Surgical exposure of the hip joint and femur with a special emphasis on the architecture and function of the quadriceps muscle group and femoral blood supply

Karl Grob, MD

This thesis is presented for the degree of Doctor of Philosophy of The University of Western Australia

School of Sport Science, Exercise and Health

2017
THESIS DECLARATION

I, Karl Grob, certify that:

This thesis has been substantially accomplished during enrolment in the degree.

This thesis does not contain material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution.

No part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of The University of Western Australia and where applicable, any partner institution responsible for the joint-award of this degree.

This thesis does not contain any material previously published or written by another person, except where due reference has been made in the text.

The work(s) are not in any way a violation or infringement of any copyright, trademark, patent, or other rights whatsoever of any person.

The research involving human data reported in this thesis was assessed and approved by The University of Western Australia Human Research Ethics Committee.

The investigations for this PhD thesis (macro-dissections) were performed at the Department of Anatomy at the University of Zürich and Fribourg, Switzerland. The cadaver parts were obtained from the institutional body donation program (http://www.anatom.uzh.ch/Bodydonation.html) following the ethical guidelines “On the use of cadavers and parts of cadavers in medical research and for pre-, postgrad and continued education and research with human subjects” by the Academy of Medical Sciences (SAMS).

Written patient consent has been received and archived for the research involving patient data reported in this thesis. However, written patient consent was necessary only for the case report “Knee Pain Associated with Rupture of Tensor Vastus Intermedius, a Newly Discovered Muscle: A Case Report”.

The work described in this thesis was self-funded.

This thesis contains published work and/or work prepared for publication, some of which has been co-authored.

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This thesis contains work that has been published and/or prepared for publication.

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8. *New insight in the architecture of the quadriceps tendon. Journal of Experimental Orthopaedics, submitted October 2016* (manuscript will be accepted after last minor revision)

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9. *The interaction between the vastus medialis and vastus intermedius and its influence on the extensor apparatus of the knee joint. An anatomical investigation.* (revised manuscript has been submitted to Journal of Knee Surgery, Sports Traumatology, Arthroscopy (KSSTA in October 2016, waiting for answer)

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I, Timothy Ackland certify that the student statements regarding their contribution to each of the works listed above are correct

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An important goal of any operation is to minimize damage to the patient’s anatomy and function. Understanding the anatomy and function of the musculoskeletal system is an important prerequisite primarily for orthopaedic surgeons but also for physiotherapists, and sports scientists. Over the last years many unanswered questions have accumulated with regards to the direct anterior approach to the hip joint and its potential extension, blood supply to the femur, function and architecture of the quadriceps muscle group. The following series of studies included in this thesis aimed to answer these questions.

Based on observations during daily clinical practice as an orthopaedic surgeon, but also as an anatomist, the purposes of this PhD thesis were as follows.

PART I

1. To demonstrate the neurovascular structures encountered: (a) during the direct anterior approach to the hip joint; and (b) with special emphasis on potential distal and proximal extension, and the consequent harm to the quadriceps muscle group.

2. To investigate the innervation of the quadriceps muscle group and blood supply to the femur with special emphasis on the lateral subvastus approach to the femur and a commonly used technique of vastus lateralis muscle transfer.

PART II

1. To clarify, in terms of muscle innervation, whether the discovered intervening muscle between the vastus lateralis and vastus intermedius was a variation of the former or later.

2. To investigate the architecture of the quadriceps tendon with special emphasis on all components of the quadriceps muscle group including the newly discovered intervening muscle.

3. To reveal the anatomical interaction between the vastus medialis and vastus intermedius with regards to their origins, insertions, innervation and function within the extensor apparatus of the knee joint.

Most of these questions have been answered via clinical anatomical studies. Other new questions were borne and might be answered in future publications (see section “ongoing projects”).
ACKNOWLEDGEMENTS

I would like to thank all those persons who helped me in working for my PhD. My special thanks to John Bloomfield. He was the first person I spoke to about the results of the preliminary dissections. Finally, he encouraged me to publish all my conclusions and put them together in a PhD thesis. John Bloomfield made it possible for me to attend the School of Sports Science, Exercise and Health at the UWA, where I was accepted as a PhD student by Tim Ackland, my principal supervisor. Tim Ackland was a steady companion on my way to the PhD and generally took good care of me. In fact, Tim visited me once in Switzerland on the occasion of an annual meeting and thus spared me a long trip to Australia.

A big thank goes to the two Co-supervisors Markus Kuster and Luis Filgueira. Markus Kuster and I are long-standing friends in the professional field, as orthopedic surgeons, and also good personal friends. His evaluation of my investigations was always very important to me. We both work in the field of hip and knee surgery, and were able to implement the conclusions drawn from our studies in clinical routine. I thank him for the crucial and instructive discussions we had. We helped each other to develop mutually, perfected the technique of minimally invasive hip surgery – and also benefited our patients in the process, I think.

I have much to thank Luis Filgueira for initially – at the Department of Anatomy at UWA, he made my difficult start much easier than it would have been. He gave me access to the infrastructure, material, and the important initial dissections. He also helped me to find my way in the complex jungle of bureaucracy, which is part and parcel of current research. As it happened, Luis was called to Switzerland and appointed at the Department of Anatomy in Fribourg, Switzerland. He gave me repeated opportunities to test my conclusions on further specimens. The discussions with Luis always served a source of new input and gave me the certainty that I was on the right track.

I am especially indebted to Helen und Mal Gilbey. They have also been my companions and fellow-travelers for a long time. We met in 1997 at the Department of Human Movement. Helen and Mal made it possible for us to stay in Australia by taking care of our house in Switzerland during the time. I could live with my family in their house in Perth. Helen was always the first reader of my papers. Her corrections and comments enhanced the quality of my papers enormously and contributed significantly to the success of my PhD thesis.
Myrijam Manestar has been and still is a loyal companion in my anatomical investigations. Twenty-five years ago, when I was still at medical school, Ms. Manestar aroused my enthusiasm for anatomy. I am a lecturer at the Institute of Anatomy, University of Zurich, for 15 years now and supervise operation courses for future orthopedists. Ms. Manestar always accompanied and supported me in this endeavor. Her excellent knowledge of anatomy is most impressive and she has always been a source of immense support. Quite often we pored over specimens together for several hours and interpreted the anatomy of the specimens. With her personal library of books on anatomy and her knowledge of the old literature, she enriched the conclusions of my work to an enormous extent.

I also want to thank Magdalena Vich for organizing the dissections and courses, as well as Ingeborg Franke and Sebastian Pilz for preparing the materials and the cadavers. You were always very patient with me. Quite often I performed the examinations well into the night and occasionally you also had to work long hours because of that.

A big thank you goes to Vilijam Zdravkovic, scientific head at the Clinic of Orthopedic Surgery and Traumatology of the Musculoskeletal System at Kantonsspital St. Gallen. He always supported me during the last and – what seemed to me – most difficult “mile” on the pathway to publication. He formatted my papers, arranged the figures and tables, improved legends, obtained the signatures of the co-authors, and fulfilled the innumerable wishes of the various journals. I am quite sure I would have given up long ago without Vilijam and would have drowned in the quagmire of administration and forms.

Of course a special thanks to my family, my wife Katrin and the children Nadja, Sabina and Daniela. Good ideas, as we know, do not always come in the best of moments; quite often I was physically present but my thoughts were elsewhere. You always supported me and were always interested in my work.

Last but not least, I think the several friends of Floreat Beach, namely Hans, Brian, Susie, Sue, Geoff, Hugh, Jan, David, Jane and again Helen and Mal and many more. Thanks for your hospitality. We always felt very comfortable with you. Thanks to you, Perth has become a second home for us.
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**Thesis Summary**

**Appendix A. Ongoing Projects and Papers**

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Appendix B. Video Clip added Electronically:

“Simplified functional model of the extensor apparatus of the knee joint” based on the study: “The interaction between the vastus medialis and vastus intermedius and its influence on the extensor apparatus of the knee joint. An anatomical investigation”.
Introduction

Muscles, vessels and nerves must either be transected or held aside and protected when performing surgery and creating a surgical access. An important goal of any operation is to minimize damage to the patient’s anatomy and function. In order to achieve this goal, the surgeon must be thoroughly familiar with the details of all relevant anatomical structures. Understanding the anatomy is a key aspect of successful treatment. However, several questions concerning the femoral, hip and knee joint access remain unanswered at the present time.

Understanding the function and anatomy of the musculoskeletal system is an important prerequisite not only for orthopedic surgeons, but also for physiotherapists and sport scientists. Anatomy and function are closely linked. This is especially true of the extensor apparatus of the knee joint. The quadriceps femoris muscle group is traditionally described as being composed of the rectus femoris and the three vasti (i.e. the vastus lateralis, intermedius and medialis), which arise independently and blend into the common quadriceps tendon. However, clinical experience and investigations of anatomical specimens demonstrate variability in respect of the origins and insertions of the different components. Modern anatomy textbooks do not reflect the complex anatomy and interaction between the different muscle components. Classical anatomy has defined each muscle as a separate entity with a unique function at the joint it spans. It is common to view muscles as mechanically independent actuators. As a result, many musculoskeletal models have been developed based on a simplified view of the human quadriceps anatomy.

Following careful exposure of the proximal and lateral aspect of the quadriceps muscle group while performing the direct anterior approach for total hip replacement we found a muscle belly between the vastus lateralis and the vastus intermedius, which cannot be clearly assigned to the former or the latter. Subsequent dissections in the anatomy laboratory revealed that this intervening muscle consistently fused into the middle layer of the quadriceps tendon in the form of an aponeurosis lying adjacent to the vastus intermedius (VI). As this muscle was previously attributed to the vastus lateralis (VL), its role in the quadriceps muscle group was neglected. Further preliminary dissections of the quadriceps muscle group also revealed different morphological findings in regard to its interaction and insertion compared to the classic descriptions.
Based on all these observations during surgery and anatomical dissections, the aims of this PhD thesis were multi-faceted and can be divided in two parts:

- Part I – Surgical exposure of the hip joint and femur
- Part II – Architecture and function of the quadriceps muscle group

The aims of PART I – Surgical exposure of the hip joint and femur were:

1. to demonstrate the neurovascular structures encountered during the direct anterior approach to the hip joint with special emphasis on potential distal and proximal extension, and harm to the quadriceps muscle group;
2. to investigate the innervation of the quadriceps muscle group and blood supply to the femur with special emphasis on the lateral subvastus approach to the femur, and a commonly used technique of VL muscle transfer.

The aims of PART II – Architecture and function of the quadriceps muscle group were:

1. to clarify, in terms of muscle innervation, whether the discovered intervening muscle between the VL and VI was simply a variation of the former or latter;
2. to investigate the architecture of the quadriceps tendon with special emphasis on all components of the quadriceps muscle group including the newly discovered intervening muscle;
3. to reveal the anatomical interaction between the vastus medialis (VM) and VI with regard to their origins, insertions, innervation and function within the extensor apparatus of the knee joint.

PART I – Surgical exposure of the hip joint and femur

Total hip arthroplasty (THA) was popularized by Sir John Charnley in the 1960s. Since this time the procedure has remained one of the most successful operations for improving the patient’s quality of life, and is now widely and routinely performed. There are a variety of different surgical approaches to the hip, each having its own advantages and disadvantages. The surgeon’s preference will often depend on personal experience and the training they have received. Two of the most common approaches are the posterior approach and the lateral or antero-lateral approach. The standard posterior approach requires division of the posterior hip capsule and the external rotator muscles, and is associated with high dislocation rates. The antero-lateral approach is more resistant to dislocation, but detaching the gluteus medius and minimus insertion from the trochanter is associated with abductor dysfunction and posterior limp. Efforts to reduce complications associated with surgical exposure of the hip has led some
surgeons to question these traditional operative techniques.

During the last two decades, THA performed through a direct, single anterior approach has gained interest for the treatment of hip osteoarthritis. This is due to the low dislocation rate, rapid functional recovery, and accuracy of leg length and offset restoration offered by the technique. As an orthopaedic surgeon, the author has used this approach since 2005 in 80% of patients. For the remaining 20% of patients, a posterior, lateral, antero-lateral approach, or an approach with extended trochanteric osteotomy or trochanter flip osteotomy was performed. The author favours the direct anterior approach because it is generally accomplished without detachment of any muscle from the pelvis or femur and without violating the abductor tendon as occurs in the lateral and antero-lateral approaches. Patients also appear to benefit from a rapid functional return. However, an extension of the anterior approach, which might be necessary due to intra- or post-operative complications, could endanger neurovascular structures such as the nerve supply to the quadriceps muscle group or abductor muscles. The anatomical relationship of nerve branches and blood vessels to the quadriceps with respect to the anterior approach, has not been documented. The following papers for my PhD thesis refer to this specific topic.

**Paper 1 – Distal extension of the direct anterior approach to the hip poses risk to neurovascular structures: an anatomical study.**

Grob K, Monahan R, Gilbey H, Yap F, Filgueira L, Kuster M.


**Paper 2 – Potential Risk to the Superior Gluteal Nerve During the Anterior Approach to the Hip Joint: An Anatomical Study.**

Grob K, Manestar M, Ackland T, Filgueira L, Kuster MS.


**Paper 3 – The Anatomical Course of the Lateral Femoral Cutaneous Nerve with Special Attention to the Anterior Approach to the Hip Joint.**

Rudin D, Manestar M, Ullrich O, Erhardt J, Grob K.


At the time of the investigations for the third study in 2015, Ms Diana Rudin (lead author of the study) was working as a resident in the authors’ hip team at the Clinic of Orthopedic Surgery, Kantonsspital St. Gallen. As the supervisor of the study, instructor and helper during dissections, the author supported Ms Rudin in her work (her thesis for the degree of medical
doctor). As supervisor and corresponding author I was significantly involved in drafting the manuscript. Ms Rudin presented the work at the Swiss Orthopedic Congress in 2014 and won the first prize for the “best of all studies”. The study has also been honoured by the comment of the editor-in-chief of the Am JBJS in April 8, 2016 (https://orthobuzz.jbjs.org/), as follows.

*JBJS Editor’s Choice—Prevent Nerve Damage During Anterior Hip Approaches*

*While anatomy is the foundation of all surgical practice, we at The Journal do not often publish anatomic manuscripts. We make exceptions when papers have the potential to influence the practice of orthopaedic surgery in a major way. Such an exception is the cadaver study by Rudin et al. in the April 6, 2016 JBJS.*

The authors’ focus on the course of the lateral femoral cutaneous nerve (LFCN) of the thigh. This is a highly relevant anatomic structure because of the increasing interest in the anterior approach for hip arthroplasty, for anterior approaches to the hip for open reduction of femoral-head or proximal-femur fractures, and even for surgically treating femoroacetabular impingement.

The major take-home point is the extensive variability of this nerve in terms of where it exits the pelvis and its three different branching patterns from there (see illustration). These anatomic findings should alert the operating surgeon to make skin incisions as lateral as possible and to take extra caution when creating the interval deep to the fascial plane.

Rudin et al. have performed a service to the orthopaedic community by carefully defining the high degree of variability in the course of this nerve, which often is in harm’s way during common surgical exposures. Although injury to the sensory-only LFCN will not lead to major neurological complications, the authors conclude that patients undergoing anterior hip approaches should be informed of the risks of sensory loss or dysesthesia.

Marc Swiontkowski, MD
JBJS Editor-in-Chief

The importance of anatomic knowledge is also indicated by the following published studies:


Grob K, Monahan R, Gilbey H, Ackland T, Kuster MS.

Since the first publication of the advancement of the VL muscle for the treatment of hip abductor discontinuity in 2004, the VL muscle has been used as functional flap in many patients. However, due to the questionable results of surgeries and based on the findings of the present study, this procedure has mainly been abandoned.
The majority of femur fractures are treated operatively, either with open reduction and internal fixation, or via minimally invasive surgery by intramedullary nailing or indirect reduction techniques. Both intramedullary nails and plate fixation have been recommended. For plate osteosynthesis, a lateral subvastus approach to the femur has traditionally been used. The following study gives advice on how the femur should be approached to minimize damage to the blood supply of the femur, which is important for fracture healing. Additionally, due to confusion that exists in the published literature for the nomenclature of the “perforating artery”, the term of “LISP vessels” has been introduced.

The study shows that Ligation of LISP vessels and visualisation of the femoral shaft can be performed safely, by preserving the vessels considered essential for blood supply to the femur during the open technique. Open reduction does not necessarily mean “unbiological”. The study revealed that with the subvastus approach to the femur, two important aspects should be considered. Firstly, the LISP vessels should not be ligated too close to the lateral intermuscular septum. Secondly, the linea aspera should not be exposed unnecessarily and the lateral intermuscular septum should be regarded the anatomical dorsal limit.

**Paper 5 – Effects of ligation of lateral intermuscular septum perforating vessels on blood supply to the femur.**

Grob K, Manestar M, Lang A, Ackland T, Gilbey H, Kuster MS.


**PART II: Architecture and function of the quadriceps muscle group**

During hip replacements performed via the direct anterior approach, and after careful anatomical dissection of the quadriceps muscle group, an additional muscle has been found between the VL and VI. This intervening muscle could not be clearly assigned to the either of these components of the quadriceps muscle group. Our findings were surprising as the quadriceps femoris is one of the most extensively studied muscle groups within the human body. There have been many clinical, anatomical and biomechanical accounts of this muscle group in recent years. However, despite numerous descriptions in the literature, an intermediate muscle between the VL and the VI has been given little attention in the literature.

Interpreting this intervening muscle (due to its course we named it “tensor of the vastus intermedius” – TVI) as an independent muscle and understanding its role within the extensor mechanism changes our understanding of the complex architecture and function of the extensor apparatus of the knee joint.
We submitted this study to the Journal of Clinical Anatomy, but through the review process the title of the manuscript was changed according to the wishes of the editor. We would have preferred the title of the original manuscript – “The Tensor of the Vastus Intermedius: An additional muscle component of the extensor apparatus of the knee joint”. As with the other components of the quadriceps muscle group, the TVI cannot be seen as an independent entity, which is implied by the final title of this paper.

The results of this study also influence the radiological interpretation of MRI-transections of the extensor apparatus. The distal aponeurosis of the TVI, traditionally regarded as an intermuscular septum or space between the VL and VI, does not correspond to the intermuscular plane between these two muscles. Thus, in a cross-sectional image of the thigh, the aponeurosis of the TVI is not seen as a muscle, but merely as a fascial layer or an intermuscular septum. However, knowing that the TVI exists, one can distinguish an aponeurotic sheet between the medial aponeurosis of the VL and the lateral aponeurosis of the VI. Like the other components of the quadriceps muscle group, the TVI also contributes to the multi-layered structure of the extensor apparatus of the knee joint. To recognize the wide spectrum of injuries that affect the extensor apparatus of the knee joint the radiologist must be familiar with its normal anatomy. Because the TVI has been given little scientific or clinical attention to date, any damage to its structure has not been recognized. This issue is supported by the following published case report.

