scarce, these methods offer the advantage of describing anatomy in large samples since they can be performed in living subjects. However, indirect methods have been found to be inaccurate even after correction for magnification, technique, and projection [14–16].

The bicondylar width of the femur was found 8.39 cm±0.63 cm on average. It was significantly ($P < 0.01$) greater in men than in women, but there was no significant difference between the two sides of the body. The bicondylar width is the most frequently measured anatomic parameter of the distal femur. However, there is great variability between studies regarding the definition of measuring points as well as the measurement techniques and the type of sample [1, 4–7, 9–13, 17–19]. As a result, any comparison would provide unreliable conclusions. We measured the bicondylar width of the femur according to the definition of Farrally and Moore which is the maximum distance across the condyles in the transverse plane. [18]. They reported an average of 8.31 cm in 27 Caucasian femori, which is very close to the present study result, and 7.95 cm in 32 Negro femori ($P < 0.01$). Regardless of the measurement method, most studies have demonstrated a greater bicondylar width in men than in women and no statistically significant difference between left and right side [1, 4–7, 9, 10, 12, 13, 17, 19].

The mean medial condylar depth of the femur was 5.87 cm ± 0.41 cm. Men had a significantly ($P < 0.05$) greater depth than women. The average lateral condylar depth of the femur in our sample was 5.85 cm ± 0.4 cm and it was also significantly ($P < 0.01$) greater in men than in women. No significant difference was found between the left and right femori for both measurements. In the literature, the condylar depth was uniformly defined as the maximum anteroposterior diameter of each femoral condyle, but differences in measurement techniques and sample material were consistent. Farrally and Moore (1975) reported the "anteroposterior width of femoral condyles", but they did not clarify which condyle was measured [18]. The greater depth of both femoral condyles in men than in women and the absence of side differences, which were noticed in the present study, are in accordance with most literature studies [1, 4–6, 17, 20, 21]. However, Gillespie et al. [13] measured the medial and lateral flange height and found no difference between men and women.

The bicondylar width as well as the medial and lateral condylar depths of the femur are important parameters for the design of total knee prostheses. Differences in anatomy between genders have led to the design of gender-specific implants. Lateral condyle depth of the femur has been associated with osteoarthritis, but it remains unclear whether the increased depth of the lateral condyle is a predisposing factor or the effect of knee osteoarthritis [20].

The intercondylar width of the femur was 2.05 cm ± 0.22 cm on average, while the mean intercondylar depth was 2.59 cm ± 0.20 cm. Both intercondylar notch dimensions were significantly ($P < 0.001$) greater in men than in women. No significant difference was found between the left and right femori. Intercondylar notch dimensions have a clinical impact since smaller intercondylar notches have been associated with smaller ACL width and more frequent ACL ruptures [7, 9, 20, 22, 23]. However, other studies questioned this association [8, 11, 24, 25]. This controversy led to the publication of morphometric studies of the intercondylar notch with the use of imaging techniques [7–11, 20, 22–24]. Wada et al. reported that there is an association between intercondylar width and knee osteoarhritis but this observation needs further investigation [20].

The intercondylar width has been studied extensively but this is not the case for the intercondylar depth of the femur. [7–11, 20, 22–25]. Herzog et al. compared intercondylar width measurements obtained with imaging techniques and the direct method [24]. There was no statistical significant difference between measurements obtained with calipers and MRI but there was a significant difference between calipers and X-ray [24]. Based on their observation, we compared our results with those mentioned in the literature and we noticed that they are within the range of the values reported [7–11, 20, 22–25]. The larger intercondylar notch in men and the absence of side-to-side differences, which were found in the present study, have been verified by many authors [7, 9, 10, 22, 23].

In conclusion, in the present study direct measurements of the femoral condyles were conducted in a large sample of Caucasian (Greek) subjects. The differences in anatomy between genders might add to the design of prostheses. However, recent studies have shown that gender differences of distal femur morphometry depend on other morphometric measurements of femur, such as the femur length and width [4]. In the study by Dargel et al. 2011, which included 26 measurements of the knee joint, when gender differences were corrected for differences in femur length, medial-lateral dimensions of knees were still significantly larger in men than in women; however, matched paired analysis did not prove those differences to be consistent [17]. Therefore, they proposed that new implant design might rather take into account interindividual variations in the knee joint anatomy instead of gender-specific variations. Based on the results of the present study, the contralateral healthy side can be used safely for preoperative templating in total knee reconstruction since there was no statistical significant difference.

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Clinical Study

Adequacy of Semitendinosus Tendon Alone for Anterior Cruciate Ligament Reconstruction Graft and Prediction of Hamstring Graft Size by Evaluating Simple Anthropometric Parameters

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Introduction. Preoperative identification of patients with inadequate hamstring grafts for anterior cruciate ligament reconstruction is still a subject of interest. *Purpose*. The purpose of this study was to determine whether the semitendinosus tendon length is adequate for four-strand graft harvested by common technique (without bone plug) and whether there is correlation of gracilis and semitendinosus tendon grafts length and diameter of quadrupled graft with anthropometric parameters. *Materials and Methods*. In this retrospective study, 61 patients (45 males, 16 females) undergoing ACL reconstruction using four-strand hamstring autograft tendons were included. *Results*. The length of semitendinosus tendon, harvested by the common technique, was in 21% of our cases inadequate in order to be used alone as a four-strand graft especially in females (43%). There was moderate correlation between semitendinosus and gracilis graft diameter and patient's height and weight and fair correlation to BMI. We found no statistically important predictor for graft diameter in female patients. *Conclusions*. The length of semitendinosus tendon, harvested by common technique, is usually inadequate to be used alone as a four-strand graft especially in females. The most reliable predictor seems to be patient's height in males. In female patients, there is no statistically important predictor.

1. Introduction

The anterior cruciate ligament (ACL) is the most commonly reconstructed ligament of the knee [1]. An injury to the ACL can result in significant functional impairment [2]. Strength and stiffness of the graft are important components in order to decide the kind of graft and the technique of tendon replacement.

It is widely accepted that four-strand hamstring autograft represents a successful option for ACL reconstruction [3–7]. A possible complication when using both the semitendinosus (ST) and gracilis (G) tendon graft is that of hamstring strength deficit in deep flexion and internal rotation [8–10]. Gobbi and Francisco suggest to use only ST tendon in a four-strand graft with bone plug in order to reduce donor's site morbidity and to increase graft's diameter [11], while later on in another study Gobbi again suggests a double bundle using only semitendinosus tendon for better functional rehabilitation of the knee [12]. In this type of operations, it would be essential for the surgeon to be able to predict preoperatively graft length in order to choose the ideal graft type and to avoid scar formation, pain, operating time and infection risk. Prediction of graft length could also be useful in cases of revision ACL reconstruction where usually a larger diameter graft is needed [13] or in cases of active and/or highly demanding patients or professional athletes where larger diameter grafts would be ideal.

Scott and Insall report that the length of normal ACL is 38 mm (25–41 mm) and the width is 10 mm (7–12 mm), on average [14]. In order to assure the optimal 7 cm quadrupled graft construct for ACL reconstruction (2 cm in the femoral tunnel, 3 cm intra articular, and 2 cm in the tibial tunnel), it is essential to obtain a minimum tendon length of 28 cm (ranged from 28 to 30 cm) with a minimum thickness of 7 mm [11, 15–17].

The purpose of this retrospective study was to determine whether alone the ST tendon length is adequate for four-strand graft harvested by common technique and whether there is correlation of G and ST grafts length and diameter with anthropometric parameters.

2. Materials and Methods

Sixty-one consecutive patients (45 males—16 females) undergoing ACL reconstruction using four-strand hamstring autograft tendons were included in this retrospective study. Age, gender, height, weight, and Body Mass Index (BMI) for each patient were recorded preoperatively.

Surgical operation was performed by the same surgeon in all cases, and hamstring tendon autografts (ST-G) were harvested by the same way. An oblique incision was performed on the skin over the pes anserinus attachment area on the proximal tibia. Subcutaneous fat was incised and attentive blood hemostasis was performed. The sartorius fascia was incised parallel to the direction of G tendon. On the next step, G tendon was dissected (Figure 1). The tendon was removed from its proximal attachment with a close tendon stripper (Figure 2). The detachment of the tendon on its tibial end was done close to the bone in order to preserve its maximum length (Figure 3). The same procedure was followed for ST tendon but before removal of its proximal attachment, the tendon band towards gastrocnemius muscle was dissected with a scissor under direct vision. After both hamstring tendons harvest each one of them became double strand to create a four-strand graft with both tendons. Each end of the tendon grafts was stitched with a no. 2 nonabsorbable polyester suture. After blunt removal of attached muscle and fat but before any further postharvested alteration of trimming of the graft, intraoperative measurements of both tendons were done, such as length of each and diameter of the quadrupled graft using sizing cylinders with incremental size change of 0.5 mm. The graft diameter was considered to be the dimension of the smallest cylinder that could pass through (Figure 4). In case that the graft diameter was not exactly fitted in a specific 0.5 mm increment, the size of the graft was recorded according to the drill size of our tunnels. Pretensioning of the graft on the surgical table was not performed. Finally single-bundle ACL reconstruction was performed.

Adequate length of ST tendon graft as only four-strand graft for single-bundle ACL reconstruction was considered to be 28 cm. Adequate diameter of four-strand hamstring autograft (ST-G) was considered to be more than 7 mm.

Figure 1: Hamstring tendons harvesting in the pes anserinous attachment area on the proximal tibia.

Figure 2: Excised ST and G tendon with a close tendon stripper. Photo is taken with dyonics arthroscopic video camera.

In statistical analysis, independent samples t-test was used to identify differences between the mean values of continuous variables according to gender. Chi-square statistics (χ^2) was done to investigate any possible association of the categorical variables with the diameter of the graft. Bivariate correlation coefficients (Pearson r) and multiple linear regressions were calculated to evaluate any possible association between clinical data and intraoperatively measured hamstring graft lengths and diameters. Higher correlation coefficients indicate stronger relationships between variables. Statistical package SPSS version 18.0; SPSS, Chicago, III for Windows was used for analyses. A P value of 0.01 was taken as the level of significance.

3. Results

Anthropometric measurements including the average age, weight, height and BMI, and gender of patients participating in this study are shown in Table 1. Graft characteristics are described according to gender in Table 2. Frequency of adequate ST tendon graft length according to gender is presented in Table 3. Frequency of adequate four-strand hamstring (ST-G) autograft diameter according to gender is summarized in Table 4.

Figure 3: Anatomical dissection of ST and G tendons attachment, that shows their maximum lengths in a cadaveric specimen.

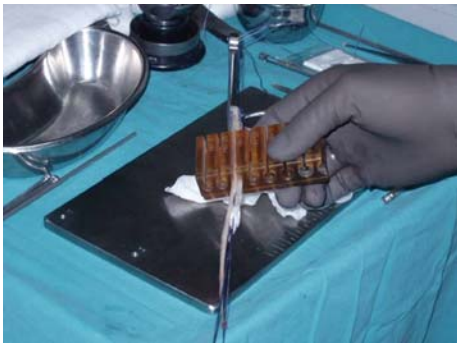

Figure 4: Intraoperative diameter measurement of a quadrupled ST and G tendon graft using sizing cylinders with incremental size change of 0.5 mm.

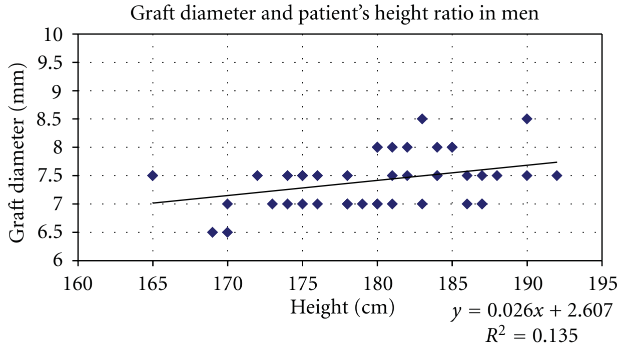

Figure 5: Scatter plots showing relationships between height and hamstring graft size (diameter) in males. Correlation coefficients and P values are included. $r = 0.368239$, r for $\chi^2 = 0.29426$, $P = 0.05$.

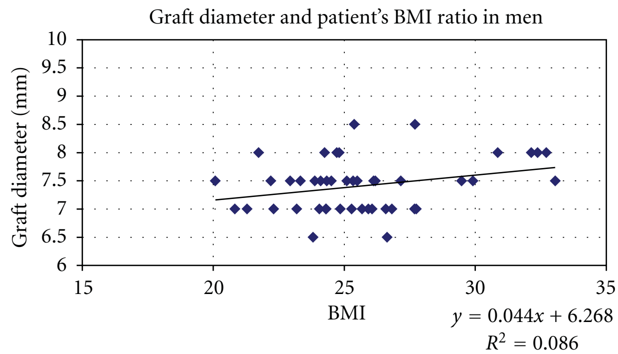

Figure 6: Scatter plots showing relationships between BMI and hamstring graft size (diameter) in males. Correlation coefficients and P values are included. $r = 0.294618$, r for $\chi^2 = 0.25$, $P = 0.01$.

Female patients were lighter and shorter with lower BMIs, and had shorter length and smaller diameter hamstring grafts with statistical significance in comparison with males.

Linear regression analyses separated by gender, considering height and BMI had showed existing statistically important correlation with graft size (diameter) only in males (Figures 5 and 6).

Considering the whole sample, hamstring graft size was correlated to patient's height and BMI (Figures 7 and 8).

Only height of patients was correlated with length of gracilis and semitendinosus graft and not BMI (Figures 9 and 10).

Pearson's correlation tests analysis in the whole sample indicates that hamstring graft size (diameter) was correlated to patient's height, BMI, and also weight. Height and weight of patients was correlated with length of G and ST tendon graft but not BMI (Table 5). According to gender, Pearson's correlation tests analysis considering weight, height, and BMI had shown existing statistically important correlation with graft size (diameter) only in males (Table 6).

Simple linear regression indicated that patient BMI and height explained approximately 17.1% and 24.7%, respectively, of the variation in quadrupled graft diameter.

Through regression analysis, we constructed the following predictive equations for quadrupled graft diameter:

(i) diameter $= 5.887 + 0.056$ (BMI) ($r = 0.33$; $R^2 = 0.171$; $P = 0.01$),

(ii) diameter $= 2.237 + 0.028$ (height in cm) ($r = 0.33$; $R^2 = 0.247$; $P = 0.01$).

These equations indicate that patients with BMI less than 19.875 and less than 170 cm tall whose weight is less than 57.4 kg are at highest risk for having a hamstring graft less than 7 mm in diameter.

Also simple linear regression for graft lengths indicated that height explained approximately 13.9% of variance in G tendon length and 19.4% of the variance in ST length. Through regression analysis, we came up with the following predictive equations for G graft length (GL) and ST graft length (SL):

(i) GL $= 3.456 + 0.132$ (height in cm) ($r = 0.33$; $R^2 = 0.139$; $P = 0.01$),

(ii) SL $= 6.508 + 0.129$ (height in cm) ($r = 0.33$; $R^2 = 0.194$, $P = 0.01$).

These equations indicate that patients with height less than 167 cm are at highest risk for having an inadequate semitendinosus graft tendon less than 28 cm in length.

When we separated these analyses by gender, we found that height and probably BMI only referring to G length were

Table 1: Means and standard deviation of demographic data.

	N	Age (years)	Height (cm)	Mass (kg)	BMI
Males	45	27.23 ± 6.49	179.73 ± 6.45	68.18 ± 27.23	25.72 ± 3.1
Females	16	24.63 ± 8.63	166.5 ± 3.62	63.13 ± 10.97	22.72 ± 3.59
Total	61	27.02 ± 7.67	176.26 ± 8.26	77.85 ± 14.09	24.93 ± 3.47

Table 2: Means and standard deviation of graft data.

	Length of gracilis (G) tendon graft (cm)	Length of semitendinosus (ST) tendon graft (cm)	Diameter of four-strand hamstring autograft (mm) (G-ST)
Males	27.33 ± 2.88	29.94 ± 2.35	7.41 ± 0.47
Females	25.59 ± 2.81	27.81 ± 1.97	7 ± 0.37
Total	26.88 ± 2.94	29.39 ± 2.43	7.30 ± 0.48

Table 3: Frequency of adequate ST tendon graft length according to gender.

	Length of semitendinosus (ST) tendon graft <28 cm	Length of semitendinosus (ST) tendon graft 28 cm	Length of semitendinosus (ST) tendon graft >28 cm
	N (%)	N (%)	N (%)
Males	6/45 (13.3%)	8/45 (17.7%)	31/45 (69%)
Females	7/16 (43.75%)	3/16 (18.75%)	6/16 (37.5%)
Total	13/61 (21%)	11/61 (18%)	37/61 (61%)

Table 4: Frequency of adequate four-strand hamstring (ST-G) autograft diameter according to gender.

	Diameter of four-strand hamstring (G-ST) autograft <7 mm	Diameter of four-strand hamstring (G-ST) autograft 7-8 mm	Diameter of four-strand hamstring (G-ST) autograft >8 mm
	N (%)	N (%)	N (%)
Males	2/45 (4.4%)	41/45 (91.2%)	2/45 (4.4%)
Females	4/16 (25%)	12/16 (75%)	—
Total	6/61 (10%)	53/61 (86.7%)	2/61 (3.3%)

Table 5: Pearson's correlation coefficients of weight, height, and BMI with hamstring tendon graft characteristics in the whole sample.

	Length of gracilis (G) tendon graft	Length of semitendinosus (ST) tendon graft	Diameter of four-strand hamstring (ST-G) autograft
Weight	0.310*	0.369**	0.567**
Height	0.373**	0.441**	0.498**
BMI	0.165	0.206	0.414**

**$P < 0.01$.
*$P < 0.05$.

Table 6: Pearson's correlation coefficients of weight, height, and BMI with hamstring tendon graft characteristics according to gender.

		Length of gracilis (G) tendon graft	Length of semitendinosus (ST) tendon graft	Diameter of four-strand hamstring (ST-G) autograft
Weight	Male	0.194	0.148	0.470**
	Female	0.193	0.266	0.408
Height	Male	0.321*	0.237	0.368*
	Female	0.067	0.378	0.227
BMI	Male	0.025	0.021	0.295*
	Female	0.194	0.210	0.391

**$P < 0.01$.
*$P < 0.05$.

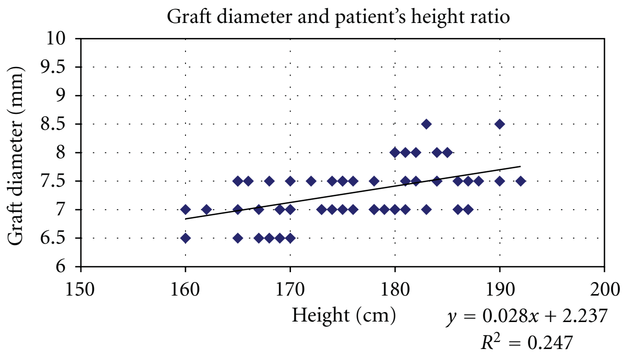

Figure 7: Scatter plots showing relationships between hamstring graft size and patient's height in the whole sample. Correlation coefficients and P values are included. $r = 0.497896$, r for $\chi^2 = 0.32773$, $P = 0.01$.