Our investigations and published data so far have demonstrated that the structures of the quadriceps muscle group are diverse. As mentioned, our dissection of the quadriceps muscle group revealed that beside the rectus femoris and the other vasti, a fifth muscle component—the TVI, consistently fused into quadriceps tendon. It can be hypothesized that all these elements of the extensor apparatus of the knee joint must also be represented in the quadriceps tendon. A thorough understanding of the architecture of the knee extensor mechanism is of clinical importance. The quadriceps tendon is involved in many orthopaedic
procedures around the knee joint including surgical approaches, tendon injuries or harvesting as a tendon graft. Patellar problems are also common after total knee arthroplasty. A better understanding of the quadriceps tendon anatomy is, therefore, fundamental for improvements in surgical techniques and for the radiological interpretation of a traumatized extensor apparatus of the knee joint. The following study investigated the multi-layered quadriceps tendon with special emphasis on all components of the quadriceps muscle group including the newly discovered TVI.

**Paper 8 – New insight in the architecture of the quadriceps tendon.**

**Grob K, Manestar M, Filgueira L, Ackland T, Gilbey H, Kuster MS**  
*J Exp Orthop, (accepted October 2016)*

During the many dissections, the author observed that the interaction between the VM and VI is more complex and intricate than as initially described. In addition, dissections of the quadriceps muscles revealed different morphological findings between the VM and VI compared to classic descriptions in the literature. The last study for this PhD thesis investigated the anatomical connection between the VM and VI, their innervations, origins, insertions and contributions to the function of the extensor apparatus of the knee joint. Based on these findings a simplified mechanical model of the function of the quadriceps muscle group has been developed (see the video clip added in the appendix). This manuscript has been submitted recently for review.

**Paper 9 – The interaction between the vastus medialis and vastus intermedius and its influence on the extensor apparatus of the knee joint. An anatomical investigation.**

**Grob K, Manestar M, Filgueira L, Kuster MS, Gilbey H, Ackland T**  
*KSSTA, Manuscript has been re-submitted after revision in October 2016*
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The interaction between the vastus medialis and vastus intermedius and its influence on the extensor apparatus of the knee joint. An anatomical investigation

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Distal Extension of the Direct Anterior Approach to the Hip
Poses Risk to Neurovascular Structures
An Anatomical Study

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Background
The anterior approach to the hip gained popularity for total hip arthroplasty in recent years. Distal extension of the anterior approach, sometimes needed intraoperatively, potentially endangers neurovascular structures to the quadriceps. The aim of this study was to determine the anatomical structures placed at risk by distal extension of the anterior approach to the hip.

Methods
Seventeen cadaveric hemipelves from twelve human specimens were dissected. The femoral nerve and its branches and the vessels arising from the lateral femoral circumflex artery were assessed in relation to the distal extension of the anterior approach. The damage caused by the introduction of a cerclage cable passer was also investigated.

Results
The area immediately distal to the intertrochanteric line is a common entry point for several nerve branches and is a useful distal landmark for surgeons to use to protect important neurovascular structures. The distal extension of the anterior approach compromises the nerve supply to the anterolateral portions of the quadriceps. Introduction of a cerclage cable passer through the anterior access also jeopardizes nerve branches to the vastus lateralis, lateral parts of the vastus intermedius, and branches of the lateral femoral circumflex artery.

Conclusions
Distal extension of the direct anterior approach to the hip is challenging to accomplish without neurovascular injury to anterolateral parts of the quadriceps muscle group. In addition, important neurovascular structures are endangered with the introduction of a cable passer through the anterior approach.
Clinical Relevance

Distal extension of the direct anterior approach to the hip beyond the intertrochanteric line may compromise neurovascular structures supplying the quadriceps muscle.

The direct anterior approach for total hip arthroplasty has recently gained popularity with good clinical results. However, there have been reports of intra-operative complications, such as femoral fracture, implant failure, and muscle trauma, that may require an extension of the surgical approach. Kennon et al. reported that the direct anterior approach could be safely extended proximally and distally even in complex revisions without clinically relevant nerve injuries. Furthermore, a textbook on surgical exposures describes and recommends this option.

While proximal extension with detachment of the tensor fascia femoris and gluteal muscles from the pelvis is part of the Smith-Petersen approach, distal extension could endanger neurovascular structures. The anatomical relationship of nerve branches and blood vessels to the quadriceps with respect to the anterior approach has not been documented, to our knowledge.

**Fig. 1-A** Anterolateral view of the right hip. The anatomy of the anterior approach is presented. The internervous space between the sartorius and the rectus femoris medially and the tensor fascia femoris laterally is widened. The rectus femoris and sartorius are reflected medially. The yellow dotted line indicates the position of the skin incision slightly lateral to the anatomical plane. The yellow arrow indicates the way of access to the hip joint proximal to the nerve branches to the vastus lateralis and intermedius and the branches of the lateral femoral circumflex artery (LFCA).
The purpose of this cadaver study was to demonstrate the neurovascular structures encountered during the direct anterior approach to the hip joint with special emphasis on potential distal extension or the placement of a cerclage cable passer around the proximal part of the femur.

**Materials and Methods**

Seventeen cadaveric hemipelves (ten paired and seven unpaired) from twelve specimens (eight male and four female) were investigated.

Seven limbs were «Thiel-fixed» and ten were embalmed in a formalin based solution. None of the cadavers showed any evidence of previous trauma or surgery to the femur or hip joint. The dissection protocol began with each lower limb being placed supine on a dissection table and...
the hip joint approached anteriorly. For improved visualization, a 25-cm long incision following the anterior half of the iliac crest to the anterior superior iliac spine was made. From there, the incision was curved downward, aiming toward the fibular head. The superficial skin and subcutaneous tissue were removed. The fascia of the tensor fascia femoris muscle was incised laterally. Staying lateral to the sartorius and rectus femoris muscles allowed us to identify the ascending branch of the lateral femoral circumflex artery where it entered the tensor fascia femoris muscle and trace it medially to its origin (Fig. 1-A). After resection of the joint capsule, the proximal margin of the muscle bellies of the vastus lateralis and vastus intermedius were localized at the intertrochanteric line. The femoral nerve was dissected proximal to the inguinal ligament, and its course was traced distally. The anterior approach to the hip joint was then extended distally along the anterior margin of the tensor muscle, while remaining lateral to the rectus femoris. All nerve branches to the vastus lateralis and vastus intermedius, the rectus, and the sartorius as well as the vessels arising from the lateral femoral circumflex artery were dissected carefully. To improve visualization of the neurovascular structures, the rectus femoris and the sartorius were transected distally and elevated medially and proximally. The tensor was mobilized from the underlying vastus lateralis. The entry point of each nerve branch into its specific muscle belly was recorded (Fig. 1-B), and the distances to two reference lines—X1 and X2, with distance X1 to X2 being 100%—were measured. X1 was the horizontal line through the middle of the neck of the femur just proximal to the intertrochanteric line, and X2 was the horizontal line through the lower margin of the lesser trochanter.
The entry points (as a percentage of the distance from X1 to X2) of nerve branches into the lateral part of the vastus lateralis (VL lat), the medial part of vastus lateralis (VL med), the lateral part of the vastus intermedius (VI lat), the medial part of the vastus intermedius (VI med), the rectus femoris, and the sartorius in relation to lines X1 and X2. Ascendens, transverse, and descendens refer to the areas where the ascending, transverse, and descending branches of the lateral femoral circumflex artery cross the midline of the femur. For better visualization, some nerve branches are marked with black paper.

X1 corresponds to the horizontal line through the middle of the neck of the femur just proximal to the intertrochanteric line, and X2 corresponds to the horizontal line through the lower margin of the lesser trochanter (distance X1 to X2 is 100%). Red double arrow = the shortest measured distance between the horizontal line X1 and the first entrance of a nerve branch, black dots in the centers of the double black arrows = the average distance, and black double arrows = 95% confidence limits.

The distances from the point where the vessels of the lateral femoral circumflex artery crossed the midline of the femur (Y) in a neutral position of rotation were also recorded. Nerve branches to the vastus lateralis and vastus intermedius were traced intramuscularly, and their courses deep into the muscle surface were studied. Finally, a cerclage cable passer (Stryker, Selzach, Switzerland) was placed around the shaft of the femur just distal to the lesser trochanter, and its proximity to the neurovascular structures was recorded. The cerclage cable passer was inserted...
once through the extended anterior approach and once through a separate lateral subvastus approach. Both passing methods were investigated as they were performed from medial to lateral and from lateral to medial.

**Results**

The distance from X1 and X2 to the points where the branches of the lateral femoral circumflex artery intersected the Y line and the distance from X1 and X2 to the points where the muscle branches of the femoral nerve entered the specific muscle belly are shown in Figure 2 as percentages (with the distance from X1 to X2 being 100%). The lateral femoral circumflex artery diverged into the ascending, transverse, and descending branches between the horizontal reference lines X1 and X2 in all cases. The ascending branch always progressed directly above the middle of the femoral neck, the transverse branch was always between reference lines X1 and X2, and the descending branch was below the reference lines.

The mean distance (and standard deviation) between X1 and the proximal nerve branches of the vastus lateralis or vastus intermedius was 34 ± 14.5 mm (range, 9 to 75 mm). In eight of the seventeen lower limbs, one or more nerve branches pierced the vastus lateralis or vastus intermedius <20 mm distal to X1. The shortest measured distance in millimeters between the horizontal line X1 and the first entry point of a nerve branch of either the vastus lateralis or the vastus intermedius was 9 mm. A vascular and nerve web of the lateral femoral circumflex artery and muscle branches of the femoral nerve coursed toward the muscle fibers of the vastus lateralis and vastus intermedius (Fig. 3). We found separate proximal-medial and distal-lateral muscle bellies of the vastus lateralis. These two muscle bellies, together with lateral portions of the vastus intermedius, were supplied by nerve branches from the same lateral division of the femoral nerve. The main nerve branch to the lateral part of the vastus lateralis coursed regularly together with the descending branch of the lateral femoral circumflex artery and vein. Additional neural supply was provided from the proximal aspect of the femoral nerve.

The blood supply to the vastus lateralis and vastus intermedius proximally was either via the transverse branch or ramifications of the ascending branch of the lateral femoral circumflex artery. The lateral part of the vastus intermedius received nerve branches from the same division of the femoral nerve that supplied the vastus lateralis. The medial part of the vastus intermedius was supplied by medial branches of the femoral nerve. Those branches supplied deep layers of the vastus intermedius, which served the articularis genus in the distal aspect. The rectus femoris and the sartorius were innervated by separate arcade-like branches of the femoral nerve that were more superficial and at a greater distance from the anterior border of the femur. Figure 2 shows the distribution pattern of the points of entry of nerves in relation to the anatomical reference lines X1 and X2.
Fig. 3 Anterior view to the proximal part of the right thigh and the right hip joint. The sartorius (not visible) and rectus muscles are lifted proximally. For better visualization, some nerve branches (yellow arrows) are marked with black paper. The ascending branch of the lateral femoral circumflex artery and the joint capsule were partially removed. The green dotted line indicates the distal extension of the anterior approach to the hip joint. Neurovascular structures lateral to the incision are endangered, with the vastus lateralis and lateral portions of the vastus intermedius affected.
Muscular portions of the vastus lateralis and vastus intermedius always joined dorsally in the direction of the linea aspera. In the deeper aspect, the nerve branches were divided; some extended to adjacent muscles. Further distally, terminal branches to the vastus intermedius also extended laterally, innervating the vastus lateralis dorsally. The intramuscular courses of the muscle branches had a specific pattern. The main branches extended between the individual muscle lamellae in a spiral-shaped manner around the femur distally, and they divided further dorsally into terminal branches (Fig. 4). The entry of nerve branches into muscles was always from the medial side in the anterior and superficial aspect of the muscles.

The introduction of a cerclage cable passer anteriorly, either from medial to lateral or vice versa, causes direct trauma to nerve branches supplying the vastus lateralis and the lateral portions of the vastus intermedius as well as to branches of the lateral femoral circumflex artery. It was
impossible to introduce the cerclage cable passer around the femur without causing some damage to surrounding muscles. Introduction of the cable passer also jeopardized the deep femoral artery, the first perforating artery of the profunda femoris artery, and the lateral femoral circumflex artery. Intramuscular nerve branches to the vastus intermedius and the articularis genus were invariably injured. There was no damage to the nerves to the medial portions of the vastus intermedius or to the vastus medialis, rectus femoris, or sartorius.

When we introduced the cerclage cable passer through a lateral subvastus access, either from medial to lateral or vice versa, it was always possible to guide it close to the femur and protect important structures. No superficial nerves or large vessels were damaged. However, some nerve branches to deeper parts of the vastus intermedius, including the nerve branch to the articularis genus, were stretched by the instrument.

In all cases, extension of the anterior approach to the femur interrupted the nerve supply to the anterolateral portions of the quadriceps muscle group (green dotted line on Figs. 3 and 5). Internally rotating the femur made it possible to turn some lateral nerve entry points away from the endangered zone. Vessels leading to and away from the femur were also injured by the extension of the direct anterior approach. Further mobilization of the incised muscles would have strained deep muscular nerve branches and vessels.
Fig. 5 Drawing illustrating the consequences of approaching the femur through an anterior approach (green arrow) compared with a lateral subvastus approach (red arrow). Extension of the anterior approach to the femur interrupts the nerve supply to the anterolateral portions of the quadriceps muscle group. When the lateral subvastus approach is used, the muscles and their anterior and superficial entering nerves can be protected. Fl and Fm = lateral and medial divisions of the femoral nerve, 1 and 19 = lateral and medial parts of the vastus lateralis, and 2 and 29 = lateral and medial parts of the vastus intermedius.

Discussion
The direct anterior approach is a true internervous approach to the hip and has been used successfully by many authors1-6. However, some have reported increased complication rates7,11,12,15, such as intraoperative trochanteric fractures, femoral fractures, and perforations of the femur. Such complications may require distal extension of the approach, which also may be required with arthroplasty revision surgery. Extension of the anterior approach by splitting the interval between the rectus femoris and the vastus lateralis has been described1,13,16. The present study shows that carrying out this extension without substantially damaging the lateral portions of the quadriceps muscles is challenging. Neurovascular structures lateral to the incision are endangered directly, affecting the vastus lateralis and lateral portions of the vastus intermedius. Deeper muscle branches and vessels are strained indirectly due to mobilization of
muscles when the surgeon accesses the femur. Patil et al. investigated the innervation pattern of the vastus lateralis muscle\textsuperscript{17}, and their findings were in agreement with those of the present study. Splitting the vastus lateralis in the mid-lateral line of the femur resulted in denervation of the posterior half of the muscle. Splitting the underlying vastus intermedius in the same plane caused damage to the nerve supplying the vastus intermedius in most cases\textsuperscript{17}. The vastus lateralis is the largest of the four quadriceps muscles, so damage to the vastus lateralis and the vastus intermedius theoretically reduces maximal quadriceps strength. However, Kennon et al. routinely used the direct anterior approach for revision surgery and suggested that this approach could be readily extended proximally and distally in complex revision cases, including stem revisions and even total femoral replacement\textsuperscript{1}. In a series of 468 consecutive revision total hip arthroplasties with distal extension, they split the vastus lateralis longitudinally in line with the skin incision and used a subperiosteal dissection to access the entire femoral shaft. They reported no clinically relevant nerve injuries. This may well be due to the fact that the distal portions of the vastus lateralis are supplied by nerve branches from the vastus intermedius and are not affected by extension to the proximal part of the femur. Furthermore, loss of some function of the vastus lateralis and the lateral part of the vastus intermedius can possibly be compensated for by the remaining portions of the quadriceps in low-demand patients. The present study shows that distal extension of the direct anterior approach is difficult to perform without causing neural damage to the proximal portions of the vastus lateralis and vastus intermedius. Alternative approaches for complex stem revisions should be considered.

The anterior access is also not ideal for the introduction of a cerclage cable passer at the proximal part of the femur for treatment of an intraoperative fissure or fracture. In this situation, a lateral subvastus approach seems more suitable and less damaging to muscle. Whether this requires a separate skin incision depends on the selection and extension of the primary incision. The present study highlights that the zone immediately distal to the intertrochanteric line is crucial. The first entries of nerve branches into muscles occur as close as 9 mm distal to the intertrochanteric line. The zone defines an anatomical barrier and should not be crossed distally unnecessarily.

The ascending branch of the lateral femoral circumflex artery consistently lies at the level of the midpoint of the femoral neck, which is an important consideration in open or arthroscopic surgery in the anterior aspect of the hip joint. The branches of the lateral femoral circumflex artery are substantially involved in the vascularization of the proximal quadriceps muscle group.

In conclusion, the present cadaver study indicated that distal extension of the direct anterior approach to the hip joint is difficult to perform without causing neurovascular injury to anterolateral parts of the quadriceps muscle group. The direct anterior approach to the hip joint is best
suited for interventions proximal to the intertrochanteric line, such as primary hip replacement, treatment of femoral head fractures, revisions of the acetabulum, and simple femoral stem revisions. An alternative approach to the hip or an extended trochanteric osteotomy should be considered for complex stem revisions necessitating distal extension. When the direct anterior approach must be extended distally, a lateral subvastus access seems more advantageous.

References
Potential Risk to the Superior Gluteal Nerve During the Anterior Approach to the Hip Joint

An Anatomical Study

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Background

The anterior approach to the hip joint is widely used in pediatric and adult orthopaedic surgery, including hip arthroplasty. Atrophy of the tensor fasciae latae muscle has been observed in some cases, despite the use of this internervous approach. We evaluated the nerve supply to the tensor fasciae latae and its potential risk for injury during the anterior approach to the hip joint.

Methods

Cadaveric hemipelves (n = 19) from twelve human specimens were dissected. The course of the nerve branch to the tensor fasciae latae muscle, as it derives from the superior gluteal nerve, was studied in relation to the ascending branch of the lateral circumflex femoral artery where it enters the tensor fasciae latae.

Results

The nerve supply to the tensor fasciae latae occurs in its proximal half by divisions of the inferior branch of the superior gluteal nerve. The nerve branches were regularly coursing in the deep surface on the medial border of the tensor fasciae latae muscle. In seventeen of nineteen cases, one or two nerve branches entered the tensor fasciae latae within 10 mm proximal to the entry point of the ascending branch of the lateral circumflex femoral artery.

Conclusions

Coagulation of the ascending branch of the lateral circumflex femoral artery and the placement of retractors during the anterior approach to the hip joint carry the potential risk for injury to the motor nerve branches supplying the tensor fasciae latae.
Clinical Relevance

During the anterior approach, the ligation or coagulation of the ascending branch of the lateral circumflex femoral artery should not be performed too close to the point where it enters the tensor fasciae latae. The nerve branches to the tensor fasciae latae could also be compromised by the extensive use of retractors, broaching of the femur during hip arthroplasty, or the inappropriate proximal extension of the anterior approach.

The anterior approach to the hip joint takes advantage of the internervous plane between the sartorius (femoral nerve) and tensor fasciae latae (superior gluteal nerve). The initial technique described by Hueter involved subperiosteal removal of the tensor fasciae latae from the anterior iliac crest, sectioning of the reflected head of the rectus femoris, and release of the piriformis. Most procedures at the hip can be performed through this approach. The anterior approach remains a standard approach to the hip joint in pediatric orthopaedic surgery for septic arthritis and developmental hip dysplasia. In adult orthopaedic surgery, it is used to expose the anterolateral aspect of the acetabulum and to access the femoral head and neck for femoral head fractures, for biopsies, for the excision of ectopic bone, or for the treatment of hip infections. Because the initial description of the anterior approach has been modified to avoid release of muscles or tendons from the pelvis or the femur, it has gained popularity in total hip arthroplasty and the treatment of femoroacetabular impingement.

Despite its widespread use, the relation between the anterior-approach incision and the superior gluteal nerve has not been well documented. The superior gluteal nerve is a motor nerve, which derives from the posterior branches of the ventral rami of the fourth and fifth lumbar and the first sacral spinal nerves supplying the gluteus medius, gluteus minimus, and tensor fasciae latae muscles. It is the only nerve that exits superior to the piriformis muscle and then divides into superior and inferior branches. Both the superior and inferior branches innervate the gluteus medius and minimus muscles. In addition, the terminal branches of the inferior branch run anteriorly and supply the tensor fasciae latae. Several cases of superior gluteal nerve damage have been reported for the lateral (transgluteal) approach described by Hardinge and the anterolateral approach described by Watson-Jones. We recently observed atrophy of the tensor fasciae latae muscle after an unproblematic total hip replacement through a direct anterior approach.

The aim of this cadaveric study was to investigate the anatomy of the terminal inferior branch of the superior gluteal nerve in relation to the tensor fasciae latae and so reveal the potential risk zones during the direct anterior approach to the hip.
Materials and Methods

Cadaveric hemipelves (n = 19) from twelve specimens (mean donor age, seventy-eight years [range, sixty-two to ninety-one years]), including seven paired and five unpaired, six male and six female, were investigated. All limbs were embalmed in a formalin-based solution. None of the cadavers showed any evidence of previous trauma or surgery involving the femur or hip joint.

The following dissection protocol was applied. Each lower limb was first placed prone on a dissection table and the hip joint was approached posteriorly as described in the literature. The superior gluteal nerve and the superior gluteal vessels were dissected at the greater sciatic notch above the piriformis muscle. The superior gluteal nerve was traced anteriorly and laterally between the gluteus medius and gluteus minimus muscles. The terminal inferior branch that was running to the tensor fasciae latae was located and was marked with a small metallic tube for identification during dissection through the anterior approach. The limb was then turned supine and the hip joint was exposed via a standard anterior approach.

To improve visualization, a long incision of 25 cm was made following the anterior half of the iliac crest to the anterior superior iliac spine. From there, the incision was curved downward, aiming toward the fibular head. The fascia lata was incised over the tensor fasciae latae muscle in line with the skin incision. By staying lateral to the sartorius and rectus femoris muscles, the ascending branch of the lateral circumflex femoral artery was identified where it enters the tensor fasciae latae muscle and was marked. The entry point of the ascending branch of the lateral circumflex femoral artery, expressed as a percentage of the muscle’s length from its proximal attachment at the iliac crest to the most distal visible muscle fibers that insert into the iliotibial tract, was recorded.

Skin and superficial subcutaneous tissue were finally removed. Again, the interval between the gluteus medius and minimus (this time from an anterior direction) was prepared and the metallic tube that marked the superior gluteal nerve was localized. The terminal branch of the superior gluteal nerve was further traced anteriorly and each nerve entry point into the tensor fasciae latae muscle was recorded. The distances between the nerve entry points and the point at which the ascending branch of the lateral circumflex femoral artery entered the tensor fasciae latae were measured. Nerve branches to the tensor fasciae latae were further traced intramuscularly.
Fig. 1 Schematic drawing of the right hip region. The superior gluteal nerve (SGN) entered the tensor fasciae latae muscle in its proximal half (denoted as 1/2) in all cases. No nerve supply to the tensor fasciae latae distal to the entry point of the ascending branch of the lateral circumflex artery (ALCFA) could be observed. In 90% of cases, one or two terminal nerve branches entered the tensor fasciae latae just 0 to 10 mm proximal to the entry point of the ALCFA. The blue dotted line indicates the area of blood and nerve supply to the tensor fasciae latae (neurovascular hilum). The mean entry point of the ALCFA was 47% of the tensor fasciae latae muscle length from its proximal attachment to the iliac crest. ASIS = anterior superior iliac spine.

Results
The terminal branch of the inferior division of the superior gluteal nerve entered the tensor fasciae latae in its proximal half in all cases (Fig. 1). The nerve branch approached the tensor fasciae latae on its proximal part on the posterior edge of the muscle, immediately after leaving the interval between the gluteus medius and minimus muscles (Figs. 2-A and 2-B). The nerve branch then divided into one to three muscular branches, coursing into the deep surfaces on the medial border of the tensor fasciae latae, and was covered by the thin fascia of the tensor fasciae latae. Of the nineteen cases, two nerve branches were found in fourteen cases, one nerve branch was found in four cases, and three nerve branches were found in one case.
The intramuscular courses of these muscle branches were as follows. The most proximal nerve branch supplied the upper part of the tensor fasciae latae by extending proximally, and the distal branch supplied the lower part of the tensor fasciae latae by extending distally. In cases in which only one nerve branch entered the tensor fasciae latae, it divided intramuscularly into proximal and distal intramuscular branches. In seventeen cases, one or two terminal nerve branches entered the tensor fasciae latae between 0 and 10 mm proximal to the entry point of the ascending branch of the lateral circumflex femoral artery (Fig. 1). The mean entry point of this artery branch was 47% (range, 41% to 54%) of the tensor fasciae latae muscle length from its proximal attachment to the iliac crest. No nerve branch entered distal to the entry point of the ascending branch of the lateral circumflex femoral artery.
Fig. 2 The right hemipelvis of a specimen from a male donor is shown in a standard view (Fig. 2-A) and an enlarged view (Fig. 2-B). The anterior superior iliac spine (ASIS) is indicated by the red dot. In Figure 2-A, the yellow dotted line refers to the position of the skin incision of the anterior approach to the hip joint slightly lateral to the anatomical plane between the tensor fasciae latae and sartorius muscles. The terminal branch of the superior gluteal nerve (SGN) exits from the greater sciatic foramen superior to the piriformis muscle and runs anteriorly between the gluteus medius and minimus muscles (yellow arrow). The SGN courses in the deep surface on the medial border of the tensor fasciae latae and finally supplies the tensor fasciae latae close to the entry point of the ascending branch of the lateral circumflex femoral artery (ALCFA). In Figure 2-B, the blue dotted circle indicates the neurovascular hilum. In its proximal half, the tensor fasciae latae is highly vulnerable. Extracapsular placement of retractors might endanger its nerve supply. In Figure 2-B, the blue arrowheads indicate the location where the ALCFA and its accompanying veins were ligated or were coagulated during surgery (see also Figure 3).
Discussion

Recent reports on the superior gluteal nerve have focused on the lateral approach (transgluteal, according to Hardinge), the transtrochanteric approach, or the anterolateral approach (according to Watson-Jones) to the hip and their potential dangers and safe zones. With injury to the superior gluteal nerve, paralysis of the gluteus medius and minimus and the tensor fasciae latae muscles may occur, causing abductor weakness and a positive Trendelenburg sign. The importance of preventing injury to this nerve has been emphasized. The greater trochanter, posterior superior iliac spine, and anterior superior iliac spine have been described as landmarks to appropriately display the anatomy of the superior gluteal nerve. Reported distances from the apex of the greater trochanter to the inferior branch of the superior gluteal nerve ranged from 2 to 3 cm up to 6 to 8 cm. Other studies defined a safe area of up to 5 cm adjacent to the greater trochanter.

Although the anterior approach protects the nerve branches to the gluteus medius and minimus, it can affect the innervation of the tensor fasciae latae. The present study shows the result of nineteen dissections of the nerve supply to the tensor fasciae latae, with the entry point of the ascending branch of the lateral circumflex femoral artery into the tensor fasciae latae as a landmark. This artery branch regularly crosses the operative field during the anterior approach to hip, in the distal portion of the wound (Fig. 3). The artery runs proximally and crosses the center of the neck of the femur on the intertrochanteric line. To prevent bleeding complications, the ascending branch of this artery is identified and is ligated or coagulated. In 90% of cases in this study, one or two terminal nerve branches entered the tensor fasciae latae within 10 mm above the entry point of this artery branch and were always proximal to this entry point. Therefore, the ascending branch of the lateral circumflex femoral artery may be a reliable landmark during surgery to protect the nerve branches to the tensor fasciae latae.
Fig. 3 The intraoperative image of the direct anterior approach to a right hip as used for hip arthroplasty. For better exposure of the joint capsule, two extracapsular cobra retractors were placed medially and laterally to the neck of femur. A Langenbeck retractor held the rectus femoris medially and the tensor fasciae latae muscle laterally. The blue arrowheads indicate the location where the ascending branch of the lateral circumflex femoral artery (ALCFA) and its accompanying veins were ligated or were coagulated during surgery. The yellow dotted line indicates the authors’ preferred capsulotomy to access the hip joint. The anterior superior iliac spine (ASIS) is indicated by the red dot.

In 1898, Frohse made a general statement regarding the blood and nerve supply to a muscle, indicating that the vessels have a common entrance with the nerves or enter within proximity of each other\textsuperscript{39}. The results of the present study supported a neurovascular hilum or «area nervo vasculosa,» as described in the historic literature\textsuperscript{40}. The neurovascular hilum of the tensor fasciae latae is located on the medial deep surface slightly proximal to the middle of the muscle (47% of the length of the tensor fasciae latae from proximal to distal). In 1955, Brash described the position of nerve entry for the tensor fasciae latae at the deep surface about in the middle of the muscle in 76% and at the deep surface near the posterior border of the muscle in 24%\textsuperscript{41}. In 1920, Reid also found the nerve entry point for the tensor
fasciae latae to be in the middle third of the deep surface of the muscle, and, in 1923, Bryce located the entry point in the proximal third of the deep surface of the tensor fasciae latae muscle\textsuperscript{42,43}. In 1908, Frohse and Fränkel described the nerve supply to the tensor fasciae latae at the midpoint of the posterior border of the muscle\textsuperscript{44}.

The proximal part of the tensor fasciae latae is a vulnerable area for potential lesions to its nerve supply; the anterior approach to the hip joint occurs exactly in this region. The ascending branch of the lateral circumflex femoral artery may serve as an important landmark. Clamping, coagulation, ligation, and transection of this artery branch close to the muscle belly may damage the terminal branch of the superior gluteal nerve. Another source of potential injury might be the insertion of retractors and instruments\textsuperscript{45}. The intracapsular, rather than extracapsular, placement of retractors will certainly be advantageous to protect the surrounding soft tissue\textsuperscript{11}. Further care must be taken during the preparation and broaching of the femur in hip arthroplasty. Insufficient exposure of the femur during broaching might lead to direct damage to fibers of the tensor fasciae latae muscle, including its motor nerve branches\textsuperscript{45-47}. When proximal extension of the anterior approach to the hip joint is necessary, care must also be taken where the nerve branch emerges from the interval between the gluteus medius and minimus muscles (Fig. 2-B). Our cadaver dissections suggest that manipulation at the posterior medial origin of the tensor fasciae latae endangers the nerve.

There is little information in the literature regarding injury to the tensor fasciae latae with respect to the anterior approach to the hip joint, as most studies have concentrated on the gluteus medius and minimus muscles\textsuperscript{20,46-49}. In a cadaver study, van Oldenrijk et al. measured the proportional muscle damage of the tensor fasciae latae relative to the midsubstance cross-sectional area using computerized color detection. The median tensor fasciae latae midsubstance muscle damage was 35% of the crosssectional area after the direct anterior approach to the hip joint\textsuperscript{50}. Bremer et al. performed a retrospective, comparative magnetic resonance imaging (MRI) study of the direct anterior and the transgluteal approach and found that fatty atrophy of the tensor fasciae latae muscle was similar in both groups\textsuperscript{46}.

Lüdemann et al.\textsuperscript{51} assessed the muscle trauma in minimal invasive hip arthroplasty involving the direct anterior approach by MRI in twenty-five patients preoperatively and at six months after total hip replacement. Postoperatively, they detected a significant reduction in the cross-sectional area on the involved side postoperatively (29% compared with the non-involved side and 23% compared with preoperatively; \(p < 0.001\)) and increased fatty degeneration of the tensor fasciae latae\textsuperscript{51}. In a cadaver study, Meneghini et al. measured the muscle damage to the tensor fasciae latae with use of the minimally invasive anterior ap-
proach compared with the minimally invasive posterior approach.\textsuperscript{45} Tensor fasciae latae muscle damage occurred in all specimens subjected to the anterior approach, with a mean of 31\% (range, 18\% to 58\%). The tensor fasciae latae surface was mostly damaged in the midsubstance of the muscle, which is exactly the area where the superior gluteal nerve enters the tensor fasciae latae. Damage to the muscle belly of the tensor fasciae latae does not automatically imply damage to the nerve branches, but it does endanger the nerve that is very superficial within the muscle belly (Figs. 2-A and 2-B). Also, tension and force applied to the tensor fasciae latae might be harmful to the nerves in its midsubstance. Terminal nerve branch lesions of the superior gluteal nerve are probably underdiagnosed because they are not always symptomatic. The patient whom we observed having atrophy of the tensor fasciae latae after a primary hip replacement (Fig. 4) with the direct anterior approach had an excellent clinical and functional result identical to the contralateral side, where a modified anterolateral approach had been used previously. The patient noticed merely a cosmetic difference. Markhede and Stener measured the abduction force in two patients who underwent an excision of the tensor fasciae latae for a soft-tissue tumor. Both isometric and isokinetic abduction strength on the affected side were reduced to 62\% and 86\%, respectively, of the nonaffected side for these patients.\textsuperscript{52} This reduced abduction strength can probably be compensated for in some daily activities; however, electromyography and cadaveric studies have emphasized the tensor fasciae latae as an important thigh flexor during the swing phase and thigh abductor during the mid-stance phase of gait. The tensor fasciae latae balances the weight of the body and the non-weight-bearing lower limb during walking.\textsuperscript{53} Although some authors believe that damage to the tensor fasciae latae may not be of functional importance, further clinical outcome studies, gait analyses, and electromyography measurements are necessary to determine the functional implications. We believe that knowing the exact anatomy of the tensor fasciae latae and its nerve supply is important to avoid surgical damage to the nerve.
Fig. 4 A photograph showing the pelvis of a seventy-two-year-old female patient after hip arthroplasty on both sides. A direct anterior approach was performed on the right side in 2012 and a modified Watson-Jones approach was performed in 2007 on the left side. One year after the second surgery, during a routine walking check, atrophy of the tensor fasciae latae muscle was noted. Apart from the cosmetic changes on the right side (indicated by the red arrow), the patient did not report any discomfort on either side.
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The Anatomical Course of the Lateral Femoral Cutaneous Nerve with Special Attention to the Anterior Approach to the Hip Joint

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Background
Injury to the lateral femoral cutaneous nerve (LFCN) is a risk during the operative anterior approach to the hip joint. Although several anatomical studies have described the proximal course of the nerve in relation to the anterior superior iliac spine (ASIS) and the inguinal ligament, the distal course of the LFCN in the proximal aspect of the thigh has not been sufficiently studied. The aim of this cadaveric study was to examine the branching pattern of the nerve, with special consideration to the anterior approach to the hip joint.

Methods
Twenty-eight cadaveric hemipelves from 18 donors (10 paired and 8 unpaired specimens) were dissected. The LFCN branches were localized proximal to the inguinal ligament and traced distally into the area of the proximal aspect of the thigh. Distribution patterns of the nerve with respect to its relationship to the ASIS and the internervous plane of the anterior approach to the hip joint were recorded.

Results
We found 3 different branching patterns of the LFCN: sartorius-type (in 36% of the specimens), characterized by a dominant anterior nerve branch coursing along the lateral border of the sartorius muscle with no, or only a thin, posterior branch; posterior-type (in 32%), characterized by a strong posterior nerve branch; and fan-type (in 32%), characterized by multiple spreading nerve branches of equal thickness. In 50% of the specimens, the LFCN divided into ≥2 branches superior to the inguinal ligament. Sixty-two percent of the LFCN branches entered the proximal aspect of the thigh medial to the ASIS; 27%, above; and 11%, lateral to the ASIS. The LFCN consistently coursed within the deep layer of the subcutaneous fat tissue.

Conclusions
Injury to branches of the LFCN cannot be avoided in approximately one-third of surgical dissections that use the anterior approach to the hip joint. To protect the anterior branch of the LFCN, the skin...
incision should be as lateral as possible. The posterior branch of the LFCN is most vulnerable in the proximal aspect of the anterior approach to the hip joint, where it can be expected to course within the deep layer of the subcutaneous tissue.

The use of the direct anterior approach has gained popularity in recent years in total hip arthroplasty and the treatment of femoroacetabular impingement. It remains a standard approach to the hip joint in pediatric orthopaedic surgery for developmental hip dysplasia or septic arthritis. In adult orthopaedic surgery, it is used to expose the anterolateral aspect of the acetabulum, to access the femoral head and neck for the treatment of femoral head fractures, and to access the region for biopsies, for the excision of ectopic bone, and for the treatment of an infected hip. The anterior approach to the hip joint takes advantage of the internervous plane between the sartorius muscle (femoral nerve) and the tensor fasciae latae muscle (superior gluteal nerve). Despite the soft tissue-preserving nature of the anterior approach, there is a great danger of damaging the lateral femoral cutaneous nerve (LFCN); the literature shows diverse rates of injury to the LFCN of between 0.1% and 81%. Although injury to the LFCN does not represent a major neurological complication, patients may report numbness or a burning sensation in the anterolateral region of the thigh and, in the worst cases, dysesthesia.
Fig. 1 Schematic drawing of the right hip. At the level of the ASIS, in total, 45 LFCN branches in 28 cadaveric hemipelves were found. The course of all 45 dissected branches of the LFCN in relation to the ASIS is shown. Twenty-eight (62%) of the branches entered the proximal aspect of the thigh medial to the ASIS, 12 (27%) entered just above, and 5 (11%) entered lateral to the ASIS. In 50% (14) of the specimens, the LFCN divided in 2 to 4 branches superior to the inguinal ligament (black dotted line). In 50% (14), only 1 nerve branch could be found (see inset).