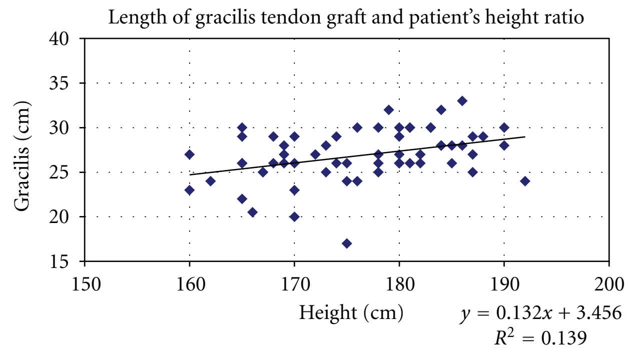

Figure 9: Scatter plots showing relationship between height of patients and length of G tendon graft in the whole sample. Correlation coefficients and P values are included. $r = 0.373363094$, r for $\chi^2 = 0.32773$, $P = 0.01$.

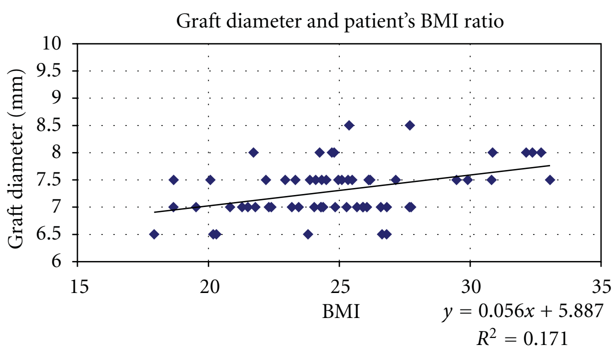

Figure 8: Scatter plots showing relationships between hamstring graft size and patient's BMI in the whole sample. Correlation coefficients and P values are included. $r = 0.413521$, r for $\chi^2 = 0.32773$, $P = 0.01$.

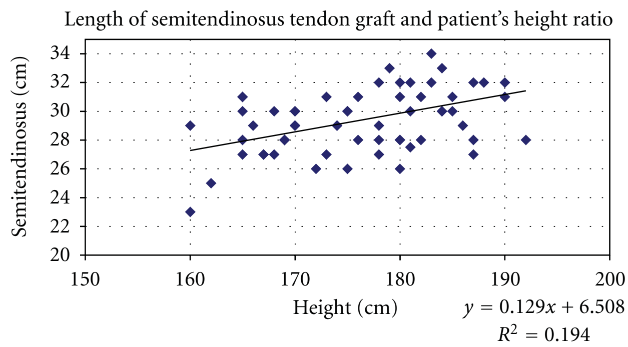

Figure 10: Scatter plots showing relationship between height of patients and length of ST tendon graft in the whole sample. Correlation coefficients and P values are included. $r = 0.441248$, r for $\chi^2 = 0.32773$, $P = 0.01$.

the best predictors for graft diameter in male patients. We found no statistically important predictor for graft diameter in female patients (Table 6).

4. Discussion

In our study in one out of five patients (21%) the length of ST tendon, harvested by the common technique, was inadequate in order to be used alone as a four-strand graft. Especially in female patients, the length of ST tendon was less than 28 cm in 43.75%. Moreover, according to our findings, height and weight are considered to be moderate predictors of the adequacy of the semitendinosus tendon length when using alone ST four-strand graft or of the four-strand ST and G graft diameter for ACL single-bundle reconstruction harvested by common technique (without bone plug). The most reliable predictor seems to be patient's height in males. In female patients, there is no such statistically important predictor.

The use of ST and G grafts seems to have good results in many studies [18–21], while other studies report similar results by the use of ST only tendon as a quadrupled graft in reconstruction of ACL [22–24]. Gobbi et al. recommended using only one tendon whenever possible because the ST alone seem to have an advantage over the ST-G construct with regard to internal rotation weakness following harvest of two tendons, although there is not much clinical difference in both techniques [12]. In order to assure the optimal 7 cm quadrupled graft construct (2 cm in the femoral tunnel, 3 cm intra articular, and 2 cm in the tibial tunnel), it is essential to obtain a minimum tendon length of 28 cm (ranged from 28 to 30 cm) [11]. Increased research of double-bundle reconstruction and development of new operative techniques necessitate preoperative planning of size parameters for ideal graft choice [25]. Furthermore, a new technique of ACL reconstruction with double-bundle, single tendon (ST) seems to offer the possibility of reconstructing both the AM and PL bundles without disrupting the function of hamstring muscles. This is achieved due to preservation of gracilis tendon, which offers stability in deep flexion and internal rotation strength and protects from further ACL injuries [12]. But even in this case, the minimum graft length needed is 28 cm (2 cm in the femoral tunnel, 3 cm intra-articular, and 2 cm in the tibial tunnel) [12]. Additionally, it has been demonstrated that the average diameter of the normal ACL is 11 mm; therefore, a graft of minimum thickness of 7 mm is recommended [15–17]. The thicker the graft is the stronger and stiffer the graft will be. The biomechanical properties of the graft are certainly affected by its diameter.

According to Vernon et al., the use of ST tendon alone is adequate in almost all cases [26] and the rate of insufficiency for a quadrupled reconstruction is only one in 300 cases and is almost always the result of improper graft harvest [27]. In contrast to our results regarding the adequacy of semitendinosus tendon as a four-strand graft for ACL reconstruction, the ST graft length was inadequate (i.e., shorter than 28 cm) in 21% of all our patients and in 18% it was marginally adequate (28 cm) and only in 61% of our patients semitendinosus tendon graft length was longer than 28 cm. This is a high percent of possible cases in which ST four-strand tendon graft could be inadequate for ACL reconstruction and additional G tendon graft would be needed and comes in contrast to claims of other authors who support and recommend to use of only one tendon whenever possible [7]. Referring to female patients, these rates are more impressive, while in 43.75% of all cases the ST graft length was inadequate, and in 18.75% it was marginally adequate and only in 37.5% of our female patients ST tendon graft length was longer than 28 cm (Table 3). Additionally simple linear regression for graft lengths indicated that patients with height less than 167 cm are at highest risk for having an inadequate ST graft tendon less than 28 cm in length.

Referring to graft diameter and according to our results, the majority of patients (86.7%) had an adequate quadrupled graft diameter (7 to 8 mm), while 10% of patient's grafts were inadequate (less than 7 mm). Referring to female patients, this percent becomes 25%. Only 2 patients (3.3%) had graft diameter greater than 8 mm (Table 4). Pinheiro et al. report that males with height equal to or greater than 1.80 m achieved a higher percentage of 9 mm grafts and larger average of graft diameter in comparison to the other patients with a height less than 1.80 m males or females or both [28]. In our sample, the two men with graft diameter greater than 8 mm had height greater than 1.80 m (1.83 m and 1.90 m). The hypothesis of Pinheiro et al. [28] is confirmed in our cases, but we cannot reach to safe conclusion because of the small number of our cases.

Hamstring graft size according to our study could be predicted by evaluating preoperatively some simple anthropometric parameters. According to our results ST, and G graft diameter was most strongly correlated to patient's weight (moderate correlation, $r = 0.567$), then to height (moderate correlation, $r = 0.498$) and finally to BMI (fair correlation, $r = 0.414$). Treme et al. in a study of 50 consecutive patients observed a positive effect of the BMI on graft diameter [29] in contrast to Tuman et al. and Pinheiro et al. who claim that BMI does not influence graft diameter [28, 30]. Referring to patient's weight in the study of Pinheiro et al. had less influence in graft diameter, contrary to us and to Treme et al. who found the strongest correlation with weight [28, 29]. Finally Schwatzberg et al. found moderate correlation between weight and graft diameter in a study of 119 consecutive patients [31]. In another series of 536 patients, height was found to be a strong predictor of quadrupled hamstring graft diameter in 234 male patients [32].

The lengths of the hamstring graft can also be predicted by preoperative anthropometric measurements. In our study, the length of G and ST graft was most strongly correlated with height (fair correlation, $r = 0.441$) and then with weight (weak correlation, $r = 0.369$) of patient's, but there was no correlation with BMI. Also in a study of 80 patients, Pinheiro et al. claim that height is the most important variable that influences most the graft length [28]. Treme et al. noted that height and leg length were strongly correlated with the hamstring tendon lengths [30]. Chiang et al. in a study of 100 patients conclude that the patients' height could be used to predict both ST and G tendon lengths in Chinese patients [33]. Tuman et al. after studying 106 patients concluded that height was also the most important variable but mainly in women [30]. Schwatzberg et al. claim weak correlation to patient's height [31].

We found no statistically important predictor for graft diameter in female patients. Female patients were significantly lighter and shorter with lower BMIs and had shorter length and smaller diameter hamstring grafts in comparison with males. This result is in accordance with studies of Tuman et al., and Treme et al., who claimed that, mean values of graft diameter as well as weight and height in males were greater than in females [29, 30]. Chiang et al. also in their findings showed that men had significantly longer tendons than women [33]. In our study, simple linear regression for graft diameter indicated that patients with BMI less than 19.875 and less than 170 cm tall whose weight is less than 57.4 kg are at highest risk for having a hamstring graft less than 7 mm in diameter.

There are some limitations in our study. Firstly, the sample of female patients is not adequate in order to exact secure conclusions. Moreover, we were unable to investigate if smaller size of hamstring graft tendon in women were related to gender or to the smaller average anthropometric measurements [28]. This was due to the fact that our groups according to gender had great differences of anthropometric variances. Secondly, we recognize the fact that our results could be influenced by the size of the sample, which could influence our data and as a consequence our results. For example, the correlation of BMI and the length of the graft could change if we had operated patients with great BMI. However, we believe that this patient group is a representative sample of patients that we operate for ACL deficiency. Thirdly, we did not evaluate the different level of sport activity of our patients and any possible correlation with graft diameter of length. Finally, in some cases the graft diameter was not exactly fitted in a specific 0.5 mm increment. In these cases, the size of the graft was recorded according to the drill size of our tunnels.

The clinical relevance of this study showed that in shorter or female patients, there was a relatively higher risk of obtaining inadequate individual hamstring tendon lengths for double-bundle anterior cruciate ligament reconstruction procedures. Moreover, in our surgical practice, we used to harvest first the G tendon and then the ST tendon. After this study, we have altered our technique. The clinical importance of these findings and our suggestion is that ST tendon graft removal should always be performed before G tendon harvesting, and according to its adequacy of length (>28 cm), the surgeon should decide whether further augmentation of the ACL graft with G tendon would be necessary.

5. Conclusions

Hamstring grafts less than 7 mm in diameter and 28 cm in length are not so rare. According to our findings we come to the conclusion that the length of ST tendon, harvested by the common technique, is usually inadequate in order to be used alone as a four-strand graft especially in females. Identification of these patients is still a subject of research. The potential of size prediction of autograft hamstring tendons in ACL reconstruction could contribute to choose the best graft and surgical technique individualized on patient's needs and in accordance with their special characteristics. By that way the possibilities of a good postsurgical result would be multiplied in difficult cases of patients like women, children, and professional athletes or revision of ACL. Also special surgical techniques such as quadrupled ST double-bundle ACL reconstruction and the DBST (double bundle, single-tendon) technique could be used more wisely avoiding unnecessary complications such as scar formation, pain, and operating time and infection risk. Height and weight are considered to be moderate predictors of the adequacy of the semitendinosus tendon length when using alone ST four-strand graft or of the four-strand ST and G graft diameter for ACL single-bundle reconstruction harvested by common technique (without bone plug). The most reliable predictor seems to be patients' height in males. In female patients, there is no such statistically important predictor.

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Research Article

Application of Soft Tissue Artifact Compensation Using Displacement Dependency between Anatomical Landmarks and Skin Markers

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Soft tissue artifact is known to be one of the main sources of errors in motion analysis by means of stereophotogrammetry. Among many approaches to reduce such errors, one is to estimate the position of anatomical landmarks during a motion with joint angle or displacement of skin markers, which is the so-called compensation method of anatomical landmarks. The position of anatomical landmarks was modeled from the data of the so-called dynamic calibration, in which anatomical landmark positions are calibrated in an ad hoc motion. This study aimed to apply the compensation methods with joint angle and skin marker displacement to three lower extremity motions (walking, sit-to-stand/stand-to-sit, and step up/down) in ten healthy males and compare their reliability. To compare the methods, two sets of kinematic variables were calculated using two different marker clusters, and the difference was obtained. Results showed that the compensation method with skin marker displacement had less differences by 30–60% compared to without compensation. In addition, it had significantly less difference in some kinematic variables (7 of 18) by 25–40% compared to the compensation method with joint angle.

1. Introduction

Skin marker-based stereophotogrammetry is the most commonly used technique to analyze motions, despite significant errors due to the deformation of soft tissues such as skin and muscle. The displacement of skin markers relative to the underlying bones is called soft tissue artifact (STA), and it is responsible for errors in motion analysis. Skin marker displacement can be as much as 40 mm in the lower extremities [1, 2]. Error in computed angle due to STA ranges from 10° to 20° and is especially significant in abduction/adduction and internal/external rotation motions [1, 3, 4].

Methods proposed to reduce STA errors are based on either one of two principles: (1) treating the STA as an independent noise irrespective of motor tasks and (2) modeling a systematic pattern of STA in relation to motor tasks. Representatives of the first category are the studies of Challis [5], Ball and Pierrynowski [6], and Alexander and Andriacchi [7]. Challis [5] and Ball and Pierrynowski [6] made models of skin marker cluster deformation using geometric transformations, such as scaling and shearing. Alexander and Andriacchi [7] attempted to model the trajectory of skin marker displacements relative to the underlying bones using the Gaussian function.

The second category includes methods that assessed task-related patterns of STA by obtaining the positions of anatomical landmark—which indicates the skeletal pose—and skin markers at multiple postures or in an ad hoc motion. Cappello et al. [8] and Cappello et al. [9] proposed the double anatomical landmark calibration, in which anatomical landmark positions are measured by a pointer at two static postures in a motor task. Lucchetti et al. [10] proposed the so-called dynamic anatomical landmark calibration to identify anatomical landmark positions in an ad hoc motion. Instead of measuring STA skin marker displacements relative to the underlying bones, they innovatively assessed the relative movement of anatomical landmarks in reference to the coordinate frame defined by the cluster of skin markers, referred to as technical coordinate frame defined by skin markers (TCF). They modeled the displacement of

Table 1: Definition of anatomical coordinate frame (ACF) of lower extremities.

Segment	Definition
Pelvis	Origin: the mid-point of left and right anterior superior iliac spine
	z: connecting left anterior superior iliac spine to right anterior superior iliac spine
	y: orthogonal to the plane defined with left and right anterior superior iliac spine and the midpoint left and right posterior superior iliac spine
	x: the cross vector of Y and Z
Thigh	Origin: the midpoint of lateral and medial epicondyles
	y: connecting the origin to femoral head
	x: orthogonal to the plane defined with lateral epicondyle, medial epicondyle, and femoral head
	z: the cross vector of X and Y
Shank	Origin: the midpoint of lateral and medial malleolus
	y: intersection of the plane defined by lateral malleolus, medial malleolus, and head of fibula and the plane defined by tibial tuberosity and the midpoint of lateral and medial malleolus; positive direction is proximal
	x: orthogonal to the plane defined by lateral malleolus, medial malleolus, and head of fibula
	z: the cross vector of X and Y
Foot	Origin: calcaneus
	y: intersection of the plane defined by calcaneus, first metatarsal head and fifth metatarsal head, and the plane defined by calcaneus and second metatarsal head; positive direction is proximal
	x: orthogonal to the plane defined by calcaneus, first metatarsal head, and fifth metatarsal head
	z: the cross vector of X and Y

anatomical landmarks against motion time or joint angle to correct anatomical landmark positions relative to TCF when performing a motor task.

As an alternative to anatomical landmark position compensation with joint angle, Ryu et al. [11] proposed anatomical landmark position compensation with skin markers. They assumed that anatomical landmark displacement is associated with skin marker displacements in the same TCF and attempted to model the relationship between them. They showed that the method was more effective than the anatomical landmark position compensation with joint angle, although they tested only by analyzing knee motions of a patient wearing an external fixator on the shank.

The present study applied the two anatomical landmark position compensation methods in real lower extremity movements of healthy people. This involved motion analysis of the hip, knee, and ankle joints in three lower extremity motions, walking, sit-to-stand/stand-to-sit, and step up/down, in 10 healthy males. The performance of the compensation method with skin markers was compared to the method with joint angle.

2. Methods

2.1. Experimental Setup. A motion measurement system with six cameras (Falcon, MotionAnalysis) was used to measure lower extremity motions (sampling frequency 60 Hz, measurement volume $4 \times 3 \times 2$ m). The accuracy of the system was assessed by comparing the measured distance between two marker positions to the known distance, such that the variation of the distance indicates error, as described by [12]. Mean error of the marker distance was 0.63 mm, maximum error was ±3.30 mm, and SD of the distance was 0.82 mm.

Ten healthy young males with no previous history of musculoskeletal or neurological disorders related to the lower extremities participated in the experiment. The mean height, weight, and age of the participants were 1.75 m (SD = 0.03), 69.3 kg (SD = 5.8), and 26.2 years (SD = 3.0), respectively. All the participants signed informed consent forms.

The anatomical coordinate frame defined by anatomical landmarks (ACF) of the pelvis, thigh, shank, and foot of the participants was defined according to [13]. Left/right anterior superior iliac spine and posterior superior iliac spine defined the ACF of the pelvis, whereas femoral head and lateral and medial epicondyles were used for the thigh. Detailed definitions of the ACFs for all lower limb segments are presented in Table 1.

Twenty reflective markers (20 mm diameter) were placed on the right lower limb segments of the participants (Figure 1). Four markers (P1–P4) are located on the palpable point of anatomical landmarks of the pelvis, and four markers (F1–F4) were placed randomly on the foot. Two sets of six markers (T1–T6 and S1–S6) were placed on the thigh and the shank, respectively. These were grouped into two marker clusters: T1–T4 and T3–T6 for the thigh and S1–S4 and S3–S6 for the shank.

The participants performed six motor tasks: (1) standing static posture; (2) flexion/extension, abduction/adduction, and internal/external rotation of hip joint; (3) hip joint swing motion with fixed knee joint; (4) sitting static posture; (5) knee joint motion with fixed ankle; (6) walking, sit-to-stand/stand-to-sit, and step up/down. Standing and sitting static postures were held for 1-2 minutes for anatomical landmark calibration, and hip joint flexion/extension,

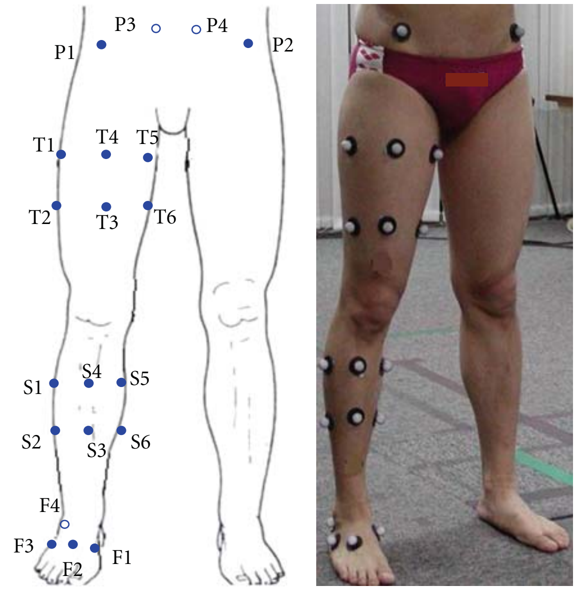
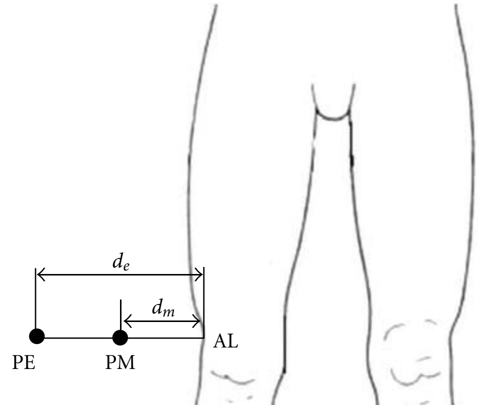
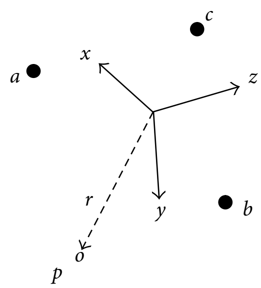


FIGURE 1: Marker placement on the participants.



$$\mathrm{AL} = \mathrm{PM} + d_m \frac{\mathrm{PM} - \mathrm{PE}}{\|\mathrm{PM} - \mathrm{PE}\|} \text{ or } \mathrm{AL} = \mathrm{PE} + d_e \frac{\mathrm{PM} - \mathrm{PE}}{\|\mathrm{PM} - \mathrm{PE}\|}$$

FIGURE 2: Anatomical landmark position identification with a pointer.



$$x = \frac{a - b}{\| a - b \|},\ y = \frac{(c - b) \times (a - b)}{\| (c - b) \times (a - b) \|},\ z = x \times y$$

$$r = [(p - o)\cdot x, (p - o)\cdot y, (p - o)\cdot z]$$

o: the origin of coordinate frame, which can be selected appropriately.