The LFCN is a purely sensory nerve, and its fibers usually derive from the second and third lumbar nerve. The nerve emerges from the lateral border of the psoas major, follows an intrapelvic course crossing the iliacus obliquely, and runs toward the anterior superior iliac spine (ASIS). The nerve pierces the fascia lata beneath the inguinal ligament and runs laterally and distally within the subcutaneous tissue of the anterolateral region of the thigh. The exit from the intrapelvic passage or entry into the thigh region can vary, as several anatomical studies have shown. While most anatomical textbooks do not describe the distribution pattern of the LFCN in the proximal aspect of the
anterolateral thigh region\textsuperscript{27-30}, some authors describe a division of the LFCN into an anterior (femoral) and posterior (gluteal) branch after passing behind or through the inguinal ligament\textsuperscript{18,23,24,31}. There is a lack of detailed information about the distribution and variation in the course of the LFCN in the proximal aspect of the thigh, the region in which the anterior approach to the hip joint is performed.

The aim of this study was to describe the course of the LFCN in the proximal aspect of the thigh with respect to the anterior approach to the hip joint and to provide guidance on how the LFCN can be protected during surgery.

Materials and Methods

We studied 28 cadaveric hemipelves (10 paired and 8 unpaired; 12 specimens from male donors and 16 from female donors; mean age at death of 79 years; range, 65 to 93 years). The specimens were embalmed in either a formalin-based (n = 20) or Thiel (n = 8) solution\textsuperscript{27}. None of the cadavers showed any evidence of previous trauma or surgery to the femur or hip joint.

The following dissection protocol was applied. Each lower limb was first placed on a dissection table, and the branches of the LFCN were localized proximal to the inguinal ligament through an ilioinguinal approach\textsuperscript{32}. To improve visualization, a long incision of 30 cm was made following the anterior half of the iliac crest to the ASIS. From there, the incision was curved downward, over the muscle belly of the tensor fasciae latae. All nerve branches of the LFCN were carefully traced distally in the subcutaneous tissue of the proximal aspect of the thigh. The branching pattern and distribution of the LFCN within the proximal aspect of the thigh were described with respect to 3 landmarks: the lateral border of the sartorius, the medial border of the tensor fasciae latae, and the ASIS.

Results

There was a high variability in the number of LFCN branches at the level of the ASIS. In total, we found 45 branches of the LFCN in the 28 cadaveric hemipelves studied. In 14 specimens, there was only 1 branch that could be traced; in 12 specimens, 2 branches; in 1 specimen, 3 branches; and in another specimen, 4 branches. In the 14 specimens with \(\geq 2\) branches, the LFCN divided superior to the inguinal ligament, whereas in the specimens with 1 branch, it divided inferiorly.

Twenty-eight (62\%) of the 45 LFCN branches entered the proximal aspect of the thigh medial to the ASIS; 12 (27\%) entered just above, and 5 (11\%) entered lateral to the ASIS (Fig. 1). In the proximal aspect of the thigh, distal to the ASIS, the subcutaneous fat tissue was consistently divided into a superficial and a deep layer by a weak fascia, and the nerve branches of the LFCN regularly ran within the deep layer (Figs. 2 and 3).
Fig. 2 The course of the LFCN medial to the ASIS is shown. The LFCN exits the intrapelvic passage beneath the inguinal ligament and divides into an anterior and a posterior branch. The nerve runs within the deep layer of the subcutaneous fat. Black paper was placed beneath the nerve branches for better visualization.
Fig. 3 Figs. 3-A, 3-B, and 3-C The 3 observed types of branching pattern of the LFCN. Black paper was placed beneath the nerve branches for better visualization (right panels). Fig. 3-A, left panel Schematic drawing of the sartorius type of branching pattern. A dominant anterior branch runs along the lateral border of the sartorius muscle and further branches in the anterior aspect of the thigh. No other branch, or only a very thin posterior branch, can be found. Injury to the nerve can be avoided by a lateral incision away from the lateral border of the sartorius muscle (small white arrow and dotted line). Fig. 3-A, right panel Anterolateral view of a right hip region showing the sartorius type of LFCN branching pattern. A dominant anterior branch pierces the fascia lata beneath the inguinal ligament and runs along the lateral border of the sartorius muscle distally within the subcutaneous tissue of the anterolateral region of the thigh. The laterally incised and lifted anterior superficial aponeurosis of the tensor fasciae latae protects the dominant anterior branch of the LFCN. The yellow arrow indicates the anterior approach.
to the hip joint. Fig. 3-B, left panel Schematic drawing of the posterior type of LFCN branching pattern. A strong posterior branch, equal in thickness to, or thicker than, the anterior branch runs laterally and crosses the medial border of the tensor fasciae latae muscle immediately distal to the ASIS. A deep proximal extension of the anterior approach endangers the nerve. Injury to the posterior branch can be avoided by a distal incision (small white arrow and dotted line). Fig. 3-B, right panel Anterolateral view of a right hip region showing the posterior type of LFCN branching pattern. A strong posterior branch runs laterally over the tensor fasciae latae muscle. Proximal deep dissection to the ASIS should be avoided. Fig. 3-C, left panel Schematic drawing of the fan type of LFCN branching pattern. Multiple nerve branches of equal thickness spread over the anterolateral region of the proximal aspect of the thigh, crossing over the tensor fasciae latae muscle and the lateral border of the sartorius. During the anterior approach to the hip joint, injury to some branches of the LFCN cannot be avoided, even with the most lateral and proximally restricted approach (small white arrows). The skin incision (white dotted line) inevitably crosses the nerve branches. Fig. 3-C, right panel Anterolateral view of a right hip region showing the fan type of LFCN branching pattern. Multiple nerve branches spread over the anterolateral region of the proximal aspect of the thigh, where the anterior approach to the hip joint is performed. Injury to LFCN branches during the anterior approach to the hip joint cannot be avoided with this branching pattern (in contrast to the other 2 branching patterns).

Fig. 4 Anterolateral view of a right hip region showing the sartorius type of LFCN branching pattern. Black paper was placed beneath the nerve branches for better visualization. The strong anterior branch of the LFCN can be protected by a lateral incision of the anterior superficial aponeurosis of the tensor fasciae latae. The deep surgical dissection shows the ascending branch of the lateral circumflex femoral artery (indicated by the Pean clamp). The yellow arrow indicates the anterior approach to the hip joint.
Branching Patterns of the LFCN

Three types of branching pattern of the LFCN were observed.

Sartorius-Type

In 10 (36%) of the 28 specimens, a dominant anterior branch of the LFCN coursed along the lateral border of the sartorius muscle. No other branch, or only a very thin posterior branch, could be found (Figs. 3-A and 4).

Posterior-Type

In 9 (32%) of the 28 specimens, a strong posterior branch, equal in thickness to, or thicker than, the anterior branch, could be traced. The posterior branch of the LFCN consistently branched off laterally and crossed the medial border of the tensor fasciae latae muscle immediately distal to the ASIS (Fig. 3-B). The posterior branch regularly ran together with 1 or 2 fine vessels within a membranous layer that separated the superficial subcutaneous fat from the deep subcutaneous fat.

Fan-Type

In 9 (32%) of the 28 specimens, multiple nerve branches of equal thickness spread over the anterolateral region of the proximal aspect of the thigh, crossing over the tensor fasciae latae muscle and the lateral border of the sartorius (Figs. 3-C and 5).

Discussion

The Hueter, or Smith-Petersen, anterior approach was used by Judet and Judet to expose the hip joint in arthroplasty techniques beginning in 1947. The approach takes advantage of the interval between the sartorius and tensor fasciae latae muscles to access the hip joint. The upper aspect of this approach provides visualization of the entire ilium and hip joint. The distal extension is limited by multiple nerve branches that supply anterolateral parts of the quadriceps muscle group. The initial technique involved partial removal of the tensor fasciae latae from the anterolateral aspect of the iliac crest and the release of the reflected head of the rectus femoris. Nearly all surgery of the hip can be performed through this approach, and it remains a standard approach in pediatric orthopaedic surgery for the treatment of developmental hip dysplasia, for femoral neck and pelvic osteotomies, and for articular arthrodesis. In adult orthopaedic surgery, it is used to expose the femoral head, the femoral neck, and the anterior aspect of the acetabulum. Since the initial description, the approach has been modified to allow exposure of the acetabulum and femur through a single, anterior incision that does not require the release of muscles or tendons from the pelvis or
femur, and it has gained popularity as a versatile approach for minimally invasive hip arthroplasty and for the treatment of femoroacetabular impingement\(^2\). However, the LFCN and its branches may be jeopardized during this approach. Although injury to the LFCN does not represent a major neurological complication, damage can cause sensory loss, from temporary to permanent, or result in dysesthesia or meralgia paresthetica. The reported rate of injury of the LFCN with the anterior approach varies considerably, from 0.1% to 81%\(^{15-17,37,38}\). This variation may be explained by different interpretations or lack of recognition of LFCN injury, or the diversity of skin incisions chosen for the anterior approach\(^2,16,33,34,38\). While some authors observed that most symptoms of LFCN paresthesia resolved after 6 to 24 months\(^{12}\), others reported only a small number of patients with complete resolution\(^{13}\). The present study showed that 2 parameters influence the potential risk of LFCN injury: the individual distribution pattern of the LFCN in the proximal aspect of the thigh, and the technique and skin incision used for the anterior approach.
Fig. 5 Anterolateral view of the right hip region showing the fan-type of LFCN branching pattern. Black paper was placed beneath the nerve branches for better visualization. The LFCN divided proximal to the inguinal ligament (in the intrapelvic passage). Multiple nerve branches (4 in number, blue dots) pierce the inguinal ligament and spread over the anterolateral region of the proximal aspect of the thigh, crossing over the tensor fasciae latae muscle and the lateral border of the sartorius. Proximal nerve branches course together with fine vessels (red arrow, upper panel). Nerve branches run within a weak fascia (membranous layer) that divides the subcutaneous fat tissue into a superficial and a deep fat layer. The orange dots mark the point where LFCN branches cross either the lateral border of the sartorius or the anterior border of the tensor fasciae latae. The green dots indicate (from medial to lateral) the lateral border of the sartorius, the anterior border, and the middle and the posterior border of the tensor fasciae latae.
With a sartorius type of LFCN pattern (found in 36% of the hemipelves that we studied), the injury to the nerve can be avoided by a more lateral incision away from the lateral border of the sartorius muscle (Fig. 3-A). In these particular cases, as reported by Judet and Judet\(^{35}\), the anterior superficial aponeurosis of the tensor fasciae latae protects the dominant anterior branch of the LFCN (Fig. 4). Therefore, damage to the LFCN can be easily avoided.

With a posterior type of LFCN pattern (found in 32% of the hemipelves that we studied), even a more lateral incision would not prevent damage to the posterior branch in its proximal aspect (Fig. 3-B). Care should be taken when the approach requires greater access proximal to the ASIS. Most importantly, in this area, the skin incision should be restricted to the superficial level of the two-layered subcutaneous soft tissue, as the posterior branch of the LFCN runs regularly within a membranous sheet of the subcutaneous tissue (Figs. 2, 3-C, and 5). The posterior branch can be protected by blunt dissection and proximal mobilization together with its accompanying vessels.

With a deep proximal extension of the anterior approach, including removal of the tensor fasciae latae from the anterolateral aspect of the iliac crest\(^{34,35}\), the posterior branch cannot be preserved from damage, resulting in sensory dysfunction in the lateral thigh or trochanteric region\(^{37}\).

With a fan type of nerve pattern (found in 32% of the specimens that we studied), injury to some branches of the LFCN cannot be avoided, even with the most lateral and proximally restricted approach (Fig. 3-C).

On the basis of our findings, with carefully placed incisions, careful dissection, and confining the anterior approach to the hip to the area inferior and lateral to the ASIS, the injury rate to branches of the LFCN should not exceed one-third of all cases. Additionally, if a proximal extension of the anterior approach to the hip joint is necessary, as with pediatric orthopaedic surgery for developmental hip dysplasia\(^{7}\) or in revision arthroplasty\(^{4,39}\), additional damage to the posterior branch of the LFCN must be expected. Under these circumstances, and in cases of a well-expressed posterior branch (posterior-type, 32% of the specimens studied), dysesthesia in the lateral thigh and gluteal region is inevitable.

Ropars et al.\(^{31}\) dissected the LFCN bilaterally in 17 human cadavers and recorded the branching pattern of the nerve. On the basis of their measurements, using the anterior margin of the tensor fasciae latae and the ASIS as landmarks, they defined 3 zones of differing risk for the anterior branch, the posterior branch, and both branches of the LFCN. The nerve was found to be potentially at risk between 27 and 92 mm distal to the ASIS where it crossed the anterior border of the tensor fasciae latae muscle. Consistent with the present study, they also recommended to position the skin incision as lateral and distal as possible.

However, a predetermined skin incision more lateral and distal may be undesirable, as it does not correspond to the internervous plane of the anterior approach to the hip joint and, therefore, pre-
vents good visualization and access to the operative area. In contrast to previous investigations, the present study provides information about the course of the LFCN within the layers of subcutaneous fat. The superficial and deep subcutaneous fat layers are divided by a discrete membranous layer (Figs. 3-C and 5). At the site where the anterior approach is performed, the LFCN consistently ran within this membranous layer deep in the subcutaneous fat (Fig. 2). Proximal branches were generally accompanied by fine vessels (Fig. 5). This information is also of interest when neurolysis of the LFCN or an ultrasound-guided LFCN block has to be performed. Therefore, a skin incision at the ASIS is not problematic per se, as long as the incision remains in the superficial subcutaneous fat layer. Nerve branches of the LFCN, which are not always visible at first glance during surgery, can be gently shifted by blunt dissection proximally and medially together with the membranous layer and the deep subcutaneous fat. Rigorous use of retractors into the subcutaneous soft tissue should be avoided.

Membranous layers have been described in other areas of the human body. In the lower anterior abdominal wall and the peritoneum, it has been named Scarpa fascia or Colles fascia, respectively. Markman and Barton studied the anatomy of the subcutaneous fat tissue in the trunk and extremities and confirmed the presence of a membranous layer in the thigh. Others noted that the anatomy of the membranous layer varied with sex, adiposity, and body region and that it was thicker in the lower compared with the upper extremity and on the posterior compared with the anterior aspect of the body.

Many anatomical studies have described the LFCN anatomy and its variations in relation to the ASIS, the approach for iliac crest bone harvesting, or the surgical management of meralgia paresthetica. In the present study, most LFCN branches entered the thigh above (27%) or medial to (62%) the ASIS. In 11% of the specimens, nerve branches were found crossing the iliac crest lateral to the ASIS (Fig. 1). These results are consistent with previous observations, wherein a lateral course of the LFCN was found in 4% to 19% of cases. In particular, a lateral course of an LFCN branch must be considered in cases when a proximal extension of the anterior approach to the hip joint is needed.

In the present study, the LFCN divided superior to the inguinal ligament in 50% of the cases, which is a far greater percentage than described by others (28% to 38%). This might be because, in contrast to the methods of previous investigations, the present dissections began proximal to the inguinal ligament in the intrapelvic space. From there, the LFCN branches were traced distally. This method may decrease the risk of missing the identification of nerve branches. In 50% of the dissected limbs, 2 to 4 nerve branches could be found. Three, 4, and even 5 LFCN branches have been observed in other studies. Variations have been described, where the LFCN is replaced by the femoral branches of the genitofemoral nerve or anterior branches of the femoral nerve. No such finding was observed in the present study.

The results of this study suggest that, in approximately one third of patients in whom an anterior approach to the hip joint is used, certain injury to the LFCN cannot be avoided (see fan-type, Fig. 3-
C). Patients undergoing this approach should therefore be informed of the risk. The following intraoperative modifications may minimize LFCN injury during the anterior approach to the hip joint. The skin incision should be as lateral as possible over the anterolateral aspect of the tensor fasciae latae muscle. A strict subfascial dissection (beneath the superficial aponeurosis of the tensor fasciae latae) and above the tensor fasciae latae muscle fibers will protect the anterior branches of the LFCN but not the posterior branches of the LFCN. The posterior branch of the LFCN is most vulnerable in the proximal aspect of the anterior approach. Therefore, a proximal extension of the skin incision should be limited to the superficial subcutaneous fat layer and not enter the membranous layer. If surgery necessitates a deep proximal extension, damage to the posterior branch is most likely, as is damage to the entire LFCN if the nerve courses laterally in relation to the ASIS.
References


Limitations of the Vastus Lateralis Muscle as a Substitute for Lost Abductor Muscle Function

An Anatomical Study

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Abstract

Abductor insufficiency after hip arthroplasty resulting from an impaired gluteus medius and minimus remains an unsolved problem in orthopaedic surgery. The vastus lateralis (VL) was described as a functional substitute for abductor insufficiency in 2004. We carried out a macrodissection of twelve cadaveric hemipelvises to investigate the innervation of the VL and adjacent muscles to assess the extent the VL can be safely transferred. Results showed that direct muscle branches to proximal portions of the VL are too short to allow a significant shift; the shift may be as small as 13 mm. Nerves that supply the VL also extend to the vastus intermedius. This innervation pattern makes it impossible to shift the VL significantly without damaging branches to both.

Keywords: hip, abductor insufficiency, reconstruction, vastus lateralis, innervation

The vastus lateralis (VL) is widely used as a muscle flap in plastic surgery1-3; its consistently long and large-calibre vessels make it a suitable flap for skin and soft tissue reconstruction. In 2004, Beck et al. first described the VL muscle as a functional flap for the treatment of hip abductor discontinuity4,5. This functional use of the VL as a transferable contractile unit has markedly raised the standards for employing muscle flaps. The surgeon is faced with the difficult task of relocating the VL proximally while not damaging the muscle, its vascularization and nerve supply. The task is rendered more difficult because the VL is innervated in a two-fold manner. Shorter proximal branches of the femoral nerve supply the proximal portion of the muscle while longer distal nerve branches located in the vascular pedicle supply distal portions4,6. The short nerve branches to the VL are the limiting factor to the extent the VL can be transferred. To retain the motor function, nerve branch length and the pattern of their ramification in the deeper aspect of the musculature must be considered; this has not yet been investigated in detail.
The aim of the present study was to investigate the innervation of the VL and adjacent muscles with special emphasis on a potential proximal transfer. The study intended to answer the question – to what extent can the VL safely be transferred without jeopardizing the innervation of the muscle?

Materials and Methods

Twelve cadaveric hemipelvises with legs from eight specimens (four paired and four unpaired) were investigated using macrodissection techniques. All limbs were embalmed in a formalin-based solution. No cadaver showed evidence of previous trauma or surgery at the femur or hip joint. The thighs were examined according to a standardized dissection protocol. Each lower limb was placed supine on the dissection table and the hip joint was approached anteriorly.

The ascending branch of the lateral circumflex femoral artery (LCFA) was identified and traced medially to its origin. Distal to the joint capsule, the proximal margin of the muscle bellies of the vastus lateralis muscle and vastus intermedius muscle were localized. The femoral nerve was dissected proximal to the inguinal ligament and its course was traced distally. The intermuscular space between the VL and the rectus femoris was identified and the descending branch of the LCFA localized. All muscle branches from the femoral nerve to the sartorius and the rectus femoris were identified. Both the sartorius and the rectus femoris were transected distally and raised proximally, thus gaining access to the proximal aspect of the VI and VL muscles.

Finally, all nerve branches to the VL and VI were dissected carefully. The lengths of all nerve branches to the VL and the «branch-off» angles of all proximal nerve branches to the VL in relation to the longitudinal axis of the femur (in both anterior-posterior and lateral-medial views) were measured (Figs. 1 and 2). The nerves were then traced intramuscularly in their distal course, and their dividing pattern was studied.
Fig. 1. Schematic drawing of the proximal thigh with the nerve supply to the vastus lateralis muscle (VL) – anterior and lateral views. Based on the «branch-off» angles (α, red) of all proximal nerve branches to the VL in relation to the longitudinal axis of the femur, the potential theoretical proximal shift (D, blue arrow) of the VL can be calculated by the formula $D = 2 \cdot \cos \alpha \cdot a$ ($a$ = the length of the nerve branch).

Results

In all cases, the VL was innervated in a two-fold manner: from the proximal and the distal aspect. The shortest proximal branches, which were two to four in number, had a mean length of 36 mm (range: 19–50 mm). The muscle branches to the VL and to the VI were interwoven with vessels of the ascending and transverse branches of the LCFA. The short muscle branches to the VL coursed at a mean angle of 50 degrees (range: 30–70 degrees) in an anteroposterior direction and at a mean angle of 48 degrees (range: 35–65 degrees) in a mediolateral direction towards the longitudinal axis of the femur (Table 1).
Fig. 2. Antero-lateral view of the proximal left thigh with the nerve supply to the vastus lateralis and intermedius muscles is shown. The nerve branches are highlighted by underlined pieces of black paper. The red point marks the centre of the neck of the femur on the intertrochanteric line. The gray pin indicates the distal border of the lesser trochanter. The blue arrow (D) corresponds to the potential magnitude of shift of the vastus lateralis, which can be calculated by the length of its short nerve branches (a) and «branch off» angles respectively (see also Fig. 1, formula D = 2 * cos α * a). On this image the rectus femoris is reflected proximally and medially. Normally this muscle lies protectively on the nerve branches and prevents them from being shifted proximally. The bulky psoas muscle further impedes the advancement of the VL. The blue dots mark the branches of the lateral femoral circumflex artery (for better visualization partially dissected).
A long distal nerve branch always ran to the lateral portion of the VL. These branches regularly coursed with the descending branch of the LCFA in a neurovascular pedicle (Fig. 3). The lengths of these nerve branches were on average 113 mm (range: 78–161 mm). In three cases (one paired and one unpaired), the VL was supplied by an additional proximal pedicle (mean = 74 mm, range: 68–81 mm) (Table 1). The short muscle branches to the VL ramified before they entered the muscle and side branches supplied various portions of the muscle (Figs. 4, 5 and 6). Within the musculature, in the direction of the linea aspera, the nerve branches were partly arranged in a crisscrossed pattern; nerve branches that primarily supplied the VL ran as terminal branches to lateral portions of the VI and vice versa. In turn, nerve branches in distal portions of the VI sent terminal branches laterally to the VL (Figs. 7 and 8).

Based on the mean length \( a \) of the shorter muscle branches to the VL and their angles \( \alpha \) in relation to the longitudinal axis of the femur, the mean potential proximal shift \( D \) of the VL was 46 mm (range 21–69 mm) in the anterior and 47 mm (13–75 mm) in the posterior view, calculated by the following formula: \( D = 2 \cdot \cos \alpha \cdot a \) (Figs. 1 and 2). Table 1 summarizes the results of this calculation.

### Table 1

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**Fig. 3** Antero-lateral view of the proximal right hip joint and thigh with the nerve supply to the proximal quadriceps muscle group. Some nerve branches are highlighted by underlined pieces of black paper. The red pin marks the centre of the neck of the femur on the intertrochanteric line. The gray pin indicates the distal border of the lesser trochanter. The rectus femoris is reflected proximally and medially. A Hohmann hook (H) is reflecting the joint capsule and the psoas muscle medially. The lateral femoral circumflex artery (LFCA) with its branches (de, descending branch; as, ascending branch transected; tr, transverse branch; and mu, muscular branch to the rectus femoris muscle are shown). Arrow heads: Orange: Short nerve branches to the vastus lateralis. Yellow: Long nerve branch to the vastus lateralis. Green: Nerve branches to the vastus intermedius. The long distal nerve branch to the lateral portion of the vastus lateralis (yellow arrow head) regularly runs with the descending branch of the LFCA (de) in a neurovascular pedicle.
Discussion

The VL flap has attracted significant interest in recent times. Initially it was used as a musculocutaneous transplant to cover regional defects in the hip, thigh and knee\textsuperscript{3-11}, later as a free flap for reconstruction of head and neck defects\textsuperscript{3,12,13}. One of the features of the VL that renders it suitable for this purpose is its long and high-caliber vascular pedicle with little anatomical variation\textsuperscript{1}. Donor site morbidity is reportedly low and no functional impairment has been observed\textsuperscript{14}. Beck et al. first described the VL as a functional flap as a substitute for hip abductors. It was found that either advancement or rotational transfer of the VL muscle could be used to bridge a discontinuity between the remaining gluteus medius and the proximal femur\textsuperscript{4,5}. It is believed that the VL, could act as a substitute for lost abductor muscle function. In a recent retrospective study of 11 adults who underwent a shift of the proximal vastus lateralis, a significant improvement in abductor function after surgery was observed improving the patients’ quality of life\textsuperscript{15}.

When shifting the VL as a functional flap, one has to protect its vascularization as well as its innervation. The present study suggests that it is difficult to retain the nerve supply, particularly to the proximal aspect of the VL, which would take over the function of abductors after a proximal shift. The innervation pattern of the VL and VI excludes a significant proximalization of the VL – and the free flap respectively – without damage to nerve branches of the VL and VI (Fig. 6).

The same is also true for nerve branches in the deeper aspect, running crosswise between the VL and the VI (Figs. 7 and 8). Additionally, direct muscle branches to proximal portions of the VL are too short to allow a significant shift of the muscle. Movement of the VL beyond a certain distance causes tearing of nerves. Furthermore, nerve branches enter the VL muscle at a specific angle in relation to the longitudinal axis of the femur (Fig. 2). This must be taken into account when calculating the potential magnitude of the shift. In short muscle branches to the VL, which are at a wide angle to the longitudinal axis of the femur, the shift may be as small as 13 mm (Table 1). Advancement of the VL is further impeded by the rectus femoris. This muscle lies protectively over the nerve branches and prevents them from being shifted proximally. Thereby, the theoretical pathway of muscle shift is further shortened. The iliopsoas muscle also constitutes a certain obstacle for a VL shift (Figs. 4 and 6). The iliopsoas muscle obstructs the shortest pathway of muscle branches to the proximal VL. The fact that these nerve branches to the VL are interwoven with vessels of the LCFA further complicates the advancement.
In agreement with the published literature\(^6,4\), we always found a two-fold innervation of the VL. In contrast to earlier studies, however, all of our specimens consistently demonstrated several short muscle branches to the proximal VL. As these nerve branches are interwoven with vessels of the ascending and transverse branches of the LCFA, their surgical preparation holds the risk of damage. One of the distal nerve branches to the VL consistently runs together with the descending branches of the LCFA, which according to the literature, is supposedly easily exposed\(^3\). Most muscle flaps of the VL are confined to the area supplied by this vascular pedicle. For the reconstruction of abductors, the entire VL is shifted proximally\(^4,15,16\). Based on nerve measurements, a possible proximal shift
of the VL of 7–10 cm has been estimated. According to our investigations, a shift of this magnitude would cause denervation of some proximal and distal portions of the VL. Only those portions of the muscle of the VL that are supplied by the main neurovascular pedicle might survive as a functional unit.

However, Kohl et al. found a significant improvement in Merle d’Aubigne Score, gluteus medius muscle force and quality of life after VL advancement. Their findings were based on clinical observation and measurements, but in the final analysis, they do not attempt to prove that the VL preserves its entire contractile ability after the shift. To our knowledge no EMG studies of a transferred VL have ever been performed.

Betz et al. evaluated the outcome of nine patients after advancement of the VL and reported a higher grade of muscular fatty involution of the advanced VL compared to the opposite side, suggesting partial denervation as a potential cause. A transferred proximal VL probably has a minimal muscle function and may, at best, act as a tenodesis. This would also explain the positive results achieved by other static techniques such as synthetic meshes for reconstruction of hip abductors or suturing of compromised hip abductors to the remaining VL or the iliotibial band.
Fig. 5 Anterior-distal view of a proximal right quadriceps with its nerve branches to the vastus lateralis (orange arrow heads) and vastus intermedius (green arrow heads). These nerve branches, are interwoven with vessels of the lateral femoral circumflex artery (LFCA) and vein (red dots). The rectus femoris is reflected and therefore not visible. The hidden large red pin marks the centre of the neck of the femur on the intertrochanteric line. The gray pin indicates the distal border of the lesser trochanter. The short muscle branches ramify before they enter the muscle and side branches supplied various portions of the muscle. The long distal nerve branch to the lateral portion of the vastus lateralis runs with the descending branch of the LFCA in a neurovascular pedicle.
Considering the present findings regarding the innervation of the VL, one might question whether it is justified to perform a proximal transfer of the VL for reconstruction of the abductor function. Some authors believe that removal of the VL does not affect the knee function significantly because it is a synergist to other knee extensors. However, the VL is the largest component of the quadriceps muscle group. Harvesting the VL is an invasive procedure due to the size of the muscle. According to published reports, removal of the VL significantly reduces strength during extension of the
knee joint\textsuperscript{21,16}.

The question arises as to whether other techniques such as shifting the tensor fascia latae\textsuperscript{22}, shifting the anterior half of the gluteus maximus\textsuperscript{23,24} or a combined transfer of the anterior portion of the gluteus maximus and tensor fascia latae\textsuperscript{25} should be given preference over VL transfer. A recent online report describes a cross-flap technique where a long strip of the fascia latae and gluteus maximus was transferred under the VL (VuMedi. Cross-flap technique for the treatment of gluteal insufficiency. Available at: www.vumed.com//video/cross-flap-technique-for-the-treatment-of-gluteal-insufficiency/. Accessed June 27, 2013). An alternative to the advancement of the VL described for the treatment of abductor-deficient hips is the rotational transfer of the VL\textsuperscript{5}. As proximal portions of the VL are hardly touched during rotational transfer, innervation of the muscle appears to undergo less damage. However, in the distal aspect, where the muscle is mobilized with reference to the VI, it will be necessary to transect terminal nerve branches to the distal VL. This in turn affects nerve supply to the VL exactly in the region where the muscle would be positioned as a substitute for the abductors.
Fig. 7 Display of the intermuscular plane between the vastus lateralis and vastus intermedius muscle. Nerve branches that primarily supply the vastus lateralis (orange arrow heads) ran as terminal branches (green arrow head) to lateral portions of the vastus intermedius. The proximal advancement of the vastus lateralis (blue arrow) would inevitably root out terminal branches to vastus intermedius.
Fig. 8 Schematic drawing of a longitudinal section (a) and cross section (b) through the thigh showing the nerve supply to the vastus lateralis (VL) and vastus intermedius (VI). Nerve branches that primarily supply the VL ran as terminal branches to lateral portions of the VI (green arrows) and vice versa (red arrows). Nerve branches in distal portions of the VI, in turn, sent terminal branches laterally to the VL. P = patella. F = femoral nerve branches.

As in previous studies, the present study is based on the anatomical dissection of cadavers and not on neurophysiological tests. Patients may well have more forgiveness in the tissues and tolerate more stretching before a definite palsy occurs.

In summary, only certain portions of the VL would retain their contractile ability after transfer. This is limited to the region supplied by the muscle branch in the main pedicle. The removal of the VL as a transfer or free flap affects not only the VL but also the adjacent quadriceps muscles. Importantly, peripheral portions of the muscle that are crucial for bridging the defective abductors, would be
denervated during mobilization of the VL. Nevertheless, the transferred muscle mass of the VL, although not fully functional, appears to exert some stabilizing effects. This could possibly explain the positive results reported in the published literature. The present anatomical study calls for clinical investigations (EMG studies) to illustrate the functionality of the quadriceps muscle group in patients when the vastus lateralis has already been transferred. According to our research the innervation pattern of the VL prevents its use as a full substitute for lost abductor muscle function.

References

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Effects of ligation of lateral intermuscular septum perforating vessels on blood supply to the femur

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Introduction
With a subvastus approach to the femur, the vessels that perforate the lateral intermuscular septum (LISP-vessels) must be ligated. The effect on the blood supply to the femur remains unclear. The purpose of the current study was to investigate the effect of ligation of the LISP-Vessels on the blood supply and to examine the anatomy of the LISP-vessels and the anastomoses around the femur.

Materials
In six human cadavers the LISP vessels were ligated by a lateral subvastus approach on one side. The contralateral side served as control group. After bilateral injection of different coloured silicon dyes into the lateral and medial circumflex femoral artery (green), deep femoral artery (red) and the superficial femoral artery (blue) dissection was performed bilaterally. The arterial perfusion on both sides was compared and the anatomy of the LISP vessels studied.

Results
The medullary perfusion of the femur was not altered by the ligation of the LISP vessels. It did also not lead to a decrease in periosteal vessel filling. The LISP vessels were shown to be a part of a complex and rich anastomotic network and play an important role in the perfusion of the femur and quadriceps muscle group. The ligature could be compensated for by this anastomotic network. Branches to the periosteum separate from the LISP vessels immediately after perforating the lateral intermuscular septum. The linea aspera turned out to be an important area for the femoral blood supply.
Discussion and conclusions

Exposure of the femur through a lateral subvastus approach with ligation of LISP vessels causes a certain degree of soft tissue trauma. However, by using a gentle surgical technique the periostal perfusion of the femur can be preserved by a potent anastomotic network after ligation of the LISP vessels if they are not ligated to close to the lateral intermuscular septum and the linea aspera is not unnecessarily exposed.

Keywords: Subvastus approach to the femur, lateral intermuscular septum perforating (LISP) vessels, blood supply to the femur Femur fracture, plate osteosynthesis.

Introduction

The majority of femur fractures are treated operatively, either with open reduction and internal fixation, or minimal invasively by intramedullary nailing or indirect reduction techniques. Both, intramedullary nails and plate fixation have been recommended. For plate osteosynthesis a lateral subvastus approach to the femur has traditionally been used. However, several authors have suggested that minimally invasive techniques, with percutaneous submuscular insertion of the plate and indirect reduction techniques resulted in reduced healing time, lower rates of nonunion and a decreased need for bone grafting1–8. Preservation of blood supply to bone fragments with minimally invasive techniques is the most likely reason for these improvements9–12. On the other hand, an increased rate of malunion (malrotation, leg shortening and varus/valgus deviation) has been reported with minimally invasive techniques13–20.

With an open reduction, the vessels that perforate the lateral intermuscular septum (Lateral Intermuscular Septum Perforating-Vessels = LISP-vessels) must be ligated21–27. While the periosteum can be preserved with careful operative management, the effect of the ligature of these vessels to the blood supply of the femur remains unclear and has not been investigated yet.

The purpose of the current study was to investigate the anatomy of the LISP-vessels and the anastomoses around the femur and to examine the effect of ligation of the LISP-vessels on the blood supply to the femur whilst leaving the periosteum intact.

Materials and methods

Six human Thiel-fixed cadavers28 without evidence of previous trauma or surgery to the femur, mean age 79 years (range 69–85), were obtained for this study. On one side, a lateral subvastus approach to the entire femur was performed. All LISP vessels between the greater trochanter and lateral femoral condyle were identified and ligated laterally, about 2 cm above the intermuscular septum. The common femoral arteries were then dissected bilaterally through a longitudinal incision in the ingui-
nal region. All branches were prepared and cannulated with a plastic tube for silicon injection. Differently coloured silicon dyes were injected bilaterally in close succession first into the deep femoral artery (red), then the lateral and medial circumflex femoral arteries (green), and last the superficial femoral artery (blue). The femora on both sides were finally harvested to evaluate the filling of the periosteal vessels with the different coloured dyes. The contralateral side without ligation of the LISP vessels served as control group. The perfusion pattern of the femur as well as the surrounding soft tissue was studied and compared macroscopically. Furthermore the anastomotic network on each level was recorded.

**Results**

Appropriate filling of all injected vessels was achieved. In two of the six cadavers some air bubbles were seen on the non-operated side. However, it did not result in a different filling pattern of the smaller vessels compared to the other specimen. The branches of the deep femoral artery were filled with red, the branches of the medial and lateral circumflex artery with green and the branches of the superficial femoral artery with blue silicon dye (Fig. 1). Where different coloured vessels met, anastomoses between the different vessels were visible (Figs. 2 and 3).

The subvastus approach to the femur with ligation of the LISP-Vessels did not lead to a decrease in periosteal vessel filling but to redistribution. In all zones, periosteal vessel filling was found, irrespective of whether the LISP vessels were ligated or not. Overall, there was slightly better periosteal filling in zone 4 (intertrochanteric region, proximal to the lesser trochanter) when compared to the other zones and a minor decrease of periosteal filling in zone 3 (posterior diaphysis) compared to zone 1 (condylar region and distal metaphysis of the femur), 2 (anterior diaphysis) and 4 after ligation of the LISP vessels (Fig. 4).

The dissection of the untouched side revealed that the periosteal vessels as well as the surrounding muscle branches lateral and dorsal to the diaphysis originated from the deep femoral artery (red). Vessels proximal to the lesser trochanter were filled mainly by the medial and lateral circumflex femoral arteries (green) and the distal aspect of the femur from all three sources, the superficial femoral artery (blue), circumflex femoral arteries (descending branch of the lateral circumflex femoral artery, green) and the terminal branches of the deep femoral artery (distal LISP-arcade, fourth perforating artery, red).
After ligation of the LISP-vessels, the contribution of the lateral and medial circumflex femoral arteries (green) increased in the middle half of the femur and proximally in the peritrochanteric region (Figs. 5 and 6). Most periosteal vessels were anastomotic branches from the descending branch of the lateral circumflex femoral artery (Fig. 7) after ligation of the LISP vessels. Distally, in the metaphyseal and epiphyseal region the change was minimal with a slight increase in contributions from the superficial femoral artery.