FIGURE 3: Coordinate frame definition with three markers (a, b, and c) and position vector of a point (p) relative to the frame.

abduction/adduction, and internal/external rotation were performed to identify the center of the hip joint. Hip joint swing motion with fixed knee and knee joint motion with fixed ankle were conducted as ad hoc motions for the dynamic anatomical landmark calibration. Walking, sit-to-stand/stand-to-sit, and step up/down were performed as target motions for analysis.

2.2. Anatomical Calibration. Anatomical landmark calibration was performed in both standing and sitting static postures using a pointer on which two markers with a known distance were mounted (see Figure 2). In the standing static posture, the position of lateral and medial epicondyles of the thigh, and that of first, second, fifth metatarsal heads, and calcaneus of the foot were identified. The position of femoral head was estimated as the center of marker trajectory in various hip motions, based on the functional method of [14]. The accuracy of the functional method was computed with the distance between two hip joint centers estimated from the pelvis and thigh. The average distance was 18 mm of [14] and 22.3 mm of this study. Then, the positions of head of fibula, tibial tuberosity, lateral, and medial malleolus of the shank were identified in the sitting posture.

Geometric calculations were used to determine the positions of thigh and shank anatomical landmarks relative to the TCFs on the corresponding body segments and on neighboring segments. For example, if there are three skin marker a, b, c and an anatomical landmark p, a TCF is defined by the skin markers, and the position of p relative to the TCF is computed like Figure 3. The anatomical landmark position relative to the TCFs on neighboring segments is computed because the neighboring segment is unaffected by STA during ad hoc motions, such as hip joint swing with knee fixed (extended) and knee joint motion with ankle fixed (dorsiflexed). Thus, this information is used to calibrate the anatomical landmark position during ad hoc motions like Figure 4.

Two thigh TCFs (TCF^1 by T1, T2, T3, and TCF^2 by T4, T5, T6) and two shank TCFs (TCF^1 by S1, S2, S3, and TCF^2 by S4, S5, S6) were defined to compare the reliability of the two compensation methods. The difference between two values of kinematic variables, which is calculated with two sets of TCFs, was used as reliability measure. The local coordinates of each anatomical landmark of the thigh and shank were fixed in each TCF. The local coordinates of each thigh anatomical landmark were also fixed in a shank TCF and that of each shank anatomical landmark were fixed in the TCF of the foot by markers F1–F4.

2.3. Pose Calculation of Coordinate Frames. The poses of all the TCFs and ACFs during ad hoc motions and three target motions were calculated using the Singular Value Decomposition algorithm of [15]. The methods find a transformation

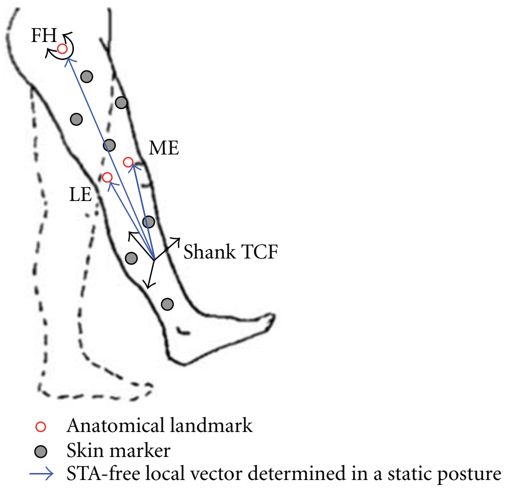


FIGURE 4: Anatomical calibration in hip joint swing motion with knee fixed (FH: femoral head, ME: medial epicondyles, LE: lateral epicondyles, TCF: technical coordinate frame).

matrix that minimizes the sum of the transformation errors as in (1). The position vector and orientation matrix of each TCF was obtained from the transformation matrix, which was estimated by the algorithm between the local coordinates and global positions of the three relevant skin markers in the TCF. Likewise, the transformation matrix of each ACF was obtained from the local coordinates and estimated global positions of the relevant anatomical landmark in the ACF

$$b_i = Ra_i + t + \varepsilon, \tag{1}$$

where a_i: local position vector of marker i, b_i: global position vector of marker i, R: rotational matrix (3×3), t: translation vector (3×1), and ε: random error (3×1).

Find R & t to minimize

$$\sum_{i=1}^{n} \|Ra_i + t - b_i\|^2, \tag{2}$$

where n: Number of markers (≥ 3).

2.4. Anatomical Landmark and Skin Marker Displacement. The displacements of the anatomical landmarks and skin markers on the thigh during the hip joint swing motion with fixed knee were obtained in reference to the two thigh TCFs. The positions of anatomical landmarks (lateral epicondyle [LE], medial epicondyle [ME], and femoral head [FH]) were reconstructed using a shank TCF and the relevant anatomical landmark local coordinates (3)

$$b = Ra + t, \tag{3}$$

where a: local coordinate of anatomical landmark, b: global coordinate of anatomical landmark, R: rotational matrix (3×3) of shank TCF, and t: translation vector (3×1) of shank TCF.

Anatomical landmark displacements were calculated as the difference between the local coordinates of the reconstructed anatomical landmarks and those fixed in the standing static posture for the two thigh TCFs as in (4)

$$\text{Displacement} = l_s - l_t, \tag{4}$$

where l_s: local coordinate of anatomical landmark, which is reconstructed from shank TCF relative to thigh TCF and l_t: local coordinate of anatomical landmarks relative thigh TCF, which is computed from static posture.

$$\begin{gathered} l_s = \left[(b-o)\cdot x \quad (b-o)\cdot y \quad (b-o)\cdot z \right], \\ x = \frac{s_i - s_j}{\left\| s_i - s_j \right\|}, \\ y = \frac{\left(s_k - s_j\right) \times \left(s_i - s_j\right)}{\left\| \left(s_k - s_j\right) \times \left(s_i - s_j\right) \right\|}, \\ z = x \times y, \end{gathered} \tag{5}$$

b: global coordinate of thigh anatomical landmark, s_n: position of one marker of skin marker cluster of thigh, $n = i$, j, and k, and o: the origin of a thigh TCF, which can be selected appropriately.

Likewise, the displacement of skin markers T4 (for thigh TCF1) and T3 (for thigh TCF2) was calculated to model the anatomical landmark displacement with the displacement of a skin marker, which is not a member of a marker cluster. They were computed by subtracting the local coordinates in each thigh TCF fixed in the static posture from the measured ones during motion. In the same way, the displacements of anatomical landmarks (head of fibula, tibial tuberosity, lateral, and medial malleolus) and skin markers S4 (for shank TCF1) and S3 (for shank TCF2) during the knee joint motion with fixed ankle were obtained in reference to the two shank TCFs.

The relationship between the displacements of anatomical landmarks and skin markers was represented in a linear model using a simple regression form because of its simplicity and repeatability. Each axial component of an anatomical landmark displacement was plotted with the three axial components of the relevant skin marker displacement. The skin marker component with the highest correlation coefficient with anatomical landmark displacement was identified. It is possible to use multiple regression models with three components, but in this case, there will be multicollinearity in the model and the developed model will be much varied by analyzers.

Anatomical landmark displacement with joint rotation in the sagittal plane was modeled to compare the alternative method of [11] with the anatomical landmark compensation method with joint angle by [10]. For example, the plot between anatomical landmark displacement in the thigh and flexion/extension of hip joint was shown like Figure 5. Anatomical landmark positions during the target lower extremity motions were corrected using the developed anatomical landmark displacement models. At each frame of

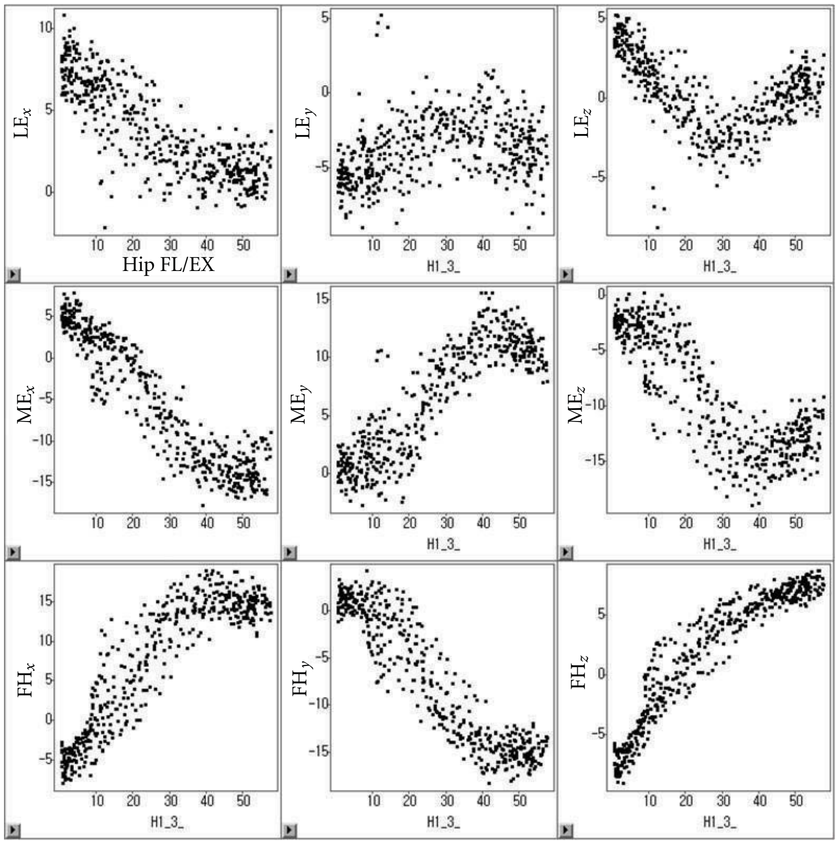


Figure 5: Scatter plot of anatomical landmark displacement and hip joint flexion/extension (FL/EX) of a participant (LE: lateral epicondyle, ME: medial epicondyle, FH: femoral head, x, y, and z: axial component of x, y, and z-axis).

the motion, anatomical landmark displacements were estimated from the models. Local coordinates of the anatomical landmarks in each TCF fixed during the static posture were adjusted in relation to the relevant anatomical landmark displacements.

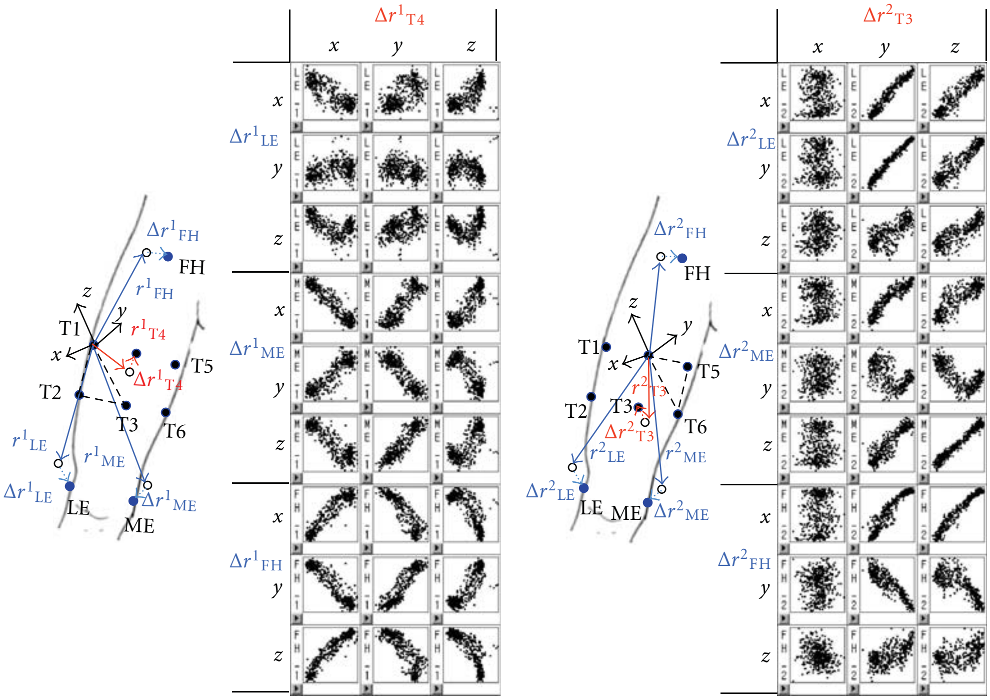
2.5. Motion Analysis Methods. Target lower extremity motions (walking, sit-to-stand/stand-to-sit, and step up/down) were analyzed using three methods: the compensation method with skin markers [11], with joint angle [10], and Singular Value Decomposition algorithm [15]. The method of [15] was used to analyze the target motions without anatomical landmark compensation.

2.6. Evaluation of Motion Analysis Reliability. Reliability of the three methods was determined by the difference between two sets of kinematic variables estimated using two marker clusters, as described by the method of [10]. The effect of STA on skin markers varies across different locations, such that the kinematic variables estimated from two different marker clusters without STA compensation will greatly differ. The kinematic variables included three angular motions (abduction/adduction, internal/external rotation, and flexion/extension) and three transitional motions (anteroposterior, longitudinal, and medio-lateral motion) of hip, knee, and ankle joint.

2.7. Statistical Analysis. Two-way analysis of variance (ANOVA) was conducted to determine if motion analysis differences are affected by the type of analysis method and the type of target motion. For each kinematic variable, time series differences were obtained. Then, two-way ANOVA was performed with the type of analysis method and type of motion as independent variables. Differences found to be significantly affected by analysis method or motion type were further examined using the Student-Newman-Keuls (SNK) test to determine if the differences are statistically different from one another.

3. Results

3.1. Anatomical Landmark Displacement Model. There was a dependency between the displacements of the anatomical landmarks and the skin marker in the corresponding TCFs in the ad hoc motions. The plots between the thigh anatomical landmark displacements (Δr^1_{LE}, Δr^1_{ME}, Δr^1_{FH} in TCF^1, and Δr^2_{LE}, Δr^2_{ME}, Δr^2_{FH} in TCF^2) and the thigh skin marker displacements (Δr^1_{T4} in TCF^1, Δr^2_{T3} in TCF^2) for a participant are shown in Figure 6. Most anatomical landmark displacements had a high dependency with at least one of the three axial components of the displacements of the skin markers. However, the y and z components of Δr^1_{LE} had a weak dependency with the displacement of T4,



(a) Marker cluster 1

(b) Marker cluster 2

Figure 6: Scatter plot of anatomical landmark and skin marker displacement on the thigh of a participant (LE: lateral epicondyle, ME: medial epicondyle, FH: femoral head, x, y, and z: axial component of x, y, and z-axis).

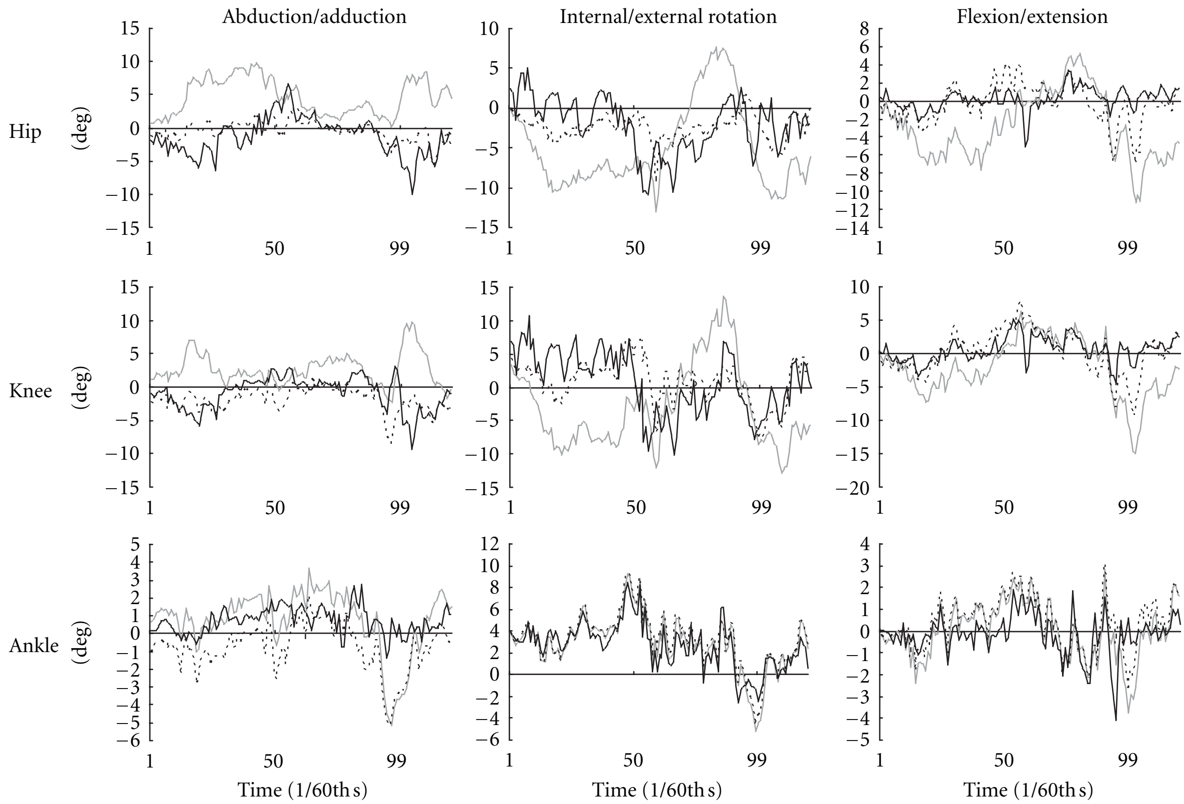
and this is similar with the y component of Δr^2_{ME} and z component of Δr^2_{FH}. Likewise, most of the shank anatomical landmark displacements (HF, TT, LM, and MM) had a high dependency with the shank skin marker displacements (S4 and S3). This study identified one axial component of the skin markers that was highly correlated with each component of anatomical landmark displacements.

A simple model for each axial component of anatomical landmark displacements was made from those having a linear regression form in relation to the axial component of the skin marker displacement having the highest correlation coefficient. The anatomical landmark displacement model was confined to linear form because it is simple to develop and it makes the anatomical displacement models consistent between model developers. For example, of a total of 42 models for anatomical landmark displacements for one participant, 32 models had R^2 values higher than 0.5.

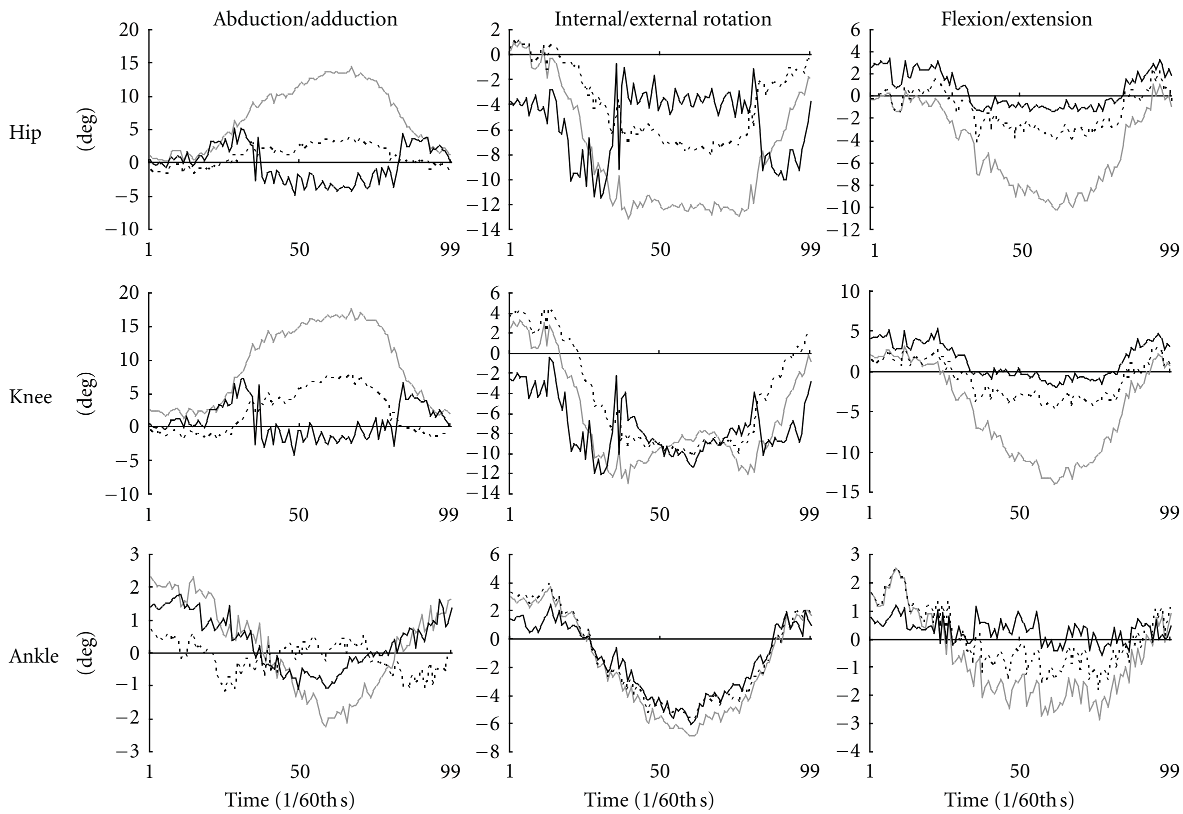
3.2. Motion Analysis Difference. Figure 7 presents the differences between the joint angular motions of lower extremities estimated using two marker clusters during walking and sit-to-stand/stand-to-sit. The differences between the two estimated angular motions of the hip and knee joints are apparently more reduced with anatomical landmark compensation using skin marker displacement and joint angle than without anatomical landmark compensation. On the other hand, the differences during ankle angular motions were similar for all three methods and did not vary with compensation. These same trends were observed in step up/down motions.

Two sets of estimated kinematic variables were calculated by averaging the differences over time for the 10 participants. Mean differences between these two sets were analyzed using two-way analysis of variance (ANOVA). The effect of motion type (walking, sit-to-stand/stand-to-sit, and step up/down), analysis method (compensation with skin marker displacement and joint angle, and without compensation), and their interaction with the mean differences for 18 kinematic variables are shown in Table 2. For most kinematic variables, the mean differences were significantly affected by the analysis method, except for the antero-posterior motion of the hip joint and the longitudinal motion of the ankle joint. They were not significantly different for varying motion types, except for internal/external rotation of all three joints. Furthermore, the interaction of the motion type and analysis method was significant only for the knee flexion/extension, ankle internal/external rotation, and hip medio-lateral motions.

The student Newman-Keuls (SNK) test of the mean differences for the three methods showed that compensation with skin marker displacement was more effective than without compensation for most kinematic variables and more effective than compensation with joint angle for some of them. For most angular joint motions, compensation with skin marker displacement had significantly smaller (33–60%) mean differences than without compensation, except for ankle flexion/extension (see Figure 8(a)). Compensation with skin marker displacement had significantly smaller mean differences than compensation with joint angle for the flexion/extension of the hip and ankle (27 and 41%,



(a) walking



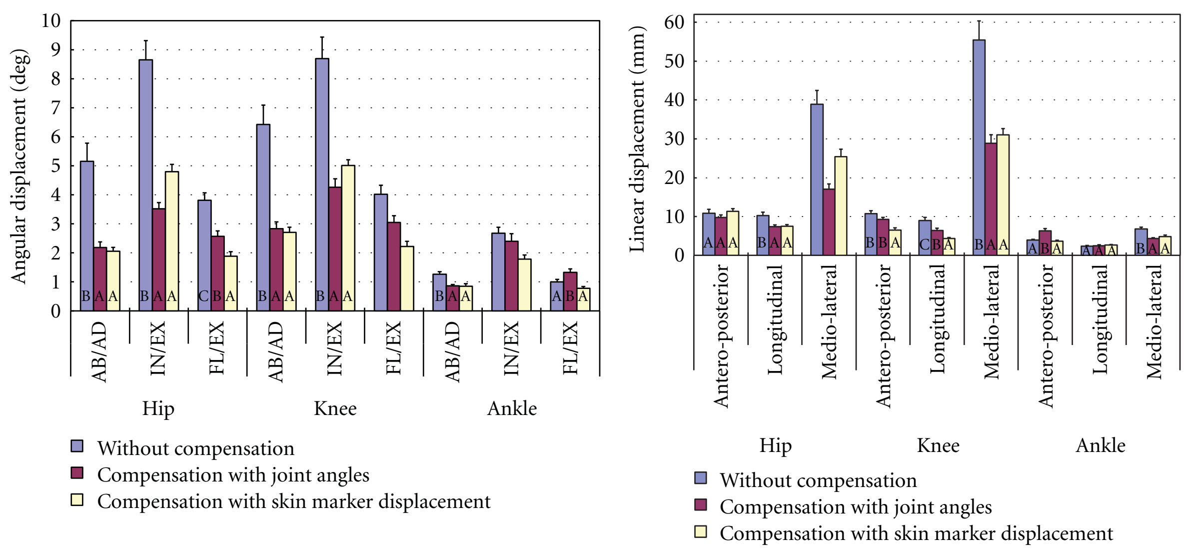
(b) Site-to-stand/stand-to-sit

Figure 7: Differences between two angular motions estimated using two different marker clusters for a participant (compensation with skin marker displacement: solid black; compensation with joint angle: dashed black; without compensation: solid gray).

Table 2: ANOVA summary of mean difference of kinematic variables between marker clusters.

Joint	Kinematic variable	Motion type	Method	Motion type × Method
	abduction/adduction	×	○	×
Hip	internal/external rotation	○	○	×
	flexion/extension	×	○	×
	abduction/adduction	×	○	×
Knee	internal/external rotation	○	○	×
	flexion/extension	×	○	○
	abduction/adduction	×	○	×
Ankle	internal/external rotation	○	○	○
	flexion/extension	×	○	×
	Antero-posterior (X)	×	×	×
Hip	Longitudinal (Y)	×	○	×
	Medio-lateral (Z)	×	○	○
	X	×	○	×
Knee	Y	×	○	×
	Z	×	○	×
	X	×	○	×
Ankle	Y	×	×	×
	Z	×	○	×

○: significant ($\alpha = 0.05$); ×: not significant.



(a) Angular motion

(b) Linear motion

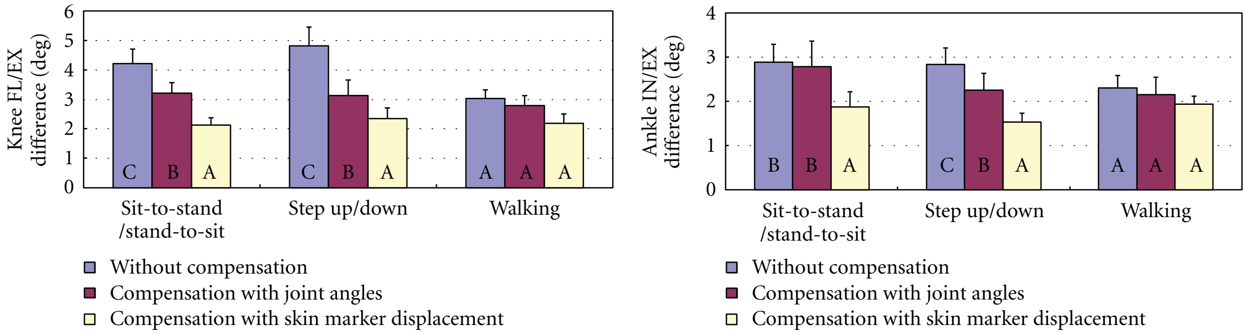
Figure 8: SNK test of the mean differences for different analysis methods.

resp.). For knee flexion/extension and ankle internal/external rotation where the interaction effect existed, compensation with skin marker displacement had significantly smaller mean differences than without compensation and compensation with joint angle in sit-to-stand/stand-to-sit and step up/down motions, but not in walking (Figure 9).

Moreover, compensation with skin marker displacement had significantly smaller (27–52%) mean differences than without compensation for five of the nine linear motions (see Figure 8(b)). It also had significantly smaller (30–42%) mean differences than compensation with joint angle for three motions. For hip medio-lateral motion where the interaction effect existed, compensation with skin marker displacement had significantly smaller differences than without compensation but had significantly larger mean differences than compensation with joint angle in walking and step up/down motions (Figure 10).

4. Discussion and Conclusions

Both anatomical landmark compensation methods (with skin marker displacement and joint angle) showed good



(a) Knee flexion/extension

(b) Ankle internal/external rotation

Figure 9: SNK test of the mean differences of knee flexion/extension and ankle internal/external rotation.

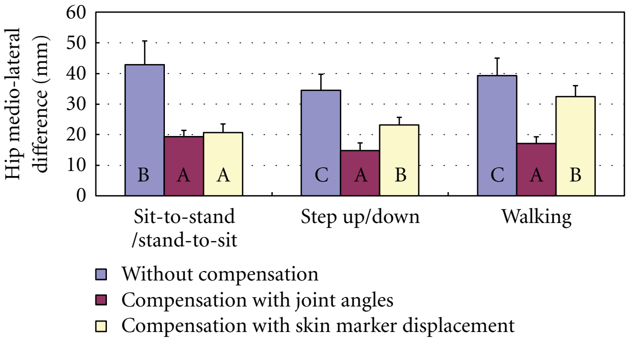


Figure 10: SNK test of the mean differences of hip medio-lateral motion.

reliability in real lower extremity motions. In the study, differences between two marker clusters for the hip and knee kinematic variables (all but hip antero-posterior motion) were significantly reduced by 30–60% by anatomical landmark compensation with skin marker displacement compared to that without compensation. Reduction of the differences by anatomical landmark compensation with joint angle ranged from 10 to 60%.

Of the two anatomical landmark compensation methods, the one using skin marker displacement showed slightly better reliability in analyzing lower extremity motions. Results showed that the differences of five kinematic variables (hip flexion/extension, ankle flexion/extension, knee antero-posterior, knee longitudinal, and ankle antero-posterior motion) were significantly reduced by compensation with skin marker displacement by 30–40% more than joint angle compensation regardless of the target motion. The former method also significantly reduced the differences of knee flexion/extension and ankle internal/external rotation in sitting and stepping than the latter method by 25–30%. Compensation with joint angle was 35–50% more reliable than with skin marker displacement for only one variable (hip medio-lateral motion) in some target motions.

Compensation with joint angle had some limitations in analyzing the kinematics of the ankle joint. While compensation with joint angle was as good as with skin marker displacement in analyzing hip and knee joint motions, it had larger mean differences than without compensation for some variables of the ankle joint. This seems to be because of the relatively large inaccuracy of the joint angle used in anatomical landmark compensation. Without compensation, the mean difference of knee flexion/extension was as large (4.0°) as that of hip flexion/extension (3.8°); the joint angle estimated without compensation was used to estimate anatomical landmark positions in compensation with joint angle. In contrast, anatomical landmark displacements of the shank (5–20 mm) were small relative to those of the thigh (15–40 mm). Therefore, the unreliable knee joint angle seems to have a large effect on the anatomical landmark position estimation of the shank relative to the thigh.

The compensation with skin marker displacement and with joint angle still had some residual differences. Even in a stationary posture, mean differences between two sets of kinematic variables estimated using two marker clusters, which represent the instrumental errors in this study, were 0.1–3° and 1–16 mm for angular and linear motions, respectively. During target motions, mean differences for compensation with skin marker displacement and compensation with joint angle were 1–5° and 5–30 mm for angular and linear motions, respectively.

This study had a limitation that it only evaluated the reliability of compensation methods, but not accuracy. To compute the accuracy of the compensation methods, tracking the position of underlying bones is necessary, and errors in kinematic variables should be compared to validate the compensation methods. But this study could not do it due to practical reasons, thus further study will be needed to validate the methods.

Moreover, the relationship between the displacement of the anatomical landmarks and those of skin markers reflected STA partially. STA in the thigh can occurr with hip and knee joint motions and that in the shank with knee and ankle joint motions. However, this study obtained the relationship in the thigh from only hip joint motions and those in the shank from only knee joint motions. Therefore, the relationship would not consider the whole STA of real lower extremity motions in which both the proximal and distal joints move together. A further study will be necessary to analyze and use the relationship using additional motions such as ankle joint motion with knee fixed and knee joint motion with hip fixed.

This study applied the compensation methods in some lower extremity motions and compared their reliability. Compensation with skin marker displacement was more reliably than with joint angle, although both methods were superior to without compensation. For hip and knee motions, both anatomical landmark compensation methods reduced differences between marker clusters by half in the three motions than without compensation. Compensation with joint angle had some weaknesses in analyzing ankle motion, whereas compensation with skin marker displacement consistently showed less difference between marker clusters than without compensation.

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Research Article

Meniscofibular Ligament: Morphology and Functional Significance of a Relatively Unknown Anatomical Structure

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Purpose. A relatively unknown ligamentous structure of the posterolateral corner of the knee joint, the so-called meniscofibular ligament (MFL), was investigated as regards its macroscopic morphology, its histological features, and its reaction to knee movements. *Material and Methods*. MFL was exposed on 21 fresh-frozen unpaired knee joints. Its microscopic morphology was examined utilizing for comparison the fibular collateral and the popliteofibular ligament. *Results*. MFL was encountered in 100% of the specimens as a thin striplike fibrous band extending between the lower border of the lateral meniscus and the head of the fibula. MFL was tense during knee extension and external rotation of the tibia, whereas its histological features were similar to those of fibular collateral and popliteofibular ligament. *Discussion*. Its precise histological nature is studied as well as its tension alterations during knee movements. The potential functional significance of the MFL with respect to its role in avoidance of lateral meniscus and lateral coronary ligament tears is discussed. *Conclusions*. MFL presumably provides an additional protection to the lateral meniscus during the last stages of knee extension, as well as to the lateral coronary ligament reducing the possibility of a potential rupture.

1. Introduction

The posterolateral corner of the knee joint is an anatomical area where serious interest has been appeared recently by anatomists as well as orthopaedic surgeons. The complexity of the anatomical structures constituting this area and the confused nomenclature of the ligaments and capsular thickenings concentrate the interest of many researchers [1–4]. Such a raised interest is due to the fact that posterolateral corner injuries with or without cruciate ligaments ruptures can lead to an unexplained instability [3]. The posterolateral corner elements prevent varus angulation, posterior shift, and excessive external rotation of the knee [5].

As regards lateral meniscus connections with the surrounding tissues, special attention has been paid to the meniscofemoral ligaments, the coronary ligament, and the popliteomeniscal ligaments-fascicles [6–8]. However, little data exists with regards to a relatively unknown and difficultly identified capsular thickening of the posterolateral corner, the so-called meniscofibular ligament (MFL) [9, 10]. MFL in animals very early in 1942 was included in Haines' original drawings, without any relative mention within the manuscript of his work [11]. However, Zivanovic later in 1964 prescribed comprehensively the morphological features and the potential functional properties of the MFL in humans [12]. The purpose of the present study is to investigate the presence and microscopic morphology of MFL, its reaction to knee movements, and its histological features. Moreover, we discuss the ligaments anchored to the lateral meniscus, as well as the morphological features and potential MFL functions.

2. Material and Methods

The potential presence of the MFL at the area of the posterolateral corner of the knee joint was detected on 21 fresh-frozen unpaired knee joints utilized for educational and research purposes at the Laboratory of Anatomy of the Medical School of the Aristotle University of Thessaloniki. In specific and according to the procedure of classical method of anatomical practice, the popliteal fossa was opened by routine dissection. The superficial to the popliteus tendon anatomical structures were removed to provide a clear vision for observing the capsular and ligamentous connections of the lateral meniscus. The aforementioned connections were repeatedly recorded as photographs during the course of the dissection. Furthermore, we noticed the changes of MFL tension during knee flexion and extension. At last, we excised the MFL along with its attachments to the head of fibula and the lateral meniscus, and we conducted appropriate histological examination in order to determine the precise histological nature of MFL. For comparison we performed histological examination in sections taken by the adjacent fibular collateral and the popliteofibular ligament in order to determine more accurately the histological nature of the encountered meniscofibular band. The tissues were stained with hematoxylin and eosin. For better histological analysis of the MFL elastin staining was utilized.

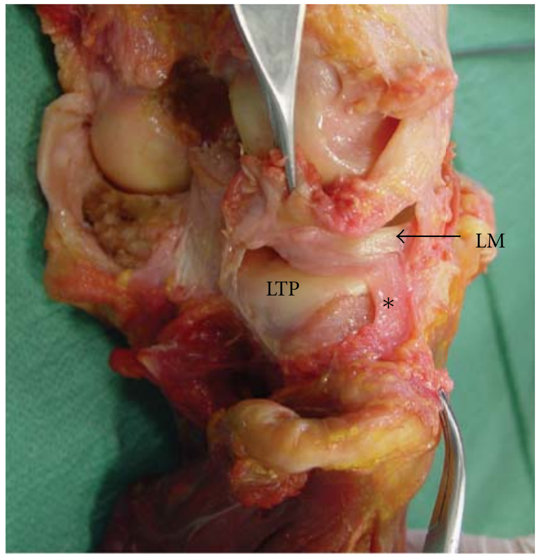


Figure 1: Posterolateral aspect of the right knee joint after excision of the overlying anatomical structures. The fibrous capsule and the lateral coronary ligament have been removed to provide a clear vision of the meniscofibular ligament (*) (LM: lateral meniscus, LTP: lateral tibial plateau).