The arteries to the periosteum branched off just after the LISP-vessels pierced the lateral intermuscular septum. These branches connected with further anastomoses to other periosteal branches.
Fig. 2 Lateral view to the vastus lateralis and vastus intermedius muscle. Muscular anastomosis are seen. Red: filling from the deep femoral artery (terminal muscular branches of the LISP vessels). Green: filling from the circumflex femoral arteries (terminal muscular branch of the descending branch of the lateral circumflex femoral artery). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)
Fig. 3 Lateral view to two enlarged sections of the femur with its periosteal blood supply. The surrounding muscles have been removed. Periosteal anastomosis are seen. Red: filling from the deep femoral artery (terminal muscular branches of the perforating arteries). Green: filling from the circumflex femoral arteries. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

Fig. 4 The result of periosteal vessel filling on both sides in zones 1–4
Fig. 5 Schematic drawing of the filling pattern of the periosteal vessels of the femur with and without ligation of the LISP-vessels. (a) Basic pattern of periosteal vessel filling of the untouched side. (b) After ligation of the LISP-vessels. Despite no visible difference in periosteal vessel filling (see Diagram 1) after ligation of the LISP-vessels, the contribution of the lateral and medial circumflex femoral arteries (green) increased in the middle half of the femur and proximally in the peritrochanteric region. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)
Fig. 6 Lateral view of the diaphysis of a right femur after ligation of the LISP vessels (yellow dotted circle). Red: filling from the deep femoral artery (terminal muscular branches of the LISP vessels). Green: filling from the circumflex femoral arteries (terminal muscular branch of the descending branch of the lateral circumflex femoral artery). The ligation of the LISP-vessels resulted in increased vessel filling from lateral and medial circumflex femoral arteries (green). See also Fig. 5. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)
In some cases the ligation of the LISP-vessels was unintendently closer than 2 cm to the intermuscular septum, which altered the distribution to the periosteum from the deep femoral artery (red). However, it did not lead to a decline in the overall periosteal filling. After piercing the lateral intermuscular septum, the LISP-vessels separated into two muscle branches. One ran deep into the vastus intermedius, and the other remained more superficial in the vastus lateralis. The LISP-vessels also gave further ascending and descending branches, forming a rich anastomotic network (Fig. 8). The two muscular branches also supplied the fascia and the overlying skin.
**Fig. 8** Lateral view of the right distal thigh above the knee joint. After piercing the lateral intermuscular septum the LISP-vessels (yellow dotted circle) divide into muscle branches. While one of these muscle branches courses deep into the vastus intermedius, the other branch stays more superficial in the vastus lateralis muscle. In addition, the LISP-vessels also give ascending and descending branches, forming a rich anastomotic network. The distal LISP arcade derives from terminal branches of the superficial femoral artery (blue), deep femoral artery (red) and terminal branches of the femoral circumflex artery (green). The middle blue LISP vessel in this figure corresponds to the blue LISP vessel in Fig. 1 (the same specimen). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

All LISP-vessels interconnected through a longitudinal anastomotic arcade (Fig. 9). This LISP-arcade was located adjacent to the lateral intermuscular septum and close to its attachment to the linea aspera and provided multiple branches to the periosteum. Depending on the location, the LISP-vessels were filled red (deep femoral artery), green (circumflex femoral arteries) or blue (superficial femoral artery). Therefore, the LISP-vessels in the middle half of the femur originated mainly from the deep femoral artery, the vessels more proximal (close to the peritrochanteric region) originated from the circumflex femoral arteries and the distal vessels from the superficial femoral artery. The border between the different coloured LISP-vessels was a
continuum rather than well defined (Figs. 8 and 9). The entire femur is surrounded by a rich and structured anastomotic network. The main trunks of this network were the deep femoral artery with its perforating arteries, the superficial femoral artery, the descending branch of the lateral circumflex artery and the longitudinal anastomotic arcade of the LISP-vessels (Fig. 10). These longitudinal (vertical) pathways were connected to each other by circular (horizontally) running anastomoses on four levels, namely:

1. Direct anastomosis.
2. Periosteal anastomosis.
4. Anastomosis on the level of fascia, subcutaneous layer and skin.

Fig. 9

Lateral view to the right thigh. The LISP arcade is shown. The LISP vessels pierce the lateral intermuscular septum just lateral to its attachment to the linea aspera and form a longitudinal anastomotic arcade. The vastus lateralis is peeled off the lateral intermuscular septum and lifted anteriorly. The LISP-vessels (yellow dotted circle), divide into muscle branches and course to the periosteum where they anastomose with branches of the other arteries. The terminal muscle branches further supply the overlying fascia and skin. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)
Fig. 10 Schematic drawing of the extra medullary anastomotic network of the femur. The main longitudinal (vertical) pathways are (1) the deep femoral artery with its perforating arteries, (2) the superficial femoral artery, (3) the descending branch of the lateral circumflex femoral artery and (4) the longitudinal anastomotic arcade of the LISP-vessels. Beside the longitudinal components a circular (horizontal) pathways exists (**). This includes a direct anastomosis, periosteal anastomosis, muscular anastomosis and anastomosis on the level of fascia, subcutaneous layer and skin. The longitudinal pathways further communicate with the periarticular anastomotic network of the hip and knee joint.

Adjacent to the bone was a periosteal anastomosis followed by the muscular anastomosis (supplying the vastus intermedius and vastus lateralis muscle), the anastomosis of the fascia, the anastomosis of the subcutaneous layer and the skin. The longitudinal pathways further communicated with the periarticular anastomotic network of the hip and knee joint at the proximal and distal femur (Fig. 10).
The subvastus approach to the femur with ligation of the LISP vessels influenced neither the perforating arteries nor the nutrient arteries. All the nutrient arteries were filled with red silicon dye regardless of the ligation of the LISP vessels (Fig. 11). In five cases, there were two nutrient arteries and in seven cases there was one nutrient artery. All entered the cortex along the fascial attachment at the top of the linea aspera. The continuation of a nutrient artery often ended in one of the LISP-vessels (Fig. 11).

Two to four perforating arteries were found. However, a distinction between the fourth perforating artery and the terminal branch of the deep femoral artery was difficult. The terminal branches of the deep femoral artery anastomosed with the superficial femoral artery. This further contributed to the geniculate network, the third perforating artery, the descending branch of the lateral circumflex artery and the LISP-vessels. Dorsally around the linea aspera, the perforating arteries gave numerous branches to the periosteum of the medial and lateral side of the femur. These branches anastomosed laterally with periosteal vessels originating from the LISP-vessels. Additionally all the perforating arteries contributed strong branches to the hamstrings and adductor muscles (Fig. 1). Hence, beside the lateral circumflex femoral artery the perforating arteries with their terminal branches, including the LISP-vessels, indirectly supplied blood to the vastus intermedius and vastus lateralis muscle.
Fig. 11 (a) Dorsal view to the proximal third of the thigh showing the strong perforating arteries (red). The biceps femoris muscle is held medially opening the sight to the sciatic nerve and the first perforating artery. The nutrient artery branches off the first perforating artery and enters the cortex along the aponeurotic attachment at the top of the linea aspera (blue dotted circle). The continuation of the nutrient artery ends in one of the LISP-vessels (yellow dotted circles). The vastus lateralis, the vastus intermedius and the LISP arcade are hidden underneath the lateral intermuscular septum and are therefore not visible. The lateral subvastus approach to the femur with ligation of the LISP vessels does not influence either the perforating arteries or the nutrient arteries. (b) Shows the femur fragment at the point where the nutrient artery branches off the first perforating artery and enters the intra medullary canal of the femur (the same specimen as (a)). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)
Discussion
Confusion exists in the published literature for the nomenclature of the “perforating artery”29. Anatomically, perforating arteries of the thigh are strong branches that originate from the deep femoral artery, and derive their name from their anterior to posterior direction of flow when they perforate the adductor magnus muscle30–37. After this point, perforating arteries run dorsally, adjacent to the dorsal aspect of the femur, protected anteriorly by the medial and lateral intermuscular septum and its strong fascial insertions at the linea aspera. Some authors refer to three perforating arteries while others describe two to six38–40. In the lateral subvastus approach to the femur, merely the terminal or side branches of the main perforating arteries are the ones that need to be ligated, not the strong perforating arteries described above. These terminal or side branches, which pierce the lateral intermuscular septum, are frequently referred to as “perforating vessels” in the surgical sense31–36. To avoid confusion between these terminal or side branches and the main perforating arteries, we refer in the present paper to the vessels that perforate the lateral intermuscular septum as lateral intermuscular perforating vessels (LISP vessels).

Minimally invasive percutaneous accesses are commonly used and many implants and guiding instruments have been developed39,41–45. Several studies have shown improved healing times compared to the open reduction8,41,46–49. With indirect reduction techniques, it may be difficult to restore correct alignment and rotation and a high rate of malunion has been reported13,15,19,50. Buckley et al.17 observed malrotation of >108 in 38.5% after locking plates using postoperative CT scans. Malrotation has also been reported after intramedullary nailing in 22–55%51–53.

The open technique has repeatedly been blamed to cause soft tissue trauma and reduced blood supply to the bone1,9,11,40. The vastus lateralis and vastus intermedius muscle are raised and the perforating vessels (LISP vessels) have to be ligated. In the present study the periosteum was not destroyed or peeled off the bone, which better reflects the current soft tissue handling of most trauma surgeons. We were able to demonstrate anastomoses at several levels. In addition to the well-described direct connections with major vessels38,54, further anastomoses were found at the level of the periosteum, the muscles, the fascia, the subcutaneous layer and skin. Although these vascular connections have small diameters, taken together they play an important role in the process of revascularisation. This extraosseous blood supply is of great significance especially in the initial phase of fracture healing55–59. The efficiency of the vascular network with its horizontal and longitudinal anastomoses in the femur is demonstrated by the present investigation and by the fact that an obstruction of the superficial femoral artery often has no direct consequences on blood supply to the lower extremity60,61. In a cadaveric injection study using three-dimensional (3D) CT scan images Appivatthakakul et al.40 revealed minimal vascular disruption associated with percutaneous cerclage wiring. Despite interruption of at least one perforating artery in 14 of 18 specimens only minimal
disruption of the femoral blood supply was found\cite{50}. Similar to the present study, they showed a rich femoral anastomotic network which could compensate for some interruption of the longitudinal pathways.

Ligature of LISP vessels can be easily compensated for by a very rich anastomotic network (Table 1). The descending branch of the lateral circumflex femoral artery is especially important (Figs. 7 and 10) including the connections to the proximal and distal periarticular anastomotic network (Fig. 10). The significance of the descending branch of the lateral circumflex femoral artery has also been emphasised by others\cite{40,62}.

The present dissection also demonstrated that the LISP vessels should not be ligated too close to the septum, as some vessels branch to the periosteum at that very point. If LISP vessels are ligated too close to the septum, small vessels flowing to the periosteum as well as anastomosis between the LISP vessels (LISP arcade, Fig. 9) might be injured. Further studies are needed to investigate the exact effect to the periosteal blood flow.

Table 1

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The nutrient artery enters the cortex along a major fascial attachment at the site of the linea aspera. It traverses the cortex, without giving off branches, to the medullary cavity. The contribution of the nutrient artery to the medullary circulation (“intramedullary longitudinal pathway”) is of great importance\cite{57}. In the present study we found seven cases of single, and five cases of double nutrient arteries, which is consistent with the published literature\cite{29,33,63–66}. Lateral access to the femur had no impact on these nutrient arteries which entered the femur via the linea aspera. Thus, the linea aspera is of major clinical and anatomical significance. It is integral to the femoral blood supply and should not unnecessarily be exposed or damaged during surgery. This contradicts several textbooks.
where the entire length of the femur is shown stripped off soft tissue and retractors are shown placed dorsally around the femur.\textsuperscript{21–24,26,27}

Farouk et al. used an injection technique to investigate the blood supply to the femur.\textsuperscript{9–11} In their studies, performed on cadavers, plate osteosynthesis was conducted by the conventional technique on one femur, and by the minimally invasive technique on the contralateral side. Four perforating arteries were consistently found in all cadavers. On the side treated by the conventional technique, destruction of perforating arteries was noted in 57% and 72% respectively, as compared to 0% on the femur treated by the minimally invasive approach. The authors observed significant restriction of periosteal vessel filling in 90% of cases. Plate osteosynthesis by the conventional technique led to interruption of the first perforating artery in 100% of cases, and to destruction of the nutrient artery in 60% of cases.

In the present study, surgical access caused neither injury to the nutrient arteries nor to the perforating arteries, which appears to be related to the surgical technique. Exposure of the femur was confined to the extent of vision required for osteosynthesis. Destruction of the nutrient artery or the perforating arteries can only occur in cases of exposure of the linea aspera. Additionally, denudation of the intermuscular septum from the linea aspera inevitably causes significant devascularisation of the periosteum. Injury to perforating arteries, especially that of the first perforating artery which is normally the largest in diameter as well as the nutrient artery, appears to have caused serious haemorrhage in cases of in vivo osteosynthesis. This does not correspond with the observations we made during open plate osteosynthesis of the femur. Ligation of LISP vessels and visualisation of the femoral shaft can be performed safely, by preserving the vessels considered essential for blood supply to the femur during the open technique. Open reduction does not necessarily mean “unbiological”.

The present study has certain limitations; we did not prove intra-individual anatomic variations between the left and right side and similar to other studies,\textsuperscript{9–11,40} the assessment of periosteal vessel filling was based on visual and macroscopic comparison between the left and the right side. This technique is not sensitive enough to demonstrate microscopic changes and might not reflect the entire three-dimensional (3D) vascular network of the femur. Selective injection studies of individual portions of vessels including microscopic investigations and 3D CT studies may provide further information.

With the subvastus approach to the femur the following aspects should be considered. Firstly the LISP vessels should not be ligated too close (distance > 2 cm) to the lateral intermuscular septum. Secondly the linea aspera should not unnecessarily be exposed and the lateral intermuscular septum should be regarded the anatomical dorsal limit. When reducing the fracture, every effort should be made to preserve the periosteum, as it carries the periosteal anastomoses. Finally the descending branch of the lateral femoral circumflex artery should not be
injured. These rules apply for any exposure of the femur such as open reduction of a fracture and also for the extended trochanteric osteotomy in revision hip surgery.

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A Newly Discovered Muscle: 
The Tensor of the Vastus Intermedius

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Abstract

The quadriceps femoris is traditionally described as a muscle group composed of the rectus femoris and the three vasti. However, clinical experience and investigations of anatomical specimens are not consistent with the textbook description. We have found a second tensor-like muscle between the vastus lateralis (VL) and the vastus intermedius (VI), hereafter named the tensor VI (TVI). The aim of this study was to clarify whether this intervening muscle was a variation of the VL or the VI, or a separate head of the extensor apparatus. Twenty-six cadaveric lower limbs were investigated. The architecture of the quadriceps femoris was examined with special attention to innervation and vascularization patterns. All muscle components were traced from origin to insertion and their affiliations were determined. A TVI was found in all dissections. It was supplied by independent muscular and vascular branches of the femoral nerve and lateral circumflex femoral artery. Further distally, the TVI combined with an aponeurosis merging separately into the quadriceps tendon and inserting on the medial aspect of the patella. Four morphological types of TVI were distinguished: Independent-type (11/26), VI-type (6/26), VL-type (5/26), and Common-type (4/26). This study demonstrated that the quadriceps femoris is architecturally different from previous descriptions: there is an additional muscle belly between the VI and VL, which cannot be clearly assigned to the former or the latter. Distal exposure shows that this muscle belly becomes its own aponeurosis, which continues distally as part of the quadriceps tendon. Clin. Anat. 29:256–263, 2016.

Keywords: Quadriceps femoris muscle group, quadriceps tendon, tensor vastus intermedius TVI, quinticeps, extensor apparatus of the knee joint
Introduction

The quadriceps femoris is traditionally described as a muscle composed of the rectus femoris and the three vasti, the lateralis, intermedius and medialis, which arise independently and blend into the common quadriceps tendon (Putz and Papst, 2008; Platzer et al., 2010; Schünke et al. 2014; Paternoster, 2012). However, clinical experience and anatomical studies do not confirm textbook descriptions of the vastus lateralis (VL) and intermedius (VI) muscles. After careful anatomical dissection of the muscle bellies we found an additional muscle between the VL and VI, hereafter named the tensor VI (TVI), which cannot be clearly assigned to either of those muscles.

In a cadaver study, Golland et al. investigated the gross morphology of the VL with regard to fusion between adjacent muscles. They found a separate muscle belly arising from the anterior aspect of the upper femoral shaft in 29% of thighs (Golland et al., 1986). Another study revealed an additional fleshy lamella in the distal part between the VL and the VI in 36% (Willan et al., 1990).

Subdivision of the VL into various muscle bellies is logical in view of its innervation pattern. It is supplied by several muscle branches of the femoral nerve, which in turn can be divided into two parts (Patil et al., 2007; Becker et al., 2010). According to recently published anatomical observations, the proximal-ventral aspects of the bellies of the VL and VI are supplied by numerous muscle branches of the femoral nerve (F), and by branches of the lateral circumflex femoral artery and vein (LCFA and LCFV) (Grob et al., 2015). This creates the impression that the TVI belongs to the VL. However, distal anatomical exposure revealed that this muscle belly has a separate aponeurotic tendon, closely associated with the aponeurosis of the VI, which joins the quadriceps tendon distally.

The aim of the following anatomical study was to clarify, in terms of muscle innervation, whether the TVI was a variation of the VL or the VI, or a separate head of the extensor apparatus of the knee joint.

Materials and Methods

Twenty-six lower limbs of 16 embalmed cadavers, nine males (six paired and three unpaired) and seven females (four paired and three unpaired), were investigated by macro-dissection. The bodies were obtained from the institutional body donation program (http://www.anatom.uzh.ch/Bodydonation.html) following the ethical guidelines «On the use of cadavers and parts of cadavers in medical research and for pre-, post-grad and continued education and research with human subjects» by the Academy of Medical Sciences (SAMS). All lower limbs were embalmed in a formalin-based solution. The limbs of four specimens were cut transversely in the middle third of the thigh after dissection. The thighs were examined using a standardized dissection protocol. Each lower limb was placed supine on a dissection table. The hip joint was approached from the anterior aspect. The ascending branch of the LCFA was identified and traced medially. Following resection of the joint
capsule, the proximal margins of the muscle bellies of the VL and VI were located. The femoral nerve was located proximal to the inguinal ligament, then dissected and traced distally. All muscle branches of the femoral nerve to the sartorius and the rectus femoris were identified. For better access, these muscles were transected distally and lifted proximally. All muscle branches of the femoral nerve and all vessels to the quadriceps femoris were carefully dissected. The architecture of the quadriceps femoris was examined to confirm its anatomy, with special attention to the innervation pattern. Additional muscle bellies were sought. All muscle bellies in the area of the VL and VI were traced from their origin to their insertion and their affiliations were determined. An MRI of the quadriceps femoris was also studied to confirm the anatomical findings. This is illustrated by a single case in this article.