3. Results

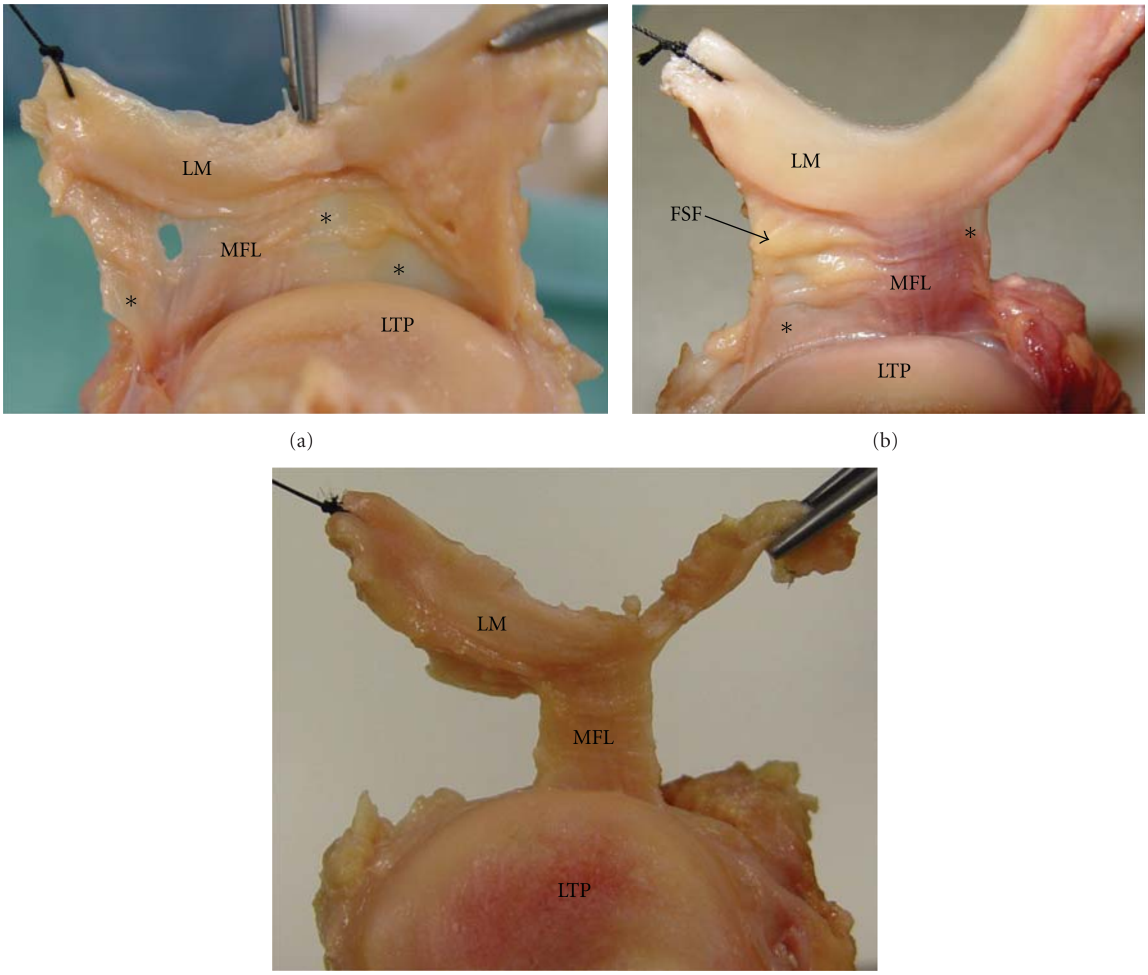
In 21 examined cadaveric unpaired knee joints (11 right-sided and 10 left-sided), thus an incidence of 100%, we noticed the existence of a thin fibrous band originating from the inferior border of the lateral meniscus at the area of the posterior part of its midportion. That band, the so-called MFL, directed backwards, outwards, and inferiorly anchored ultimately to the head of the ipsilateral fibula with the knee fibrous capsule attaching just proximal to the fibular head (Figure 1). MFL was seen to reinforce the thin lateral coronary ligament, which was extended from the lateral meniscus to the lateral aspect of the lateral tibial condyle just distal to the articular margin and proximal to the knee fibrous capsule attachment (Figure 2). In only one case (4.8%) MFL was hypoplastic, being, however, distinct. Performing knee movements we observed that MFL was tense during knee extension and external rotation of the tibia, whereas it was slack during the reverse movements.

The conducted histological examination demonstrated that MFL consisted of dense regular connective tissue with few extracellular matrices (Figure 3). At the central area of the inferior portion of the MFL plenty elastic fibers were detected (Figure 4). Furthermore, we concluded that no difference in microscopic morphology between MFL and fibular collateral and popliteofibular ligament was documented (Figure 5). It should be reported, however, that MFL is a ligament extending between meniscus and bone, such as meniscofemoral ligaments.

4. Discussion

The lateral meniscus, as it is well known, is less firmly anchored than the medial one as it is attached mainly to the fibrous capsule, via weak fibers [13]. However, lateral meniscus attachments to its neighboring structures do exist. In specific, the posterior horn is attached to the medial condyle of the femur anterior and posterior to the attachment to the posterior cruciate ligament, forming the anterior and posterior meniscofemoral ligaments [14–16]. At least one meniscofemoral ligament has been found in approximately 93% of knees, whereas 50% of them had both ligaments [17]. These ligaments can assist to withstand tibial posterior draw [18] and may act as a splint to keep the posterior cruciate ligament in position while it heals after rupture [8]. The anterior meniscofemoral ligament (of Humphrey) is slack in the extended knee and tightens with knee flexion to withstand tibial posterior draw. The converse occurs with the posterior meniscofemoral ligament of Wrisberg [8].

As regards the popliteus tendon, it provides almost consistently two fascicles, the superior, superomedial, or posterosuperior and the inferior, inferolateral, or anteroinferior bundle, which have been prescribed analytically firstly by Staubli and Birrer in 1990 [7, 19]. The presence of a third popliteomeniscal fascicle, the so-called posteroinferior fascicle, has been mentioned in the literature [6, 20]. The anteroinferior or inferolateral popliteomeniscal fascicle extends from the anterior margin of the popliteus tendon to the middle third of the lateral meniscus, whereas the posterosuperior or superomedial fascicle extends from the posterior margin of the tendon to the posterolateral aspect of the meniscus [21]. The aforementioned fascicles stabilize the lateral meniscus and when ruptured the mobility of the lateral meniscus is increased [19]. In addition, a portion of the joint capsule extending from the lateral edge of the lateral meniscus to the lateral tibial condyle, the so-called lateral coronary or meniscotibial ligament, secures the posterior horn of the lateral meniscus to the tibia [6, 22] and may be injured after excessive rotation of the knee [1]. Although the precise function of the coronary ligament has not been highly



(a) (b)

(c)

Figure 2: (a) The lateral meniscus (LM) has been raised and the lateral coronary ligament (*) along with the meniscofibular ligament (MFL) is demonstrated (LTP: lateral tibial plateau). (b) Fatty synovial folds (FSF) are shown covering part of the lateral coronary ligament. (c) The coronary ligament has been resected to allow better visualization of the MFL.

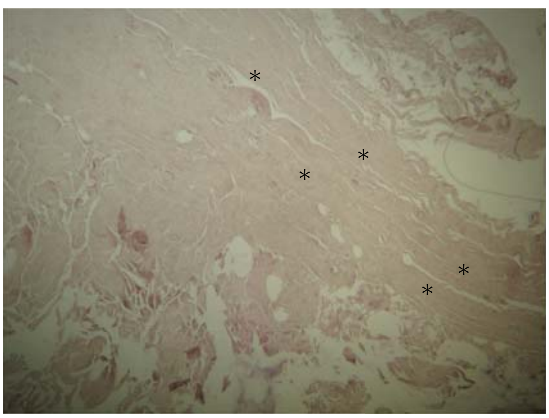


Figure 3: Demonstration of the histologic nature of the meniscofibular ligament (*) that consists of regular dense connective tissue with few extracellular matrices (hematoxylin and eosin staining, magnification ×16).

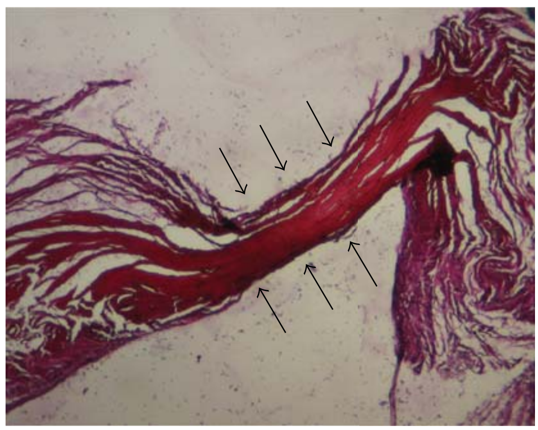
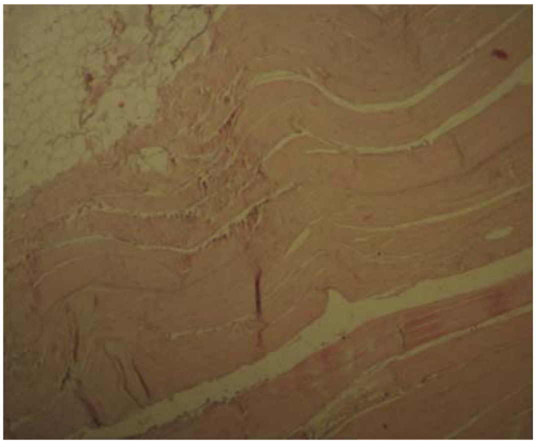
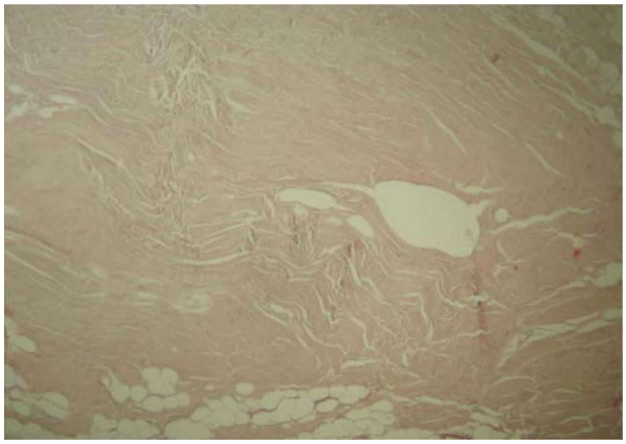


Figure 4: Numerous elastic fibres at the central area of the inferior portion of the meniscofibular ligament is shown (elastin staining, magnification ×16).



(a)



(b)

Figure 5: Histological structure of the adjacent fibular collateral ligament (a) and popliteofibular ligament (b) does not differ from that of the meniscofibular ligament (hematoxylin and eosin staining, magnification ×16).

enlightened, it is supposed to play a role in keeping the lateral meniscus adherent to the lateral tibial plateau [23]. That ligament is responsible for limiting rotational movements of the knee, whereas it permits controlled anterior and posterior movement of the lateral meniscus [24]. Coronary ligament rupture may lead to increased mobility of the lateral meniscus, posterior knee pain, and a gap in the posterior capsule [25].

An additional ligament attached to the lateral meniscus, relatively unknown and neglected in the literature, is the meniscofibular ligament (MFL), a tapelike fibrous band extending between the inferior border of the lateral meniscus and the head of the fibula. That ligament was firstly described in 1964 by Zivanovic with an incidence of 78% of the 241 European knee joints examined [12]. Later, the same author observed that ligament in 80% of East African Bantu knee joints [9], whereas Bozkurt et al. observed the MFL in 100% of their specimens, attributing the lower incidence noticed in Zivanovic's study to the lack of detection of the specifically thin MFLs appeared in some materials [10]. Similarly MFL incidence was found to be 100% in our study, with only one case (4.8%) being hypoplastic but macroscopically apparent.

As regards the morphological features of the MFL, Zivanovic found the average width to be between 8 and 13 mm and the average length between 13 and 22 mm and while MFL was less than 1 mm thick [9]. The previously mentioned author claimed that MFL size was depending on the age and stature of the examined individual without providing further data. Bozkurt et al. found the mean thickness of the MFL to be 3.84 mm, ranging from 2.6 mm to 6.1 mm, including the capsule to which it adheres [10]. Such a thickness was found to be greater than the thickness detected by Zivanovic, a fact attributed to the capsule thickening that was coestimated in the performed measurements. In our research we observed that the MFL is incorporated into the lateral coronary ligament reinforcing its posterolateral segment. Bozkurt et al., however, detected the fibrous sheets located bilateral to the MFL as parts of the knee joint articular capsule, without defining them as lateral coronary ligament [10].

The MFL functional significance is a controversial issue. According to Zivanovic MFL has an opposite effect to that of the popliteal tendon limiting forward movement and medial gliding of the posterior horn of the lateral meniscus during the latter stages of knee extension, providing that way protection to the lateral meniscus [9]. Zivanovic found MFL as a permanent structure in the mountain gorilla and the cercopithecus, very well developed since in these animals MFL is more important for the protection of the lateral meniscus during knee extension [9]. MFL was loose in extreme flexion but it was very tense when the knee joint was extended. Zivanovic considered that during evolutionary development the appeared direct joint between the lateral femoral condyle and the head of fibula seen in the knees of tetrapods has disappeared, with MFL being a rudimentary structure [9]. The small MFL thickness noted in humans attributed to the assumption of the erect posture.

On the contrary, Bozkurt et al. provided a potential relationship between MFL presence and the proximal tibiofibular joint [10]. They postulated that MFL may be responsible for backward and outward displacement of the lateral meniscus since the fibula rotates laterally during the dorsal flexion of ankle joint. It is worth mentioning that these authors noticed the MFL to be thicker in horizontal than in oblique proximal tibiofibular joints, where the fibula rotation is more restricted. It is supposed that in horizontal joints the MFL is loaded more than in oblique joints. Bozkurt et al. without providing the precise mechanism made an assumption that MFL has a protective effect in varus and external rotational traumas, whereas the same ligament may be presumably the cause of repetitive lateral meniscus tears [10].

In our study, where no evaluation of the MFL biomechanical properties was performed, we observed that the ligament was slack during knee flexion and medial rotation of the tibia and tense during knee extension and external rotation of the tibia, a notice that confirms Zivanovic's results. So, one hypothesizes that MFL could provide protection to the lateral meniscus from potential ruptures during the last stages of knee extension. In addition, we noticed that MFL reinforced the posterolateral portion of the lateral coronary ligament and not the posterior fibrous capsule of the joint, as noted by Bozkurt et al. [10]. Such an observation has not been mentioned previously in the literature for the best to our knowledge and we consider that such coronary ligament reinforcement provides protection to that ligament. Presumably, that fact supports and empowers the El-Khoury et al. notice that none lateral coronary ligament tear was encountered in excess of two thousands knee arthrograms [23]. The authors attributed this to the loose attachment of the lateral meniscus to the neighboring structures, the low incidence of ligamentous injuries over the lateral side of the knee, and the wide separation between lateral meniscus and collateral ligament. In addition, to the previous remarks we speculate that a further parameter leading to low frequence of lateral coronary ligament rupture is its potential reinforcement by the MFL.

5. Conclusions

Analysing our observations one can speculate that MFL could offer protection to the lateral meniscus from likely damage during the last stages of knee extension. Moreover, MFL reinforced the posterolateral part of the lateral coronary ligament, a fact that could explain the relative low incidence of lateral coronary ligament rupture. Certainly, further investigation should be done to highlight the exact biomechanical characteristics of the MFL, as well as the likely relation or not to lateral meniscus tears, protection of the coronary ligament, and function and traumatology of the proximal tibiofibular joint.

Abbreviations

MFL: Meniscofibular ligament.

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Research Article

The Patellar Arterial Supply via the Infrapatellar Fat Pad (of Hoffa): A Combined Anatomical and Angiographical Analysis

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Even though the vascular supply of the human patella has been object of numerous studies until now, none of them has described in detail the rich arterial supply provided via the infrapatellar fat pad (of Hoffa). Therefore, we aimed to complete the knowledge about this interesting and clinically relevant topic. Five human patellae taken from voluntary body donators were studied at the Department of Applied Anatomy of the Medical University of Vienna. One was dissected under the operation microscope, a second was made translucent by Sihlers-solution, and three underwent angiography using a 3D X-ray unit. The results revealed that the patella to a considerable amount is supplied by arteries coursing through the surrounding parts of the infrapatellar fat pad. The latter were found to branch off from the medial and lateral superior and inferior genicular arteries. Within the infrapatellar fat pad, these arteries formed a dense network of anastomoses which are all contributing to the viability of the patellar bone. Due to the rich arterial supply reaching the patella via the infrapatellar fat pad, it seems advisable to preserve the fat pad during surgery of the knee in order to reduce the risk of vascular impairment of the patella.

1. Introduction

The infrapatellar fat pad (of Hoffa) is located in the anterior compartment of the knee joint and is bordered by the inferior pole of the patella, the patellar retinacula, the patellar tendon, the anterior part of the tibia, the anterior horns of the menisci, and the femoral condyles. Further, it is attached to the intercondylar notch of the femur by the infrapatellar synovial plica also referred to as ligamentum mucosum [1]. Because of its high amount of nerve endings, the infrapatellar fat pad may become source of anterior knee pain. As reported by Bennell et al., the application of hypertonic saline into the fat pad led to pain experience in healthy volunteers [2]. In rare cases, tumour-like lesions of the infrapatellar fat pad such as osteochondroma, pigmented villonodular synovitis, synovial cysts [3], and vascular malformation [4] may lead to anterior knee pain. Furthermore, the infrapatellar fat pad may be affected by postarthroscopic alterations, postsurgery fibrosis, and shear injuries [5].

As reported by Bohnsack et al., the fat pad plays a role in stabilizing the knee joint in the extremes of motion, especially during flexion angles of less than 20° and greater than 100° [6]. Due to surgical demand, it is often removed or at least partially resected during surgery in order to improve visibility to the joint. Medial arthrotomy made too close to the patella, wide resection of the fat pad, lateral retinacular release, and cauterization of the prepatellar vessels are known to jeopardize vascular supply to the patella [7]. Hoffa's fat pad is traversed by two vertically running arteries, which branch off from the superior medial and lateral genicular arteries. Both vertical arteries anastomose with the correspondent inferior genicular arteries. Additionally, an anastomosis is found between the lateral vertical artery and the anterior tibial recurrent artery next to the lateral margin of the patellar ligament. Posterior to the patellar ligament, the two vertical arteries are interconnected by two to three horizontal arteries which are found between the inferior pole of the patella and the tibial tuberosity [8]. Due to their anatomical proximity, the infrapatellar fat pad and the patellar tendon have a shared blood supply; the latter is derived from the inferior genicular arteries and laterally also from the anterior tibial recurrent artery [9].

The human patella is mainly supplied by five to six arteries forming an anastomotic network on the anterior aspect of the bone. Especially the descending genicular artery, the medial and lateral superior genicular arteries, the medial and lateral inferior genicular arteries, and the anterior tibial recurrent artery contribute to this so-called Rete patellae. These arteries are also involved in the supply of the distal parts of the femur and the proximal aspects of the tibia [10]. The two superior genicular arteries run along the superior pole of the patella forming an anastomosis together with the descending genicular artery anterior to the insertion of the quadriceps tendon. The inferior genicular arteries give off three branches; one ascends along the lateral border of the patella, one converges towards the anterior aspect of the bone, and the third transverse running branch anastomoses with the contralateral artery deep to the patellar tendon. These vessels are also called transverse infrapatellar arteries. Inside the infrapatellar fat pad, the transverse infrapatellar arteries give rise to small vessels, so called polar vessels, which contribute to the vascular supply of the distal half of the bone [11].