Results

In all dissections (n = 26), a separately innervated TVI muscle belly was found between the muscle fascias of the VL and the VI (Fig. 1). Further distally, the TVI combined into a broad and flat aponeurosis merging into one of the deep layers of the quadriceps tendon. In 22/26 cases, the TVI could be clearly separated in the proximal aspect from the muscle bellies of the VI and VL. In the remaining 4/26 cases, no clear proximal separation was possible. All three muscles—the VL, the TVI, and the VI—presented a common, hardly-divisible origin between the intertrochanteric line and greater trochanter (Common-type) (Fig. 2). In 5/26, two or more smaller intervening muscle lamellae were also found (Fig. 2). Further distally, at the junction into the broad tendinous portion, the TVI was always adjacent to, and often integrated into, the aponeurosis of the VI. Covering the aponeurosis of the VI, the aponeurosis of the TVI reached the distal aspect of the quadriceps femoris. The aponeurosis of the VI could hardly be distinguished from that of the TVI at first glance (Figs. 3 and 4). However, the tendon of the TVI could easily be separated from both the VI and VL in 42% (n = 11) (Independent-type); the aponeurosis of the TVI was inseparable from that of the VI in 23% (n = 6) (VI-type), and could be separated from the VI but not the VL in 19% (n = 5) (VL-type) (Fig. 2). In four paired specimens, where both sides were dissected, the TVI appeared identically on both sides of the body. In the remaining six paired specimens, different types of TVI were found on opposite sides. The aponeurosis of the TVI consistently changed its course; running laterally in the mid-third of the thigh, it moved ventrally shortly before its point of entry in the quadriceps tendon (Figs. 5 and 8). In the distal aspect, the three layers originating from the VI, the TVI, and the VL could be clearly isolated in all cases. The anatomical finding of the TVI muscle and its aponeurotic tendon was also confirmed in a MRI cross section (Figs. 6 and 7).

The pattern of quadriceps tendon layers toward the proximal muscular parts was always identical:
the VI was the deepest layer, the TVI formed the deep portion of the middle layer, and the VL made up the superficial portion of the middle layer. The rectus femoris always formed the most superficial layer of the quadriceps tendon. The insertion of the TVI was at the medial aspect of the patellar base (Fig. 8). In three cases the distal aponeurosis of the TVI became narrow further distally (<3 cm) and continued as a tendon-like structure laterally and dorsally in the intermuscular septum. In one case this tendon ended in the broad aponeurosis of the VI, which was itself divided in the distal aspect. Instead of the TVI, the lateral portion of the VI aponeurosis merged into the middle layer of the quadriceps tendon.

Fig. 1

Anterior overview of a left thigh showing the quadriceps femoris muscle. The rectus femoris, the Sartorius, and tensor fasciae latae (T) are transected and reflected on either side, proximally and distally. The capsule of the hip joint is removed presenting the neck of the femur. The TVI (1) can be seen between the muscle laminae of the VL and the VI. Further distally the TVI merged into a broad aponeurosis (2) becoming a tendinous structure (3) at the level of the quadriceps tendon. GM, gluteus medius; Gm, gluteus minimus. The size of the TVI is very variable. In contrast to Figure 9, the muscle belly of the TVI in this specimen is proximally larger than that of the VL (black arrows). The origin of the TVI is more proximal than that of the VL.
At the site of origin of the TVI, the anterior aspect of the greater trochanter, fibers of the TVI spread into the insertion of the gluteus minimus (Fig. 1). From the dorsal aspect, the TVI always originated together with the VL and the VI (i.e., at the lateral lip of the linea aspera). The TVI was very variable in size (Figs. 1 and 9).

Nerve branches to the VL, TVI, and lateral portions of the VI originated from the same lateral deep division of the femoral nerve (Fig. 9). The VL, TVI, and VI could be divided only after the neurovascular structures were carefully traced. The TVI was always innervated proximally by multiple short branches in a very constricted space. However, in the deeper aspect, all the muscle branches supplying the TVI had terminal ramifications to the lateral portions of the VI. The TVI was vascularized separately from the VL through individual branches of the transverse branches of the LCFA and side branches of the ascending branch of the LCFA.

Discussion

The quadriceps femoris is one of the most extensively-studied muscle groups in the human body. There have been many clinical, anatomical, and biomechanical accounts of this muscle in recent years (Zeiss et al., 1992; Shelburne and Pandy, 1997; Willan et al., 2002; Blemker and Delp, 2006; Waligora et al., 2009; Pasta et al., 2010; Becker et al., 2010). Despite numerous descriptions in the literature, an intermediate muscle between the VL and the VI has been given little attention thus far (Testut, 1884; Le Double, 1897; Willan et al., 2002; Pabst, 2008; Moore et al., 2014;). There could be several reasons for this.

1. The muscle bellies of the VL, the TVI, and the VI are very close to each other in the proximal thigh and are covered with a complex network of vessels and nerves.
2. The TVI originates at a site rarely seen in surgical routine. Therefore, the surgeon remains unaware of the specific anatomical features of this region.
3. Further proximally, the TVI continues into an aponeurosis that is very close to the VI but is then separate at the level of the quadriceps tendon. Thus, in a cross-section of the thigh, the aponeurosis of the TVI is not seen as a muscle but merely as a fascial layer or an intermuscular septum. However, knowing that the TVI exists, one can distinguish an aponeurotic sheet between the medial aponeurosis of the VL and the lateral aponeurosis of the VI (Figs. 6 and 7).
4. The morphology of the TVI differs among individuals (Fig. 2).
The schematic drawings show the different types of the TVI and its variations with respect to interactions with the VI and VL. In 42%, the aponeurosis and muscle belly of the TVI could be clearly distinguished from the aponeuroses of VI and VL (Independent-type, see also Fig. 1). In 23% (n = 6), the aponeurosis of the TVI passed inseparably into the aponeurosis of the VI (VI-type) and in 19% (n = 5), it could be separated from the VI but not from the VL (VL-type). In 15%, the VL, TVI, and VI presented a common, hardly-divisible origin between the intertrochanteric line and the greater trochanter (Common-type). In five cases there were two or more smaller intervening muscle lamellae of the TVI.
Fig. 3 Antero-lateral view of the middle two-thirds of the left thigh. The rectus femoris is reflected and not visible. The TVI lamella can be seen between the VL and VI. The TVI merges into a broad aponeurosis that runs adjacent to the VI (see also Fig. 6). To some extent the aponeurosis of the TVI is separate from the aponeuroses of the VI and VL. In the dorsal aspect of the thigh the three muscles—VL, TVI, and VI—join (red arrows) and have a common origin at the lateral lip of the linea aspera of the femur.
**Aponeurosis of the Tensor vastus intermedius**

**Fig. 4** Lateral view of the middle section of the left quadriceps femoris muscle. The rectus femoris is reflected and, therefore, not visible. The aponeurosis of the TVI runs adjacent to the VI and is hardly visible at first glance. The black arrows indicate the border between the aponeuroses of the VI and the TVI. Proximally (scissors) the aponeurosis of the TVI is separated from those of the VI and VL.
**Fig. 5** Anterior view of a distal left thigh. The rectus femoris is transected. The distal part of the rectus femoris tendon is reflected medially. The proximal part of the rectus femoris is reflected proximally and, therefore, not visible. The separated aponeurosis of the TVI, and further distally its tendon, can be seen between the tendons of the VL and VI. The tendon of the TVI merges into the quadriceps tendon together with the tendons of the VI, VL, VM, and rectus femoris. The green pin indicates the insertion of the quadriceps tendon at the patella. In the dorsal aspect of the thigh the three muscles—VL, TVI, and VI—join and have a common origin at the lateral lip of the linea aspera of the femur.
To our knowledge, the TVI has not been described or illustrated in any textbook of anatomy. The VL is generally shown as a muscle with a single belly, separated from the VI by an intermuscular septum (Pabst, 2008; Platzer et al., 2010; Schünke et al., 2014; Moore et al., 2014). However, some authors have reported variable fusion between the VL and the adjacent musculature (Henle, 1880; Krause, 1880; Le Double, 1897). Golland et al. found a separate muscle belly of the VL arising from the anterior aspect of the upper femoral shaft in 29% of dissected thighs (Golland et al., 1986). They reported that the belly usually contributes to a tendinous lamina distally, but occasionally fuses with the VI. In another cadaver study, Willan et al. found consistent results (Willan et al., 1990) among 40 cadavers, reporting an additional muscle lamina between the VL and the VI in 36%. Two muscle bellies of the VL have also been reported by other authors (Krause, 1880; Testut, 1884; Dwight, 1887; Holyoke, 1897).
Fig. 7 (a) Anatomical cross-section through the left thigh. The skin and tendon of the tensor fasciae latae have been removed. The rectus femoris reflected medially and visible. 2: VL, 3: TVI, 4: VI. The descending branch of the lateral circumflex femoral artery (d) runs through separate fatty connective tissue (pinned and marked with a white arrow). (b) MRI cross-section through the femur in the middle third (not the same specimen as in a). The intermuscular septum between 2 (VL) and 4 (VI) corresponds to 3 (TVI). 5: rectus femoris; d: descending branch of the lateral circumflex femoral artery.
Fig. 8 Insertions of the rectus femoris, VL, TVI, and VI into the patella. The tendon of the rectus femoris is reflected distally over the patella. Both the TVI and the VL are parts of the middle layer of the quadriceps tendon. The TVI inserts at the medial aspect of the patellar base. The VM is detached from its insertion at the patella.
Henle described the VL as a multi-layered muscle with superficial and deep portions (Henle, 1880). The regular occurrence of two neurovascular sources, as described for the VL, also suggests more than one muscle belly (Frohse and Fränkel, 1913; Patil et al., 2007; Becker et al., 2010). Becker and coworkers described the VL as a muscle consisting of four distinct anatomical partitions, named the central, superficial proximal, deep proximal and deep distal portions. In seven of 10 specimens, partitioning was enhanced by an areolar fascial plane between the central and the deep distal partitions (Becker et al., 2010). Labbé reported a symptomatic, progressive restriction of the knee joint in a
9-year-old girl due to an accessory VI. Its tendon and muscle belly were completely separated from the other components of the extensor apparatus (Labbé et al., 2011). Yet other authors have referred to complex fusion between the VL and the VI (Engstrom et al., 1991; Willan et al., 2002; Becker et al., 2009). Frohse and coworkers did not distinguish between the VL and VI, suggesting instead that the extensor apparatus of the knee consists of only three muscle heads (M. triceps femoris) (Frohse and Fränkel, 1913). Despite these anatomical findings, the possibility of a separate intermediate muscle arising proximally between the bellies of the VL and the VI and inserting separately at the medial aspect of the patellar base has not previously been explored.

The deep parts of the quadriceps femoris do not vary much among individuals. However, besides the bilaminar structure of the vasti, Bergman and coworkers mention that a slip (rectus accessorius) can arise from a tendon at the edge of the acetabulum and insert into the ventral edge of the VL (Bergman, 2015). Bergman et al. refer to Grubers’ observations between 1856 and 1866 concerning a rectus femoris accessorius found in three specimens. In all three, the rectus femoris accessorius arose with a long tendon lateral to the main rectus femoris origin from the anterior inferior iliac spine and inserted into the fleshy vastus externus (VL) (Gruber, 1888). This was not observed in the present study. The TVI always originated at the anterior aspect of the greater trochanter distal to the intertrochanteric line.

In contrast to previous studies, we found at least one additional muscle belly between the VL and the VI. In many cases, the individual muscle bellies could be distinguished only after the neurovascular structures were traced. The supply to the VL was clearly delineated, in contrast to the TVI and the VI. The main part of the VL was consistently supplied by muscular branches that ran together with the descending branch of the LCFA. In contrast, the neurovascular supply to the TVI consisted of shorter proximal femoral nerve branches and vessels of the transverse or ascending branch of the LCFA. The same neurovascular structures also supplied lateral portions of the VI, which confirms that the TVI cannot be clearly assigned to the VL.

Over the years, anatomical dissections of the quadriceps femoris have mainly focused on the special features of the extensor apparatus in the distal region (Hollinshead, 1969; Zeiss et al., 1992; Hubbard et al., 1997; Andrlikoula et al., 2006; Waligora et al., 2009). It has been suggested that the VL is composed of two parts: VL obliquus (VLO) and VL longus (VLL) (Hallisey et al., 1987). These inferences were based on the pennation angles of the superficial fascicles only. No differences in respect of innervation pattern or blood supply have been reported. The VLO and VLL were not separately innervated.

Many authors have tried to decipher the architecture of the quadriceps tendon (Hollinshead, 1969; Fulkerson, 2004; Waligora et al., 2009). In this regard, the TVI should be considered a separate muscle belly. This study has demonstrated that it has its own layer in the middle layer of the quadriceps tendon. The muscle portions of the quadriceps femoris are arranged distally such that the individual
layers come together and lie above each other like the layers of an onion. In the proximal two thirds of the muscle group the external and internal layers lie adjacent to each other. However, at the level of the quadriceps tendon, the external layers lie above the inner ones. This explains why the quadriceps tendon is described as many-layered when observed in transverse section (Zeiss et al., 1992; Waligora et al., 2009).

In view of its course from the anterolateral aspect of the greater trochanter to the medial base of the patella, the TVI appears to be significant in controlling the motion of the patella. Its fibers entering the middle layer of the quadriceps tendon from the oblique lateral aspect counteract the forces of the medial fibers of the VM. The steering function of this muscle is also suggested by its rich innervation.

Alternatively, since the aponeurosis of the TVI is in close contact or fused with that of the VI over a long distance, the TVI appears to exert tension on the VI aponeurosis and medialize the action of the VI. Hence, the TVI seems to be a type of «tensor of the VI.» In contrast to the tensor fasciae latae, it is fixed to the corresponding medial muscle layer (Figs. 3 and 10).

In our opinion the TVI fulfils all criteria for an independent muscle. It is innervated by independent branches of the femoral nerve and is vascularized through separate muscle branches. Furthermore, it has a defined origin at the anterior aspect of the greater trochanter and inserts in the middle layer of the quadriceps tendon at the medial patellar base. Despite its variable connections with the adjacent muscles in the proximal aspect of the thigh, the TVI, VL, and VI can always be clearly distinguished in the distal aspect.
To date, the TVI has been attributed to the VL. Indeed, the affiliation of the TVI to the VL is confirmed by the close relationship of the two muscle heads in the proximal aspect. However, the course and function of the TVI and its neurovascular supply suggest that it is aligned more with the VI than the VL. Yet, when the nerves supplying the quadriceps femoris are viewed as a whole, the TVI should be considered together with the VL and the lateral portion of the VI as a functional unit. All three lamellar muscles are closely related and are supplied by the same deep lateral division of
the femoral nerve.

The morphology of the TVI shows intra- and interindividual differences. There are individual variations in respect of the degree of fusion between the muscle bellies of the VL and the VI (Willan et al., 2002). These connections are also found between the layers of the VI and the TVI, as well as the TVI and the VL. On the basis of this study it is not clear whether physical exercise or pathological conditions are implicated in these individual differences.

Interpreting the TVI as an independent muscle and understanding its role within the extensor mechanism would change our understanding of the complex architecture and function of the extensor apparatus of the knee joint as a whole. The present anatomical description is by no means a comprehensive report on the TVI. Further work should combine these anatomical findings with advanced imaging techniques. If the muscle bellies of the quadriceps could be distinguished by modern imaging procedures, exercise- or disease-related differences between the individual muscles could be identified.

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References

A NEWLY DISCOVERED MUSCLE: THE TENSOR OF THE VASTUS INTERMEDIUS

Knee Pain Associated with Rupture of Tensor Vastus Intermedius, a Newly Discovered Muscle: A Case Report

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Introduction
Muscle strains within the quadriceps muscle group are common and occur mostly in the rectus femoris. We report a case of an isolated rupture of the tensor vastus intermedius (TVI); a muscle that has recently been described. It belongs to the quadriceps muscle group and is closely related to the vastus lateralis and vastus intermedius.

Case presentation
A healthy 62-year old woman presented with a history of a sudden onset of left knee and thigh pain after stumbling and preventing a near fall. Rupture of the aponeurotic tendon of the TVI was diagnosed by magnetic resonance imaging (MRI). Conservative treatment was successful. Four months after injury the patient returned to her pre-injury level of activity. MRI evaluation five months post-injury revealed full resorption of the muscular haematoma and a healed TVI aponeurosis with scar tissue formation.

Conclusion
Due to its anatomic appearance, lesions to the TVI may be overlooked. The isolated rupture of the TVI in the present case further supports the recent finding, that the TVI is a distinct anatomical structure independent of the adjacent vasti.

Keywords: Muscle strains, magnetic resonance imaging, rehabilitation, knee pain, ligamentous injury, muscle injury, haemorrhage.
Introduction

Muscle strains of the quadriceps muscle group are common, and occur mostly in the rectus femoris\(^1\). They usually manifest as a result of a rapid eccentric contraction\(^2\) such as sprinting or kicking\(^3\). The injuries are usually non-disruptive to the tissue integrity and typically resolve with conservative management\(^3\). It has been shown that the primary function of the quadriceps femoris group is eccentric deceleration in the early stance phase of gait. Although the rectus femoris has the highest incidence, other muscles of the quadriceps are injured in isolation\(^1,4,5\). The tensor vastus intermedius (TVI) has recently been described as an additional component of the extensor apparatus of the knee joint, located between the vastus lateralis and vastus intermedius muscles. It originates from the anterolateral aspect of the greater trochanter and combines distally into a variable broad, flat tendon or aponeurosis merging into the quadriceps tendon (Fig. 1)\(^6,7\). We present a case of TVI rupture including the MRI findings.

Fig. 1 A schematic drawing of the left extensor apparatus of the knee joint is shown. The tensor vastus intermedius (blue) runs between the Vastus lateralis (VL) and Vastus intermedius (VI). It expands from the anterolateral aspect of the greater trochanter to the medial base of the patella. Vastus medialis (VM), Rectus Femoris (R) (transsected), Patella (P).
Case Presentation

A 62-year old, slightly obese female (BMI 31) patient presented to the orthopaedic clinic with a history of left knee and thigh pain after a stumble. She lost balance, but managed to stabilise her body with her left leg in a flexed knee position. She then experienced a sharp knee pain accompanied by a «crunching sound» in the lateral thigh. On physical examination, there was no joint effusion or ligamentous injury. The lateral quadriceps femoris muscle from its mid portion down was swollen and tender. No muscle defect was palpable. Passive knee flexion and resisted extension was painful. Passive flexion was 40 degrees with full passive extension. There was no extension lag. Straight leg raise was painful and difficult. There was no history of prior knee problems.

Anterior-posterior and lateral radiographs of the knee were normal. MR imaging demonstrated a rupture of the «intermuscular septum» between vastus intermedius and vastus lateralis. This correlates to the aponeurotic tendon of the TVI (Figure 1). There was a moderately high signal, centred about the ruptured aponeurotic tendon of the TVI with discontinuity at the muscle-tendon junction, best seen on axial T2-weighted images. Extended edema and haematoma was present in the adjacent vastus intermedius and lateralis muscles (Fig. 2).

Fig. 2 The T1-weighted cross-section (right) and the corresponding T2-weighted coronal plane (left) MR images demonstrate a rupture (discontinuity) of the aponeurotic tendon of the tensor Vastus intermedius (white arrows). See also Figure 1. Edema and Haematoma (H) is present in the adjacent Vastus intermedius (VI) and Vastus lateralis (VL). Vastus medialis (VM), Rectus femoris (R), Femur (F).
Treatment included compression bandage of the knee joint and thigh, ice application, rest and elevation for the first three days. Muscle relaxant and non-steroidal anti-inflammatory drugs were given to reduce the pain and avoid the development of myositis ossificans. After the acute phase the patient started with isometric exercises and active stretching of the muscle within pain limits. The patient was able to walk with crutches after two days and continued so for the next six weeks. After twelve weeks the patient had regained full pain-free range of motion and after four months, she returned to her pre-injury level of activity.