Therefore, the patella is supplied by two arterial pathways. First, small vessels enter the anterior aspect of the bone through vascular foramina located on the anterior surface. Additional supply is provided by polar vessels originating from the transverse infrapatellar branches of the two inferior genicular arteries. Due to its dual blood supply, there is anatomical evidence that the distal half of the patella is less endangered by avascular necrosis; on the contrary, pathologically the upper half may be separated from the blood supply by transverse patellar fractures [11]. Both arterial pathways arise from the peripatellar anastomic network [12].

In addition to the findings just mentioned, according to Björkström and Goldie, arteries piercing the quadriceps tendon and the adjoining synovial tissue may reach the patellar base. Furthermore, they identified arteries supplying the medial, lateral, and superior borders of the patella. The authors emphasize the existence of deeply situated peripatellar arteries which give rise to the aforementioned arteries [13]. Considering the findings of Howard et al. who evaluated the vascular supply of canine patellae, the vascular anatomy seems to be comparable to the situation in humans. Thus, the canine patella is supplied by numerous arterioles entering the bone along the medial, lateral, and dorsal aspects, respectively [14].

Hence, a lot of information concerning the arterial supply of the patella has hitherto been published, the topographical relationship between the feeding arteries of the patella and the infrapatellar fat pad has not been presented in details. Thus, the aim of this study was to clarify to which extent arteries supplying the patella are to be found within Hoffa's fat pad.

2. Material and Methods

For the presentation of the vascular course within the infrapatellar fat pad of Hoffa, five isolated corpora adiposa were studied at the Department of Applied Anatomy of the Medical University of Vienna. These specimens were taken from two female and three male voluntary body donators which had died at a mean age of 75 years. All parts of this study have been approved by the local ethical board (registration number 919/2010). The first two knee joints were taken from anatomic specimens that had been used in the student dissection courses and, therefore, were perfusion fixed with a mixture of 1.6% formaldehyde solution and 5% phenol solution. One specimen taken from a 79-year-old male individual was dissected layer by layer by means of a surgical microscope (Zeiss OPMI 11; Carl Zeiss GmbH, Vienna); during this procedure, for better visibility, the vessels were injected with Wright's eosin methylene blue solution (Merck, Art 1383). The injection was carried out with Insulin Syringes (BD Micro-Fine, 1 mL of 0.33 mm (29) $\times$ 12.7 mm. BD Medical-Diabetes Care Becton Dickinson France SAS, Le Pont de Claix, France). Microanatomical preparation was carried out by microsurgical forceps and scalpel blade number 15 (Aesculap, Aesculap AG, et. Co. KG.).

The second specimen taken from an 85-year-old female body donator underwent a special designed preparation following the method originally described by Sihler as modified by Liu et al. [15, 16]. By this method, soft tissue was made translucent and thus a better representation of the vessels was achieved. First, the specimen was immerged in 10% nonneutralized paraformaldehyde for at least 1 month. Then, the fixed specimen was macerated. Maceration was started with washing in tap water for 30–60 minutes. Then, the specimen was digested for at least 3 weeks in 3% NaOH solution at refrigerator temperature. The macerating solution was changed daily until all parts of the specimen became translucent or transparent. In the following step, the specimen was decalcified. For this, Sihlers solution I was to be used (one part concentrated acetic acid, one part glycerol, and six parts of an aqueous solution containing 1% chloralhydrate). This step was to be continued until the cartilage was soft while the specimen is stored in the refrigerator. Finally, the tissue was stained in Sihlers solution II. This consists of one part concentrated EHRLICH hematoxylin, one part glycerol, and 6 parts of a 1% aqueous chloralhydrate.

Staining was carried out until the specimen became deep red. Furthermore, contrasting was achieved using Sihlers solution I again at room temperature. On a rocker table working at 200 rpm, the specimen was stored in the solution until it turned purple, then the solution was changed. Then, the specimen was washed in running tap water and then stored in a 0.05% lithium carbonate solution for one hour. Finally, transparency was reached by rewashing the specimen in running tap water for 30–60 minutes. Thereafter, the tissue block was stored in glycerol at ascending concentration of 40%, 60%, 80%, and at least in 100%. Thymol crystals were added to each series. Photographic documentation of both preparations was performed using a digital full-frame photo camera (Canon EOS 5D, Canon Inc., Tokyo, Japan) mounted on the camera tube of the operation microscope. For documentation, the translucent specimen was situated on a transparent slide screen (Kaiser slimlite, Kaiser Fototechnik GmbH & Co KG, Buchen, Germany) and illuminated from below. For angiographic examination, three fresh frozen anatomic specimens of human legs were used. They were taken from two male and one female individual which had died, on average, at the age of 71 years. In the region of the canalis vastoadductorius (Hunter's canal), the femoral artery was punctured with a Butterfly (Vacutainer System) and an iodine-containing contrast agent (Iomeron®) was injected. Subsequently, the three knee joints underwent 3D radiologic imaging (Siemens Arcadis Orbic 3D, Siemens Medical Solutions, Erlangen, Germany). This specially designed scanner obtained serial cross-sections in a volume of $12 \times 12 \times 12$ centimeters by turning round the specimen by 190 degrees. According to the basic adjustment, parallel to each of the three planes 256 images were obtained as partly overlapping multiplanar reconstructions (MPR) with a slice thickness of 0.5 mm. Finally, the series of cross-sections were evaluated on the work station operating the scanner in order to trace the arteries marked by contrast media.

3. Results

After careful removal of the synovial membrane covering the inner aspect of the infrapatellar fat pad, a dense network of superficial vascular anastomoses appeared. These anastomoses were especially concentrated in the central parts of the fat pad including the distal portions adjacent to the patellar tendon. The superficial vascular plexus was formed by afferent vessels entering the fat pad from deep within the knee joint (intercondylar fossa); additional supply was received by branches of the inferior genicular arteries. The superficial vascular plexus only appeared to supply the fat pad itself and its synovial membrane, respectively, since no direct vascular connections to the bone could be detected. After removal of the superficial vascular plexus and careful microdissection of the remaining adipose tissue, a second layer of blood vessels appeared in the intermediate level of the fat pad (Figures 1 and 3). The vessels of the intermediate vascular layer themselves received their supply from the inferior genicular arteries, and laterally also from a branch of the anterior tibial recurrent artery. From within the intercondylar fossa, numerous vessels reached the dense anastomotic network in the central parts of the fat pad ((1) in Figure 2 and (c) in Figure 15(a)).

The arteries running in the intermediate vascular layer supplied the distal patellar pole by numerous small vascular connections (Figure 4).

The branches of the superior medial genicular artery ran towards the superior medial margin of the patella. Interestingly, as a constant finding in this part of the fat pad, a vessel with wider caliber was flanked by two smaller vessels in its course. After a short distance, the proximal vessel ((2) in Figure 5) joined the main branch ((1) in Figure 5). In the area of the medial insertion of the quadriceps tendon, the main vessel bifurcated ((4) in Figure 5).

The first branch ran directly to the anterior aspect of the quadriceps tendon and thus escaped from the preparation situs. The second branch originating from the bifurcation ran along the medial aspect of the patella, giving off numerous small branches, which supplied the medial border of the patellar bone. We found a small vessel arising from the descending branch which followed a tortuous course directed towards the superior pole of the patella ((5) in Figure 5). This vessel anastomosed with a similarly configured vessel arising from the superior lateral genicular artery. The distally located flanking vessel ((3) in Figure 5) joined the descending branch, after the superior polar vessel had been given off.

The previously mentioned formation of the anastomosis was found in the middle third of the superior pole of the patella, posterior to the quadriceps tendon ((2) in Figure 6). Before establishing this anastomosis, both arterial branches regularly delivered small vessels which contributed to the vascular supply of the superior pole of the bone.

The branches of the superior lateral genicular artery showed a configuration similar to that of the contralateral side. In the area of the superolateral border of the patella, we were able to identify three vessels which further contributed to the supply of the superior pole of the patella, including its lateral margin. The proximal of the three arteries ((1) in Figure 7) gave off a small branch ((2) in Figure 7) which ran towards the superior pole of the patella forming the superior anastomosis previously mentioned; thereafter, the proximal arterial branch escaped the preparation situs.

The descending branch ((4) in Figure 7) followed a strictly vertical course adjoining the lateral margin of the patella and delivered at regular intervals small vessels which supplied the lateral patellar margin. In the area of the middle third of the lateral margin, it formed an anastomosis with an ascending artery (Figure 8) which, in turn, arose from the inferior lateral genicular artery (Figure 9). Next to the superolateral patellar border, the descending branch was joined by another vessel ((2) in Figure 8).

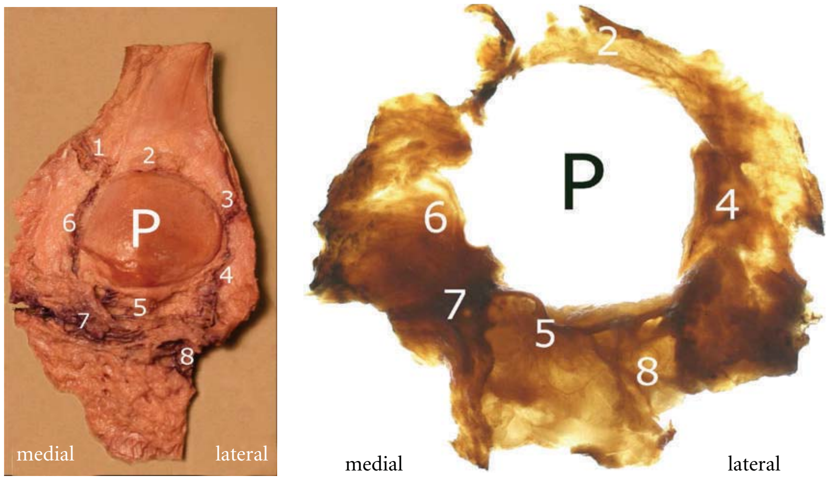
Both the medial and lateral inferior genicular arteries supplied the patella through three different pathways. There was one branch running next to the border of the bone, another which converged to the anterior surface of the bone, and a third one running directly into the fat pad.

On a closer view, the transverse branch showed a very complex morphology, giving rise to numerous branches which were not limited to one level in their course. Figures 10 and 11 illustrate the three dimensionality of these vascular structures.

In its further course, the proximal branch ((a2) in Figure 10) formed an anastomosis with the descending branch of the superior medial genicular artery at the level of the middle third of the medial patellar margin ((1) in Figure 12). The ascending artery was also accompanied by a smaller vessel ((b) in Figure 13) which joined the main ascending branch ((a2) in Figure 13).

Considering the deep vascular level, we found an anastomosis in ultimate proximity of the patellar apex forming a vascular connection between the medial and the lateral inferior genicular artery ((1) in Figure 14).

This anastomosis was also shown radiologically in Figure 15(c). Although two other anastomoses were found to be present, only the one next to the patellar apex showed direct vascular connections to the bone. Nevertheless, the three anastomoses were repeatedly linked to each other ((3) and (4) in Figure 14).



(a) (b)

Figure 1: (a) and (b): Posterior view of the dissected fat pad (a) and the isolated translucent fat pad (b) as result of Sihler's procedure: (1) branches of the superior medial genicular artery, (2) anastomosis formed by the "basic branches" of the two superior genicular arteries, (3) branches of the superior lateral genicular artery, (4) descending branch arising from the superior lateral genicular artery, (5) deep vascular layer with transversely extending arteries, (6) descending branch from the superior medial genicular artery, (7) intermediate vascular layer, (8) branch of the anterior tibial recurrent artery and its entry into the vascular arcades of the infrapatellar fat pad.

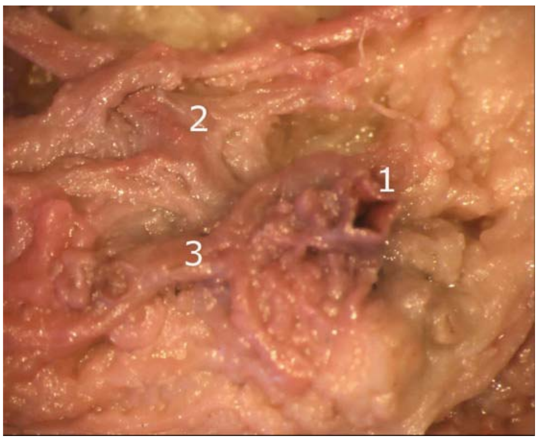


Figure 2: Termination of the middle genicular artery into the intermediate vascular layer: (1) terminal branch of the middle genicular artery, (2) and (3) vessels of the intermediate vascular layer.

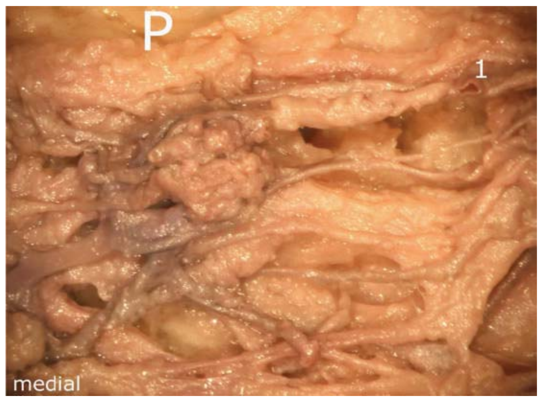


Figure 3: Representation of the intermediate vascular layer in the middle third of the fat pad, (1) afferent vessels from the depths of the knee joint (intercondylar fossa), P: patella.

4. Discussion

The main findings of our study revealed that within the central mass of the infrapatellar fat pad, the vessels showed an arrangement of three layers, with the caliber of the vessels increasing from posterior to anterior, that is, towards the patellar tendon. Interconnections between these layers were established by numerous vascular channels. Together, they thus formed a functional unit. Except for the most superficial level, which was only found in the central portions of the infrapatellar fat pad or in the dorsodistal areas of the patellar tendon, both the intermediate and the deep vascular level provided vascular supply to the distal half of the patellar bone.

The vessels with the widest caliber were located in ultimate proximity to the posterior aspects of the patellar tendon and the patellar apex. The latter originated from the inferior genicular arteries and formed anastomoses within the fat pad. We, therefore, confirm the findings of Kohn et al. [8] who already described this vascular configuration previously, the same applies to the polar vessels described by Scapinelli [11]. However, our results showed that the transverse infrapatellar arteries established a complex branching pattern both medially and laterally. Especially noteworthy was the three dimensionality of the vascular architecture within the fat pad which had not been previously documented.

Our results revealed that, in the deep vascular layer, only one anastomosis supplied the inferior patellar pole directly

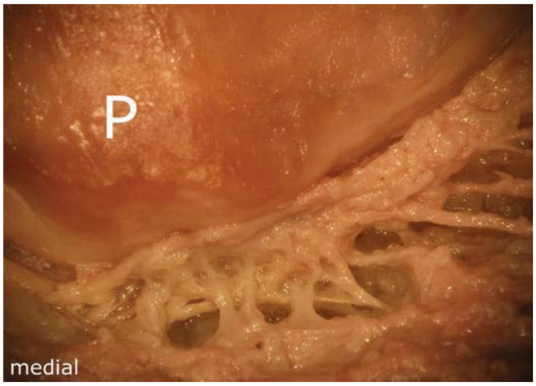


Figure 4: Distal pole of the patella. Note the numerous small vascular connections to the bone, which supply the lower half of the patella. The latter are derived from the intermediate vascular layer, P: patella.

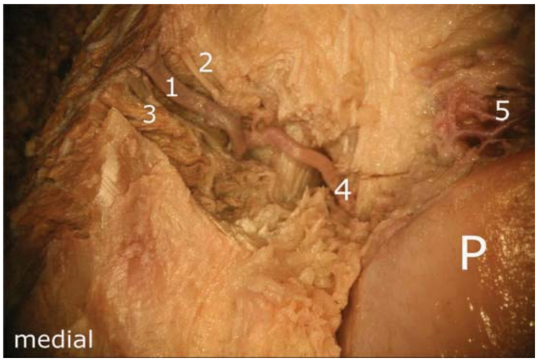


Figure 5: Branches of the superior medial genicular artery: (1) main vessel, widest in caliber, (2) and (3) accompanying vessels, (4) bifurcation of the main branch (1), (5) "basic branch" forming a dense anastomotic network next to the patellar base, P: patella.

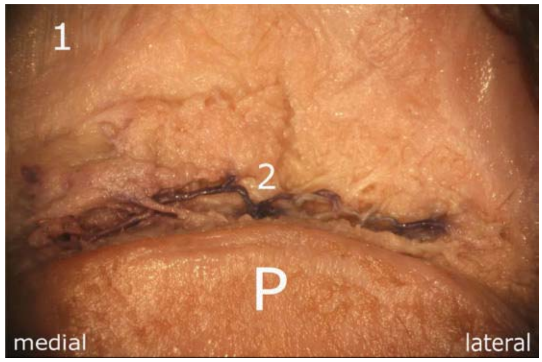


Figure 6: Anastomosis next to the superior pole of the patella. It is formed by the "basic branches" which arise from the two superior genicular arteries: (1) quadriceps tendon, (2) anastomosis, P: patella.

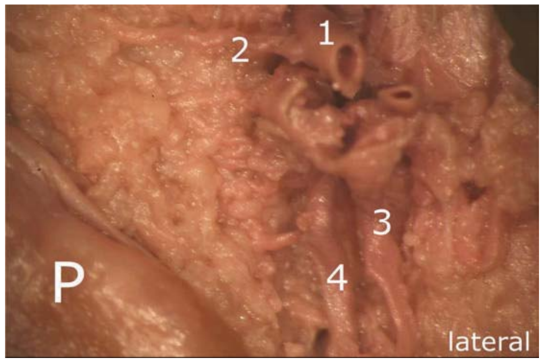


Figure 7: Branches of the superior lateral genicular artery: (1) runs towards the anterior aspects of the quadriceps tendon, (2) involved in the formation of the superior anastomosis, (3) flanking vessel which joins the descending branch (4), (4) descending branch forming an anastomosis with the ascending artery in the middle third of the lateral margin, P: patella.

by giving off small vessels. Nevertheless, it was found to be connected with the other anastomoses of the deep vascular layer ((3) and (4) in Figure 14).

As presented in Figure 10, we found a proximal, a diagonal (running towards the patellar apex), a horizontal (which anastomosed with the contralateral artery next to the patellar apex), and a distal branch (which, in its further course, turned into a vessel of the intermediate vascular level). On both sides of the patella, we found an ascending artery which anastomosed with the descending branch given off by the ipsilateral superior genicular artery in about the middle third of the lateral and medial margins of the patella posterior to the retinacula. Prior to this anastomosis, both the descending and the ascending arteries gave off small branches in their entire course at regular intervals, which supplied the lateral and medial edges of the patellar bone. Based on our results, we agree with the findings of Björkström and Goldie [13] that, besides the anterior vascular network [11] and the infrapatellar anastomoses, further arteries located posteriorly to the retinacula supply the medial and lateral borders of the patella. Interestingly, arteries originating within the quadriceps tendon had been described by other authors [13] but were not found to be present in our specimens. Instead of these vessels, in our specimens, an anastomosis was established by branches of the superior genicular arteries coursing next to the patellar base and posterior to the quadriceps tendon.

In the superomedial aspect of the patella, we found three parallel running branches originating from the superior medial genicular artery; one of them turned out to be the predominant vessel. After a short distance, the more proximally located branch joined the main branch. The main branch bifurcated next to the superomedial border of the patella. Whilst one branch ran to the anterior aspects of the quadriceps tendon and, therefore, was not available for further pursue, the other branch ran strictly vertical along the medial border of the patella. It soon gave off a small vessel, which followed a tortuous course directed towards the superior pole of the bone. The distally located flanking vessel joined the descending branch after the superior polar vessel had been given off. The branches of the lateral superior genicular artery showed a configuration which was very similar to that of the artery of the medial side. Both, the

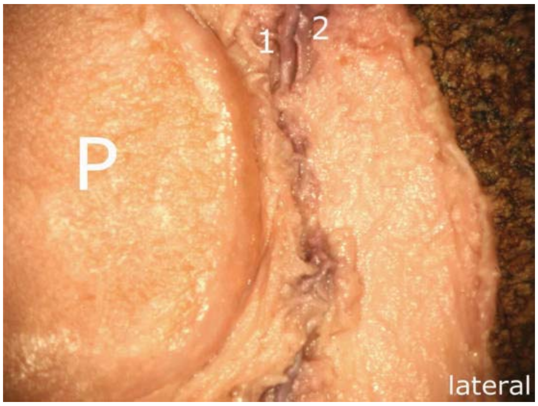


Figure 8: Course of the descending branch (corresponding to Figure 7): (1) descending branch arising from the superior lateral genicular artery (2) flanking vessel which joins the descending branch (1) P: patella.

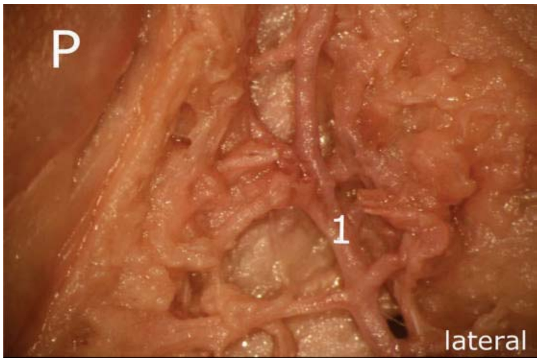


Figure 9: Note the small branches given off by the ascending artery (1) which are involved in the supply of the lateral aspect of the patella. This ascending artery departs from the lateral inferior genicular artery and anastomoses with the descending branch ((1) in Figure 8) of the superior lateral genicular artery, P: patella.

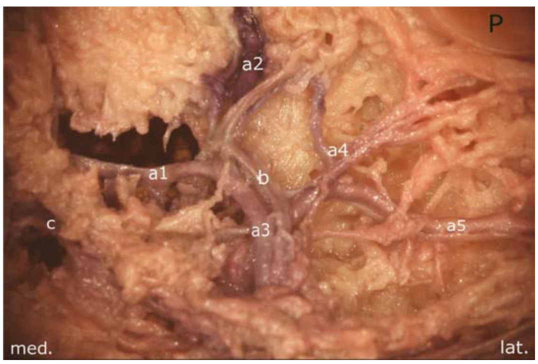


Figure 10: Medial aspect of the infrapatellar fat pad. Arteries arising from the inferior medial genicular artery. (a1) the main vessel gives off a proximal (a2), a distal (a3), a diagonally converging branch toward the patellar apex (a4) and a horizontal branch (a5). The latter is one of the strongest branches of the deep vascular level and forms an anastomosis with that of the lateral side. Except of (a5), all vessels are located in the intermediate vascular layer. P: patella.

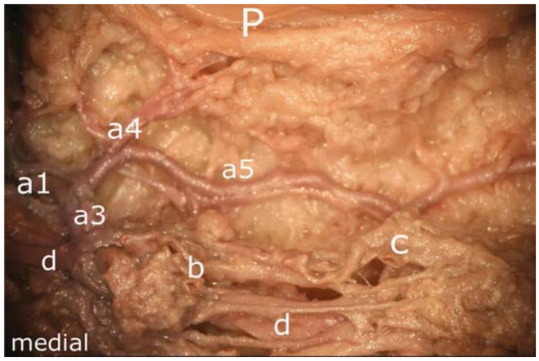


Figure 11: (In addition to Figure 10) Representation of the deep vascular layer (a5) and the intermediate one ((a1), (a3), (a4) and (d)). b and c mark terminal branches of the middle genicular artery, P: patella.

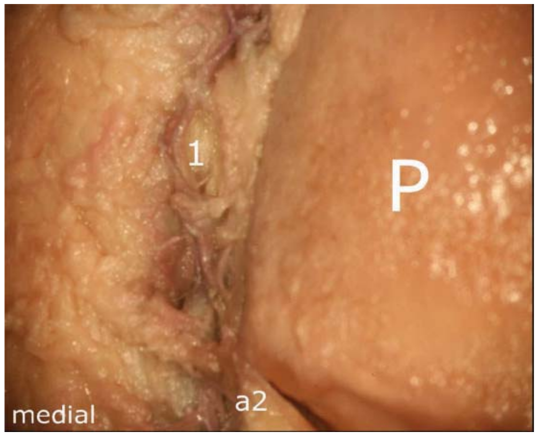


Figure 12: Anastomosis between the proximal branch of the inferior medial genicular artery (a2) and the descending branch of the superior medial genicular artery, (a2) proximal branch, (1) anastomosis, P: patella.

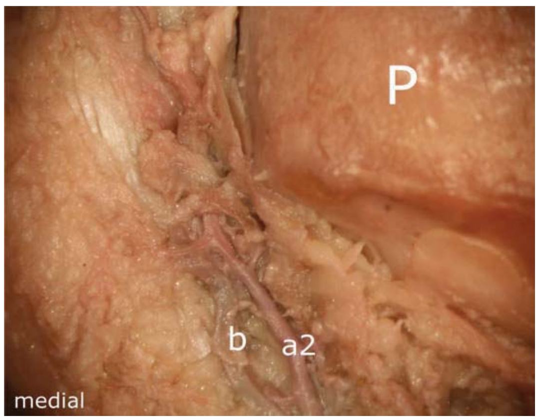


Figure 13: Ascending artery, derived from the inferior medial genicular artery ((a2) in Figure 10) (a2) ascending artery, (b) accomanying vessel which joins the main vessel (a2) at the distal medial margin of the patellar bone, P: patella.

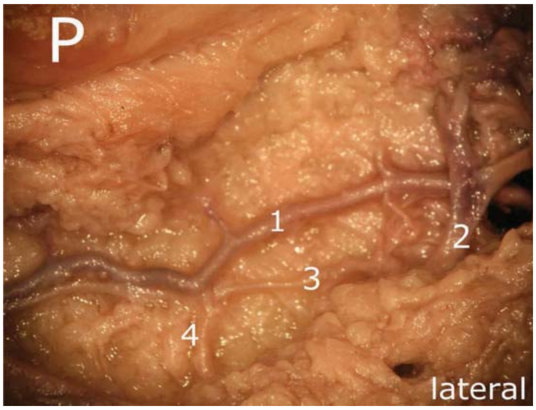


Figure 14: Deep vascular level, (1) vascular anastomosis of the deep level, out of the three it is the only one showing direct vascular connections to the bone; (2) one of the three anastomoses, (3) and (4) vascular connections between two anastomoses of the deep vascular layer, P: patella.

medial and the lateral superior polar vessels, formed an anastomosis in the superior aspect of the patella. Due to different techniques applied, this anastomosis together with its course had obviously been overlooked by other authors [10–13].

The results of our work indicate the existence of a dual supply of the entire patellar circumference, both anterior and posterior to the retinacula. The anastomoses within the infrapatellar fat pad established a vascular framing of the whole knee cap (Figures 1(a) and 1(b)).

In addition to the findings of Scapinelli [11], besides the anterior peripatellar ring, an additional arterial supply reached the patella via infrapatellar fat pad and was not limited to its central parts but also found within its superior parts and the alar folds.

Interestingly, the amount of anastomoses found in the specimen which was treated by Sihler's method was not as impressive as the results of the microsurgical dissection, although the vascular architecture behaved very similar to the the aforementioned specimen. According to Slater et al. [17], this may be due to the relatively high degree of retropatellar arthrosis this individual seemed to have suffered from.

Due to the small vessels under consideration as well as to a high amount of arteriosclerotic changes, angiographically we were only able to trace the main arteries contributing to the patellar supply.

Although numerous surgical interventions are known to jeopardize the vascular supply of the patella [7], obviously not every intervention inevitably leads to vascular impairment. Due to its characteristic arterial supply, the patella can thus assume a certain degree of tolerance.

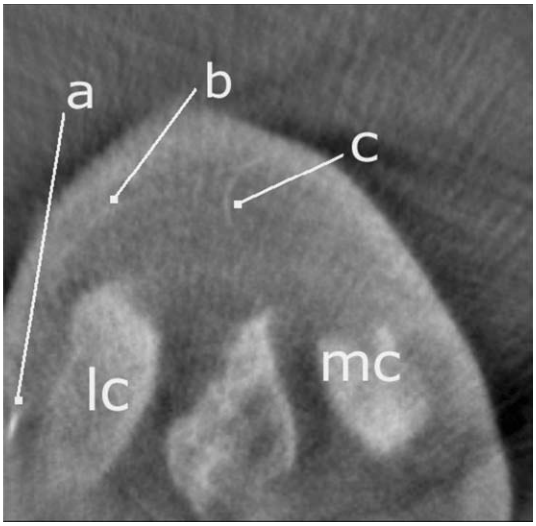
However, if a medial parapatellar approach is combined with a lateral release, this may lead to an insufficient supply of the patella and subsequently increase the incidence of bone necrosis [18] and patellar fractures [19]. Preservation of the superior lateral genicular artery during lateral release as well as preservation of the infrapatellar fat pad is considered inter alia as reliable options in order to avoid patellar fracture resulting from total knee arthroplasty [20]. The superior lateral genicular artery may easily be detected in the subsynovial layer 1-2 cm distal to the inferior margin of the vastus lateralis muscle [21]. When arthroscopically performing a lateral release, Vialle et al. emphasized selective hemostasis of the superior lateral vascular pedicle and visualization of the inferior lateral vascular pedicle in order to minimize the risk of hemarthrosis which had been reported to occur in 10 to 18% of cases [22].

Nicholls et al. compared the reduction of blood flow to both the medial and lateral access but did not find any significant difference. From this, they concluded that both the medial and lateral arteries were involved equally in the vascular supply of the patella. Blood flow was found to be reduced to 53% following a medial approach and 27% after a lateral approach. The supply of the patellar tendon was not affected by both approaches. As the infrapatellar fat pad was preserved in all patients, due to its high amount of anastomoses, great importance is attributed to this structure on behalf of the vascular supply of the patellar tendon [23]. Significant shortening of the patellar tendon after resection of the infrapatellar fat pad was presented in two articles [24, 25]. As reported by Takatoku et al., postsurgical scar formation after resection of the infrapatellar fat pad led to abnormal shortening of the patellar tendon as well as deforming of the patella in growing rabbits. Moreover, preservation of the infrapatellar fat pad seems to prevent early degeneration of the articular surface of the patellofemoral joint [26]. Sanchis-Alfonso et al. observed the healing process of the patellar tendon after patellar tendon autograft and concluded that the infrapatellar fat pad as well as the paratenon played an important role in the healing process of the patellar tendon [27].

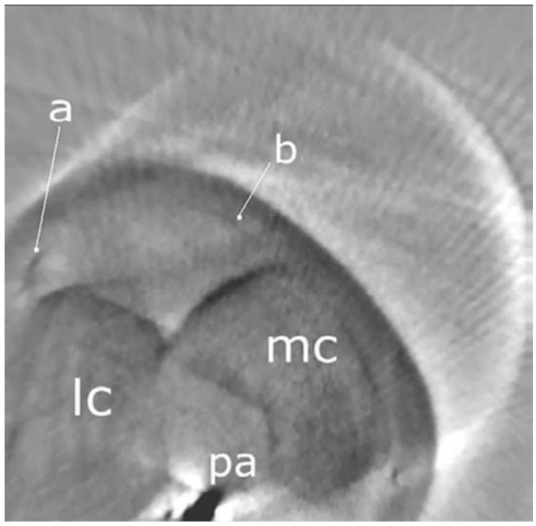
Based on a study in monkeys, Ogata et al. reported that performing a medial parapatellar approach which included a partial resection of the medial portion of the fat pad reduced the blood flow to the patella to 65% of the control animals. If the fat pad was completely removed, the blood flow decreased further to 49% of the control value. Total fat pad removal combined with a lateral release reduced blood flow to a dramatic low amount of 17% of the control value [28].

Another procedure which might endanger the patellar supply is the still controversially discussed need for patellar resurfacing. Proponents of resurfacing have justified this procedure with a lower incidence of revision surgery due to persistent anterior knee pain [29]. In addition, others have argued that forgoing patellar resurfacing has reduced the risk of patella fractures and component loosening [30].

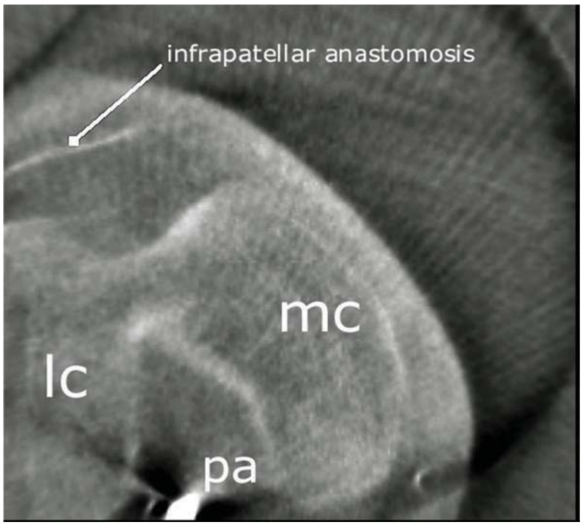
Eversion of the patella is typically performed to optimize the operation field. However, as reported by Hasegawa et al., patellar eversion has led to a significant reduction of the patellar blood flow [31]. Concerning patellar denervation performed as a part of open knee surgery, in another study, no significant differences in outcome between denervated and nondenervated patellae could be detected during a 2-year followup period [32].



(a)



(b)



(c)

Figure 15: Axial MPR reconstructions of a right knee oriented in proximodistal sequence. (a) Intermediate vascular layer formed by a branch of the inferior lateral genicular artery and a terminal branch of the middle genicular artery. a: Inferior lateral genicular artery, b: arterial branch of the intermediate vascular layer, c: terminal branch of the middle genicular artery. (b) The inferior genicular arteries give rise to transversely running infrapatellar arteries, a: lateral transverse artery, b: medial transverse artery. (c) Transverse infrapatellar arteries anastomosing in proximity to the patellar apex. lc: lateral condyle of femur, mc: medial condyle of femur, pa: popliteal artery.

There are several reasons why we recommend preserving the infrapatellar fat pad especially during total knee arthroplasty: first we believe, taking our results into consideration, that the feeding arteries provided via Hoffa's fat pad play an important role in patella viability, as they may compensate the loss of other feeding arteries caused by invasive access routes. Second, shortening of the patellar tendon may arise with fat pad resection [24–26]. Third, fat pad resection has an influence on the biomechanics of the knee joint [33], as it seems to stabilize the knee joint, especially during extremes of knee motion (flexion angles of less than 20° and greater than 100°) [6].

However, if parts of the fat pad have to be resected, we emphasize sparing at least those parts of the fat pad which are located in ultimate proximity to the patellar borders. As far as the central mass of the fat pad is concerned, the fatty tissue next to the patellar tendon should be spared as the strongest anastomoses have been found to be present in this segment which, in turn, are also an integrative part of the arterial supply of the patellar tendon [34].

Weaknesses of our study include the small number of cases, so that no reliable conclusions can be drawn with respect to variations of the vascular anatomy within the infrapatellar fat pad (of Hoffa). Counting from another publication, the number of anastomoses varies depending on the degree of retropatellar arthrosis [17]. Furthermore, definite conclusions about the percentage of blood supply which reaches the patella via infrapatellar fat pad cannot be drawn. Further studies are needed in order to better estimate to which extent the anastomoses within Hoffa's fat pad are in a position to compensate the loss of other feeding arteries.

5. Conclusions

Until now, the arterial blood supply reaching the patella via the infrapatellar fat pad (of Hoffa) has not been subject of any detailed anatomical dissection, although radiographic presentations have been previously published [7, 11, 13]. Using microanatomical dissection techniques and a sophisticated morphological method to generate translucent specimens as well as multiplanar reconstructed angiograms, we were able to demonstrate the course of anastomoses in the peripatellar portions of the fat pad, especially in its superior aspect, which have obviously been overlooked in previous articles.

Advancing minimally invasive access routes are certainly demanded in nowadays surgery and mainly claim to reduce complications of any kind. Since various surgical procedures might endanger patellar vascular supply, each step should be weighed critically in order to achieve best possible outcome for the patients.

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Research Article

The "Oblique Popliteal Ligament": A Macro- and Microanalysis to Determine If It Is a Ligament or a Tendon

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Introduction. This study investigated the importance of the "oblique popliteal ligament" (OPL), and challenges its alleged ligament status. The currently named OPL is indigenous to the distal semimembranosus (SMT); therefore, by definition is not a ligament inserting from bone to bone. Clinically, a muscle-tendon unit is different then a ligament regarding proprioception and surgery. *Methods*. Literature search was conducted on texts, journals and websites regarding the formation of the OPL. Dissection of 70 knees included macro analysis, harvesting OPL, distal SMT and LCL samples and performing immunohistochemistry to 16 knees with antibody staining to the OPL, distal SMT and LCL. *Results*. All but one text claimed the OPL receives fibers from SMT. Macro dissection of 70 knees revealed the OPL forming from the distal SMT (100%). Microanalysis of OPL, distal SMT and LCL samples from 16 knees demonstrated expression of nervous tissue within selected samples. *Discussion*. No journals or texts have hypothesized that the OPL is a tendon. Clinically it is important we know the type of tissue for purposes of maximizing rehabilitation and surgical techniques. *Conclusion*. This study suggests the OPL be considered the oblique popliteal tendon as a result of the macro and micro evidence revealed.

1. Introduction

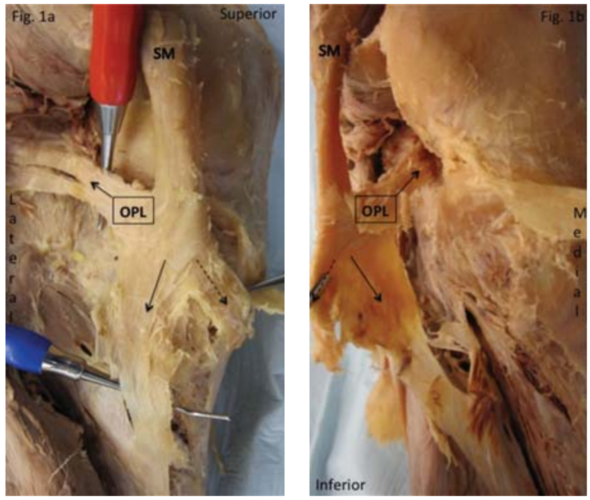
The posterior aspect of the knee has been increasingly studied because of its clinical relevance. Surgeons, biomechanists, physical therapists, all health care providers dealing with the musculoskeletal system, and anatomists need to have a definitive and precise understanding of the structures of the posteromedial knee. A previous study conducted by the authors identified the clinical importance, morphology, and accurate terminology of the distal semimembranosus muscle tendon unit (SMTU) [1]. This study also revealed that the currently named oblique popliteal ligament (OPL) was indigenous to the SMTU and, therefore, by definition is not a ligament inserting from bone to bone. This is clinically important because of the proprioception of a tendon versus a ligament, which may suggest a greater role by the distal semimembranosus tendon in posterior knee stability.

With regard to the literature regarding the oblique popliteal ligament, Woodburne's *Essentials of Human Anatomy* states that it is formed from the fibers of the distal semimembranosus tendon [2]. All other anatomical texts and atlases that consider or depict the OPL state that the distal semimembranosus tendon contributes fibers to the OPL [2–20]. Though the majority of the texts and journal papers describe the SMTU contributing to the OPL [21–32], none have hypothesized that this ligament is indigenous to the SMTU, therefore, a tendon by the true sense of the definition.

In order to provide further evidence towards this hypothesis, histological studies of the SMTU, OPL, and a well-defined ligament of the knee were needed. There have been previous histological studies completed on the various structures of the knee, the majority of which have primarily focused on the specific type of nerve ending present within these deep structures, particularly the cruciate ligaments and the menisci [33–41]. None have specifically looked at the histology of the OPL, and immunohistochemistry staining specific to the neuronal axons has not been conducted on any deep structures of the knee. Therefore, the authors conducted immunohistochemistry staining with antibodies specific to neuronal axons on the SMT, OPL, and the lateral collateral ligament (LCL) of the knee. The staining conducted allowed the author to compare the histology and neuronal components of the SMTU with the OPL and a well-defined ligament of the knee, such as the LCL. The objective of this study was to conduct a macro- and microanalysis investigation of the OPL and challenge its alleged ligament status.

2. Materials and Methods

A literature search was conducted on anatomical and specialty texts, atlases, journals, and websites regarding the morphology of the distal semimembranosus muscle tendon unit and oblique popliteal ligament. Deep dissections were performed on 43 embalmed human cadavers (23 M and 20 F, age: 55–89, average: 79.6 yrs), 70 knees in total (39 Rt and 41 Lt), to reveal the SMTU and its final attachments. Exclusion criteria are amputation, knee replacement, or any gross damage to the knee joint. The most distal portion of the SMTU was reflected medial to lateral in order to analyze whether or not the alleged oblique popliteal ligament is a continuation of the distal SMTU, or if it was a structure attaching from bone to bone. The OPL's distal (medial) and proximal (lateral) attachments were analyzed. Immunohistochemistry staining was performed on the SMTU, OPL, and LCL using the following protocols: PGP9.5 staining of human tendon/ligament sections with rabbit anti-PGP9.5 (Accurate Chemical)/goat anti-rabbit biotinylated (Vector), neuronal class III β-tubulin (NCT), and staining of human tendon/ligament sections with rabbit anti-NCT (Covance)/goat anti-rabbit biotinylated (Vector).



(a) (b)

Figure 1: (a) Deep dissection of the left posteromedial knee revealing the distal semimembranosus muscle tendon unit (SMTU) and oblique popliteal ligament (OP). SM: semimembranosus muscle. (b) Left SMTU reflected revealing that the alleged OPL is indigenous to the SMTU. Arrow: direct arm of the SMTU; dashed arrow: anterior arm of the SMTU.

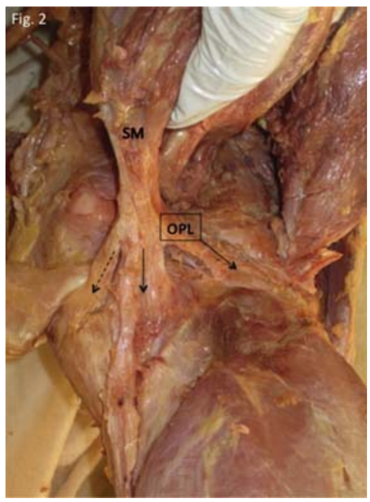


Figure 2: Deep dissection of the right posterior knee revealing the oblique popliteal ligament (OPL). SM: semimembranosus muscle. Arrow: direct arm of the SMTU; dashed arrow: anterior arm of the SMTU.

3. Results

Literature search revealed that 11 of the 19 anatomical texts and atlases that consider or depict the OPL state that the distal semimembranosus tendon contributes fibers to the OPL [2–20]. A much higher percentage was found in orthopedic or radiologic specialty articles (11 of 12 stated that the distal semimembranosus tendon contributes fibers to the OPL) [21–32] (see Table 1). Deep dissections revealed that the alleged oblique popliteal ligament's distal (medial) attachment originated from the SMTU in 100% of 70 knees. Its proximal (lateral) attachment was inserted into the joint capsule in 39/70, bone in 11/70, and both joint capsule and bone in 20/70 knees (see Figures 1(a), 1(b), 2, 3, and 4). Immunohistochemistry staining using rabbit anti-PGP9.5/goat anti-rabbit biotinylated revealed a positive stain for neuronal axons in both the SMT and the OPL and a negative stain in the LCL. Immunohistochemistry staining

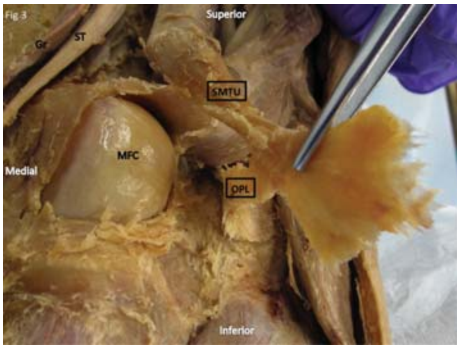


Figure 3: Deep dissection of the right posteromedial knee. Distal semimembranosus muscle tendon unit (SMTU) reflected revealing that the alleged oblique popliteal ligament is indigenous to the distal semimembranosus tendon. SM: semimembranosus muscle, SMTU: distal semimembranosus muscle tendon unit, OPL: oblique popliteal ligament, MFC: medial femoral condyle, ST: semitendinous muscle, Gr: gracilis muscle.

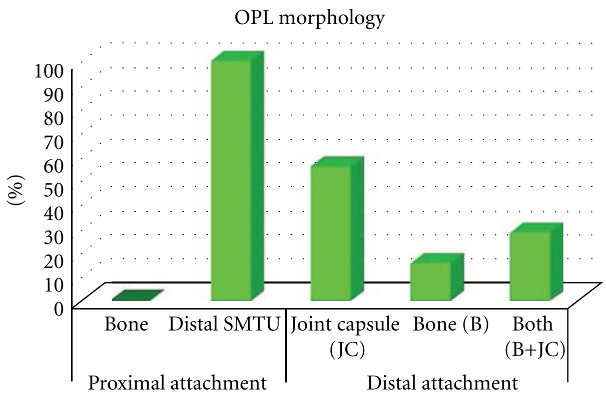


Figure 4: Oblique popliteal ligament morphology (OPL). Results: proximal and distal attachments.

using neuronal class III β-tubulin (NCT) staining of human tendon/ligament sections with rabbit anti-NCT/goat anti-rabbit biotinylated revealed a positive stain for neuronal axons in each of three tissue types, OPL, SMT, and LCL (see Figures 5(a), 5(b), 5(c), 6(a), 6(b), 6(c) and 7).

4. Discussion

Despite the fact that nearly 60 percent of anatomical texts and atlases as well as over 90 percent of specialty journal articles state that the distal semimembranosus tendon contributes fibers to the oblique popliteal ligament; none have hypothesized that this structure is itself a tendon [1–31]. A macroanalysis using deep dissection of the posterior knee revealed that the OPL's distal (medial) attachment originated from the SMTU in 100% of the knees. This provided evidence in support of the author's hypothesis; however, a microanalysis was also necessary to propitiate these findings. This study was the first to conduct a histological microanalysis of the OPL.

There have been previous studies that have used various staining protocols on the deep tissue of the knee, namely, the cruciate ligaments, menisci, and the medial collateral ligament [33–40]. The majority of this research conducted histological studies specifically targeting the morphology of nerve endings in these tissues. This was the first known study to use immunohistochemistry staining with an antibody specific to neuronal axons in the deep tissue of the knee. This was also the first study to utilize any staining protocol on the OPL.

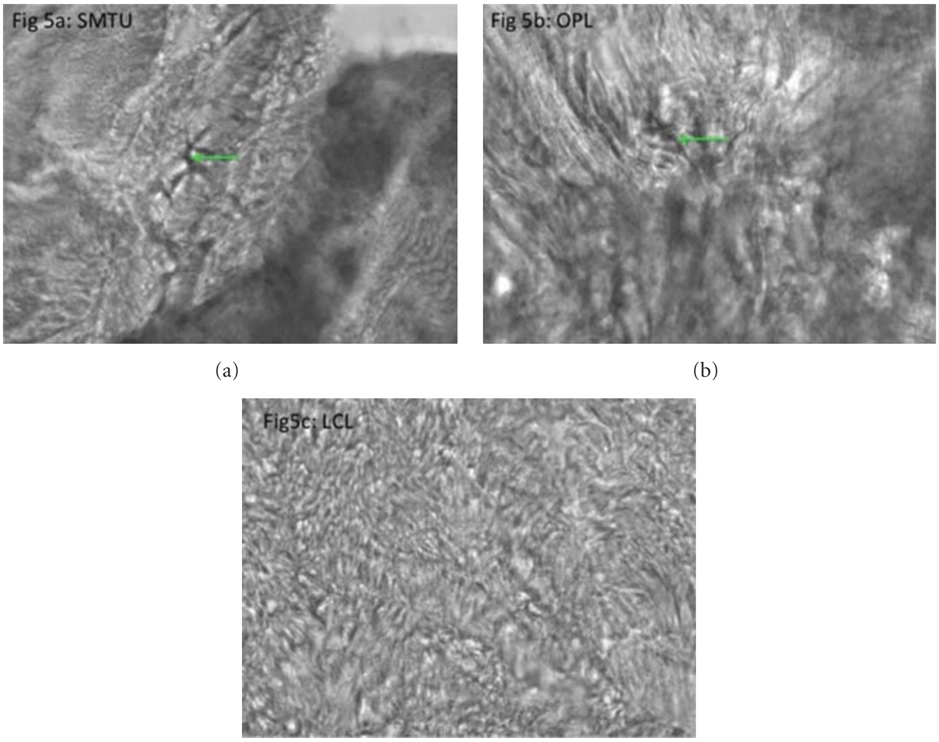
The microanalysis of the tendon properties using rabbit anti-PGP9.5/goat anti-rabbit biotinylated immunohistochemistry staining revealed neuronal axons in both the SMTU and the OPL and displayed similar histological patterns in both structures [33]. The LCL did not display a positive result for this stain and had a markedly different histology to both the OPL and SMT. Furthermore, the positive stain for neuronal axons provides grounds that Golgi tendon organs, nervous tissue specific to tendons, may be located in the OPL. These facts confirm the author's hypothesis that this structure is a tendon.

The authors are not aware of a stain specific to Golgi tendon organs. However, in pursuit of providing increased evidential proof for a change in terminology, the authors conducted a different, more definitive immunohistochemistry stain for neuronal axons using neuronal class III β-tubulin (NCT) with rabbit anti-NCT/goat anti-rabbit biotinylated. Though the histology of both the SMTU and the OPL was once again quite similar and vastly different from that of the LCL, the stain revealed a positive stain for neural tissue in all three structures: the OPL, SMTU, and LCL. This result does not nullify the results obtained from the PGP9.5 stains; however, it forced the authors to question whether or not immunohistochemistry staining for neural tissue within these structures is the most viable method for differentiating tendon from ligament.

The macroanalysis of the distal SMTU provides undeniable evidence that the OPL is indigenous to this tendon. The immunohistochemistry used in this study is proven to provide definitive results for neuronal axons within tissue samples [42] and was the first to demonstrate that there is nervous tissue within the OPL. Despite the inconclusive results of the final immunohistochemistry stains, the macro- and microevidence that the oblique popliteal ligament is not a ligament at all is overwhelming. This evidence has led the authors to propose a nomenclature change for this structure, naming it the oblique popliteal tendon.

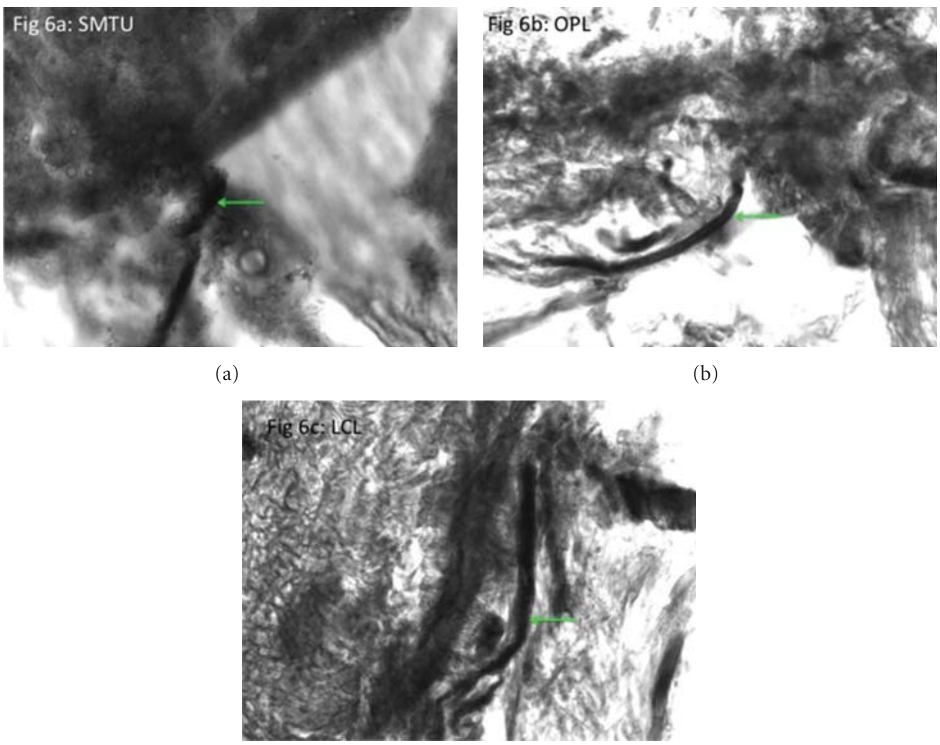
5. Conclusion

The macroanalysis of the OPL revealed unequivocally it is indigenous to the distal SMTU. The microanalysis using an immunohistochemistry stain with PGP9.5 revealed a positive result for neuronal axons within both the SMT and OPL. Further microanalysis using an immunohistochemistry stain with β-tubulin revealed a positive stain for neuronal axons in the SMT, OPL, and LCL. Though the latter result leads the authors to question the validity of differentiating tendon from ligament using this particular immunohistochemistry stain, the macroanalysis results are overwhelming, and the microanalysis reveals striking similarities in the histology of



(a) (b) (c)

Figure 5: Light microscope view (20x) of PGP9.5 stain revealing neuronal axon (arrow). (a) Distal semimembranosus muscle tendon unit (SMTU). (b) Oblique popliteal ligament (OPL). (c) Lateral collateral ligament of the knee (LCL).



(a) (b) (c)

Figure 6: Light microscope view (20x) of β-tubulin stain revealing neuronal axon (arrow). (a) Distal semimembranosus muscle tendon unit (SMTU). (b) Oblique popliteal ligament (OPL). (c) Lateral collateral ligament of the knee (LCL).

Table 1: Contribution to the OPL from the distal semimembranosus tendon via anatomical texts and atlases and specialty journals.

Anatomical Texts and Atlases	Semimembranosus contributes fibers to the oblique popliteal ligament (OPL)	Speciality journals	Semimembranosus contributes fibers to the oblique popliteal ligament (OPL)
Anatomy as a Basis for Clinical Medicine [11]	X	Some Aspects of Functional Anatomy of The Knee Joint [12]	
Atlas of Human Anatomy [13]		The Supporting Structures and Layers on The Medial Side of The Knee [31]	X (OPL)
Anatomy for Surgeons [43]	X	Anatomy of The Medial Part of The Knee [26]	
BRS Gross Anatomy [5]	X	Anatomy of The Posterior Aspect of The Knee [27]	X (OPL)
Clemente Anatomy [6]		Distal Semimembranosus Complex: The Normal MR Anatomy, Variants, Biomechanics and Pathology [21]	X (OPL)
Clinical Anatomy [9]	X	Tendinous Insertion of Semimembranosus Into The Lateral Meniscus [24]	X (OPL)
Clinical Anatomy by Systems [18] Atlas	X	Posteromedial Corner of The Knee: MR Imaging with Gross Anatomic Correlation [28]	X (OPL)
Clinical Orthopaedic Rehabilitation [4]		Avulsion of The Posteromedial Tibial Plateau by The Semimembranosus Tendon: Diagnosis with MR Imaging [32]	X (contribution to OPL)
Color Atlas and Textbook of Human Anatomy [10]	X	The Posteromedial Corner of The Knee: Medial Injury Patterns Revisited [30]	X (OPL)
Essential Clinical Anatomy [15]	X	Hamstring Muscle Complex: An Imaging Review [25]	X (OPL/arcuate)
Essentials of Human Anatomy [2]	X	A Note on The Semimembranosus Muscle [22]	X (OPL)
Grant's Atlas of Anatomy [3]	X	Semimembranosus Tendon Viewed through an Isolated Medial Meniscus Capsular Avulsion: A Case Report [29]	X (OPL/ligament of Winslow)
Gray's Anatomy 40th ed	X		
Gray's Anatomy for Students [8]			
Gray's Atlas of anatomy [7]			
Gross Anatomy in the practice of medicine [17]			
Lippincott Williams & Wilkins Atlas of Anatomy [20]			
Sports Injury Assessment and Rehabilitation [16]			
Surgical Atlas of Sports Medicine [14]	X		

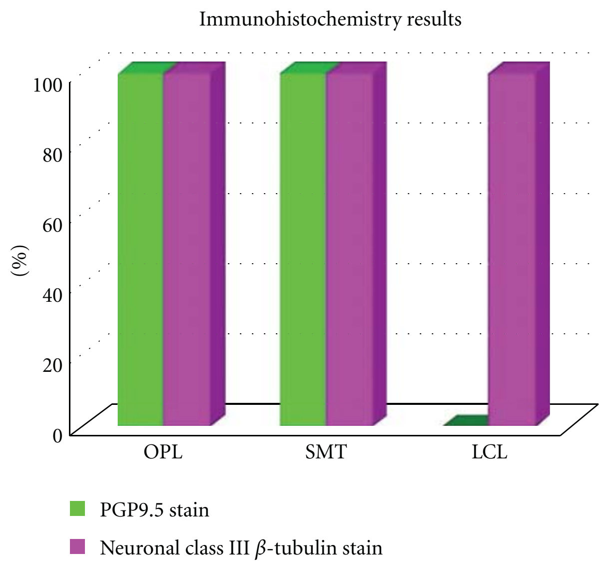


FIGURE 7: Immunohistochemistry results of PGP9.5 staining of human tendon/ligament sections with rabbit anti-PGP9.5 (Accurate Chemical)/goat anti-rabbit biotinylated (Vector) and neuronal class III β-tubulin (NCT), staining of human tendon/ligament sections with rabbit anti-NCT (Covance)/goat anti-rabbit biotinylated (Vector).

both the OPL and SMT. The authors strongly suggest that the oblique popliteal ligament be renamed the oblique popliteal tendon (O) due this macro- and microanalysis study. Clinically, this study improves terminology accuracy and medical international language, allowing for better understanding of successful rehabilitation methods and rationale for current and future surgical procedures.

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