MRI evaluation five months post-injury revealed full resorption of the muscular haematoma and a healed TVI aponeurosis with scar tissue formation. There were minor atrophic changes of the adjacent vastus lateralis and intermedius (Fig. 3). Two and a half years post-injury the patient remained asymptomatic during daily activities. However, after walks of more than one hour she occasionally experienced increased fatigue in her left quadriceps muscle accompanied by a mild pain in the area, where the TVI muscle injury occurred. Downhill walking increased this phenomenon.
Discussion

Muscle injuries most often occur with excessive eccentric muscle contractions. Biarticular muscles and muscles with a higher content of type II fibres are more susceptible to injury. Laboratory studies show that partial and complete tear injuries exhibit disruption of muscle fibers near the muscle-tendon junction. The hamstrings, followed by the quadriceps and gastrocnemius muscles, are the most commonly affected muscles. The biarticular rectus femoris is the most commonly injured quadriceps muscle. Cross et al. followed forty professional football players over three years. During this time, 25 clinical quadriceps injuries occurred, with only seven involving the vasti muscles (6 vastus intermedius, 1 vastus lateralis, and 0 vastus medialis). There are very few cases of vastus muscle strain injuries reported in the literature and because most of these injuries had no routine MRI, it is unknown what kind of vastus strain occurred.

The present report presents a case of an isolated TVI strain. The existence of this muscle has only recently been reported as a component of the lateral part of the extensor apparatus of the knee joint. The TVI originates from the anterolateral aspect of the greater trochanter and combines distally into a variable broad, flat tendon or aponeurosis (Fig. 1). Traditionally, the TVI has been attributed to the VL. Henle reported of a multi-layered vastus lateralis with different directions of their muscle fibres. Williams found that the lower anterior edge of the vastus externus consists of two tendinous laminae, which can very easily be split into two layers. Gegenbaur described intermuscular membrane («membrana intermuscularis») belonging to the VL that expands from the middle third of the femur to the lateral femoral condyle. Such an intermuscular membrane has also been illustrated on cross-section in the textbook of Poirier. Testut also mentioned a variation of the VL where a superficial and deep lamination (lamina profunda and lamina superficialis) could be distinguished. These early findings have been confirmed by investigations of Willan who noted that the vastus lateralis includes a fleshy lamella in 36% of thighs and that the tendinous continuation contributed to the quadriceps tendon.

The appearance of the TVI has also been documented sonographically in forty knees of twenty subjects (ten males and ten females). The tendinous portion of the TVI was consistently located in the fascial plane between the VL and VI at the proximal aspect of the distal third of the anterolateral thigh.

Owing to the course of the TVI from the antero-lateral aspect of the greater trochanter to the medial patella (Fig. 1), this muscle appears to be significant in terms of controlling the motion of the patella in addition to its extensor function of the knee joint. It has been hypothesized that the fibres of the TVI aponeurosis that enter the middle layer of the quadriceps tendon from the oblique lateral aspect, counteract the forces of the medial components of the quadriceps muscle group. The TVI aponeurosis, which is in close contact with the vastus intermedius over a long distance, exerts tension...
on the vastus intermedius and tightens it medially\textsuperscript{6,7}. Similar to the other components of the extensor apparatus, the TVI acts as much to power knee extension as to prevent knee flexion. The strain mechanism of the TVI caused by an eccentric action in the present case emphasizes its function to decelerate flexion of the knee joint.

It is understood that the causes of muscle injuries are often multi factorial\textsuperscript{2,9}. Use of systemic or local steroids, statins or fluoroquinolons as well as disorders such as renal insufficiency, hyperparathyroidism, rheumatoid arthritis, obesity, gout and systemic lupus erythematosus may predispose to ruptures. Besides repetitive loading during sport activity, other factors such as fatigue, inflexibility, poor coordination and intrinsic tightness, age, poor flexibility, lack of warm-up and muscle temperature may all contribute to muscle overload\textsuperscript{2,9,16-23}. Except for obesity, our patient exhibited no other comorbidity or medical condition that would have promoted this uncommon injury to the TVI. Most probably there were age-related factors, increased BMI combined with the severe eccentric overload during the stumble that led to the muscle injury in the present case.

MRI is the imaging technique of choice for evaluating acute musculotendinous injuries\textsuperscript{1} and is useful when swelling or other soft-tissue abnormalities obscure the physical examination. MRI is most sensitive in evaluating the appearance of muscle haematomas and the healing process. In our patient, MRI revealed the isolated rupture of the TVI aponeurosis (at first glance corresponding to the intermuscular septum between the vastus intermedius and vastus lateralis) that caused a large haematoma and consecutive signal changes in the adjacent vastus lateralis and vastus intermedius muscles. Because the TVI (lying between the vastus lateralis and the vastus intermedius) has been given little attention so far, any damage to its structure has not been recognized to date. Cross et al. observed straining of the vastus lateralis muscle in one case (out of 25 acute quadriceps muscle strains) and noticed straining of the adjacent intermuscular septum\textsuperscript{1}. Anatomically, the aponeurosis of the TVI runs adjacent to the descending branch of the lateral circumflex femoral artery\textsuperscript{6}. Therefore, rupture to the TVI might also cause a rupture of the adjacent vessels and result in haemorrhage. The aponeurosis of the TVI inserts through the intermediate layer of the quadriceps tendon on the medial base of the patella\textsuperscript{6}. This explains radiating pain to the knee joint in the present case.

**Conclusion**

This is the first reported case of a rupture of the TVI. Because of its anatomic appearance and relationship to the vastus lateralis and intermedius muscles, lesions to the TVI have been attributed to injuries of the latter. The isolated rupture of the TVI in the present case further supports the recent finding, that the TVI is a distinct anatomical structure independent of the adjacent vasti. Further research is needed to establish its exact function and clinical relevance.
References

New insight in the architecture of the quadriceps tendon

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Background

Published data regarding the structure of the quadriceps tendon are diverse. Dissection of the quadriceps muscle group revealed that beside the rectus femoris, vastus lateralis, vastus intermedius and vastus medialis a fifth muscle component – named the tensor vastus intermedius consistently fused into quadriceps tendon. It can be hypothesized that all these elements of the extensor apparatus of the knee joint must also be represented in the quadriceps tendon. This study investigated the multi-layered quadriceps tendon with special emphasis on all components of the quadriceps muscle group including the newly discovered tensor vastus intermedius.

Methods

Ten cadaveric lower limbs were dissected. All muscle bellies of the extensor apparatus of the knee joint were identified and traced distally until they merged into the quadriceps tendon. Connections between the different aponeurotic layers of each muscle were studied from origin to insertion. The fusing points of each layer were marked. Their distance to the patella and the distances between the fusing points were measured.

Results

Six elements of the quadriceps muscle group form a tri-laminar structure of the quadriceps tendon. The intermediate layer could be further sub-divided. The elements of the quadriceps tendon are 1. lateral aponeurosis of the vastus intermedius, 2. deep and 3. superficial medial aponeurosis of the vastus intermedius, 4. vastus lateralis, 5. tensor vastus intermedius and 6. rectus femoris. Even with differences in fiber direction – these elements join each other a certain distance proximal to the patella.

All elements were fused over a region measuring 13 to 90 mm proximal to the patella. Lateral
parts of the vastus intermedius formed the deepest layer of the quadriceps tendon. The superficial and deep layer of the medial vastus intermedius aponeurosis fused 56 mm (range, 30 to 90 mm) and 33 mm (range, 13 to 53 mm) above the patella with the aponeurosis of the tensor vastus intermedius and vastus lateralis respectively. Together they built the two-layered intermediate layer of the quadriceps tendon. The tendon of the rectus femoris forms the superficial layer. The vastus medialis inserts medially in all layers of the quadriceps tendon. Fibers of the lateral muscle components were oriented towards the medial, and fibers of the medial muscle components were oriented towards the lateral femoral condyle.

Conclusions
The three-layered quadriceps tendon is formed by six elements. These are 1. lateral aponeurosis of the vastus intermedius, 2. deep and 3. superficial medial aponeurosis of the vastus intermedius, 4. Vastus lateralis, 5. tensor vastus intermedius and 6. rectus femoris. These elements of the extensor apparatus join each other proximal to the patella in a complex onion-like architecture. Its two-layered intermediate layer shows variable fusions points. The vastus medialis contributes to the quadriceps tendon with its medial insertion into all layers of the quadriceps tendon.

Keywords: Quadriceps tendon, Tensor vastus intermedius, Extensor apparatus of the knee joint, Quadriceps muscle group.

Background
The insertion of the quadriceps femoris into the patella is traditionally described as a common tendon with a tri-laminar arrangement (Andrikoula et al. 2006; Iriuchishima et al. 2012; Sonin et al. 1995; Warwick & Williams 1973; Yablon et al. 2014), with the most superficial fibers originating from the rectus femoris, the deepest layer from the vastus intermedius and the intermediate layer from the vastus lateralis and vastus medialis. Other studies have suggested that the quadriceps tendon anatomy is more variable with a two- to four-layered or even more complex organisation, often with unequal contributions from its tendinous constituents (Waligora et al. 2009; Zeiss et al. 1992). Considering the consistent components of the quadriceps muscle group, the published variability of the tendon composition seems surprising.

In recent anatomical studies, an intervening muscle, between the vastus lateralis and vastus intermedius – named the tensor vastus intermedius - has been identified (Grob et al.; Rajasekaran & Hall 2016). Depending on the relation to the adjacent vastus lateralis and vastus intermedius muscles, different morphological types of tensor vastus intermedius were identified. The aponeurosis of the tensor vastus intermedius consistently fused into the middle layer of the
quadriceps tendon and inserted at the superior medial border of the patella. As this muscle was previously attributed to other parts of the quadriceps muscle group, its role in the organization of the quadriceps tendon was unknown (Grob et al.).


**Purpose and Hypothesis**

The newly described tensor vastus intermedius contributes to the extensor apparatus of the knee joint (Grob et al.; Rajasekaran & Hall 2016). It can be hypothesized that the tensor vastus intermedius as a fifth component of the quadriceps muscle group might represent a specific section in the in the quadriceps tendon. It has been shown, that the aponeurotic tendon fuses into the quadriceps tendon and inserts at the superior medial border of the patella (Grob et al.; Rajasekaran & Hall 2016). The purpose of the present study was to further investigate the multi-layered structure of the quadriceps tendon with special emphasis on all components of the extensor apparatus.

**Methods**

Ten cadaveric lower limbs from 7 specimens, three paired and four unpaired (5 men and 2 women; mean age at death 78 years) were investigated using macro dissection techniques. The cadaver parts were obtained from the institutional body donation program (http://www.anatomy.uzh.ch/de/koerperspende.html) following the ethical guidelines «On the use of cadavers and parts of cadavers in medical research and for pre-, postgrad and continued education and research with human subjects» by the Academy of Medical Sciences (SAMS). All lower limbs were embalmed in a formalin-based solution. The thighs were examined on the basis of a standardized dissection protocol. Each lower limb was placed supine on the dissection table. The hip joint was approached from the anterior aspect and the tensor fasciae latae muscle mobilized laterally. The femoral nerve and artery were localized via a second ilio-inguinal approach, and traced distally. With the aid of these neuro-vascular structures, the muscle bellies of
the rectus femoris, the vastus lateralis, the tensor vastus intermedius, vastus intermedius, and vastus medialis were identified. For better visualization the rectus femoris and sartorius were transsected in the mid portion and reflected. Each muscle with its aponeurosis was traced from proximal to distal until they merged into the quadriceps tendon. Connections between the different aponeurotic layers of each muscle were studied from origin to insertion (Fig. 1), with special emphasis on corresponding muscle fibers from the medial and lateral elements. The fusing points of each layer were marked. Their distance to the patella and the distances between the fusing points were measured.

**Results**

All portions of the extensor apparatus fused over a region ranging from 13 to 90 mm (mean 44 mm, SD +/- 21) proximal to the superior pole of the patella medial to the mid-line of the quadriceps tendon. The different components were structured in onion-like layers or similar to a husk of a corn. Superficial lateral and medial fibers in the proximal aspect of the thigh were piled in deeper inner layers at the level of the quadriceps tendon (Fig. 1). The thickness of the quadriceps tendon increased steadily as more aponeurotic layers of the extensor apparatus joined both medially and laterally. At the patella insertion the quadriceps tendon reached its maximal thickness of 79 mm (range 65 to 95 mm, SD +/- 0.9). Deep to the quadriceps tendon between the tendon and the femur, the muscle bundles of the articularis genus extended to the suprapatellar bursa, and the synovial membrane of the knee joint. The fibers of the articularis genus did not contribute to the architecture of the quadriceps tendon, but merely fused with the dorsal side of the aponeurosis of the vastus intermedius.
Fig. 1 Overview of the quadriceps muscle group including the newly discovered fifth component, the tensor vastus intermedius. Anterior view to the left thigh is shown. The red stickers mark the medial and lateral femoral condyles and center of the neck of the femur respectively. For better visualization the sartorius and rectus femoris muscle are transected and reflected. The components of the extensor apparatus are arranged like the layers of a husk of a corn (on the left top). Superficial lateral and medial fibers in the proximal aspect of the thigh are piled in deeper inner layers at the level of the quadriceps tendon. The vastus medialis is released from its insertion into the vastus intermedius, rectus femoris and patella.
Fig. 2 Orientation of the multilayered structure of the extensor apparatus of the knee joint. The distal aspect of a right thigh is shown. Red stickers mark the medial and lateral femoral condyles above the knee joint space. The vastus medialis is released from its insertion into the vastus intermedius and rectus femoris (reflected laterally) freeing the view to the complex multi-layered aponeurosis of the vastus intermedius. The lateral part of the vastus intermedius aponeurosis form the deepest layer of the quadriceps tendon. The medial part of the vastus intermedius aponeurosis separates into a superficial and deep medial layer with an orientation towards the lateral femoral condyle (lateral red stick). The fibers of the medial vastus intermedius aponeurosis are located above the lateral part of the vastus intermedius aponeurosis. Generally, lateral fibers are oriented towards the medial femoral condyle (medial red stick). The blue dots mark the fusing points of the intermediate layer of the quadriceps tendon and the superior base of the patella. For better visualization the fusing points are underlined with black paper. The white dotted lines indicate the fiber direction towards the condyles.

The tendon of the vastus intermedius showed a complex multi-layered structure. It converged towards the patella and divided into a lateral and medial part. The lateral part of the vastus intermedius aponeurosis formed the deepest layer of the quadriceps tendon. These lateral fibers were oriented towards the medial femoral condyle (Fig. 2). The medial part of the vastus intermedius aponeurosis separated into a superficial and deep medial layer with an orientation towards the lateral femoral condyle (Figs. 2 and 3a). The fibers of the deep medial vastus interme-
dius aponeurosis were located above the lateral part of the vastus intermedius aponeurosis. Five to 10 mm medial to the mid-line of the quadriceps tendon, the superficial and deep layer of the medial vastus intermedius aponeurosis fused with the aponeurosis of the tensor vastus intermedius and vastus lateralis respectively. Together they formed the two-layered intermediate layer of the quadriceps tendon. Therefore, the vastus intermedius contributed first to the deep layer of the quadriceps tendon through its lateral part of the vastus intermedius aponeurosis and second to the two-layered intermediate layer of the quadriceps tendon by its superficial and deep medial VI aponeurosis (Fig. 3). Jointly the different fibers continued towards the patella. The fusion point of the fibers for the deep intermediate layer was on average 56 mm (range, 30 to 90 mm, SD +/- 21) proximal to the patella (Fig. 3b). In the distal aspect the superficial medial layer of the vastus intermedius aponeurosis turned into a tendinous gliding layer of the vastus medialis. The latter, in turn, extended to the medial proximal margin of the patella, and in the deeper aspect to the tendon of the rectus femoris. The superficial medial layer of the vastus intermedius aponeurosis that fused with the aponeurosis of the vastus lateralis (superficial intermediate layer) met 33 mm (range, 13 to 53 mm, SD +/- 14) above the patella (Fig. 3b). The fibers of the vastus lateralis were often composed of bundles of individual thin fiber strands (Fig. 4). The meeting point of the superficial intermediate layer was always distal (23 mm, range, 12 to 41 mm, SD +/- 0.9) to the meeting point of the deep intermediate layer (Fig. 3b).
Fig. 3 Architecture of the multilayered quadriceps tendon. The distal aspect of a right thigh a with corresponding distal section of the quadriceps tendon b is shown. a The architecture of the quadriceps tendon consisting of the rectus femoris (R), vastus lateralis (VL), tensor vastus intermedius (TVI), vastus intermedius (VI) is shown. The medial part of the VI aponeurosis separates into a superficial and deep medial layer. Sartorius (S), patella (P). The insertions of the vastus medialis (VM) into the patella and capsule of the knee joint (blue arrow), rectus femoris (red arrow) and vastus intermedius (green arrow) is marked. Anterior insertion of the vastus medialis in the vastus intermedius (VM ant), posterior insertion of the vastus medialis into the vastus intermedius (VM post).

b The proximal two blue dots (F1 and F2) mark the fusing points of the in-
termediate layer of the quadriceps tendon. All portions of the extensor appa-
ratatus fuse over a region ranging from 13 to 90 mm proximal to the superior
pole of the patella (distal blue dot). Lateral portions of the vastus intermedi-
us (lateral VI) form the deepest layer of the quadriceps tendon. The superfi-
cial and deep layer of the medial vastus intermedius aponeurosis (black dotted arrows) fuse 56 mm (range, 30 to 90 mm) and 33 cm (range, 13 to 53
mm) proximal to the patella with the aponeurosis of the tensor vastus inter-
medius (TVI) and vastus lateralis (VL) respectively. Together they built the
two-layered intermediate layer of the quadriceps tendon. The tendon of the
rectus femoris (R) forms the superficial layer of the quadriceps tendon. For
better visualization the fusing point are underlined with black paper. The
vastus medialis is released from its insertion into the vastus intermedius and
rectus femoris. Depending on the level of virtual transection one finds two,
three or four layers (white arrows with numbers). An oblique transection
could lead to the impression of a complex multi-layered arrangement of the
quadriceps tendon.
The superficial layer of the quadriceps tendon was formed by the tendon of the rectus femoris. Proximal to the meeting points of the two-layered intermediate layer, the aponeurosis of the rectus femoris was located directly on the lateral part of the vastus intermedius aponeurosis (= deep layer of the quadriceps tendon). In other words, 56 mm (range, 30 to 90 mm) proximal to the superior border of the patella, an intermediate layer was missing (Table 1). Therefore, at this site the quadriceps tendon was seen to be composed of two layers only, separated by thin partitions of fat. In contrast, distal to the meeting points of the two-layered intermediate layer,
the quadriceps tendon was composed of four layers (Fig. 3b). The various layers of the quadriceps tendon were joined to each other through light, divisible crosswise fibers. The latter had also inlets of fatty tissue to a differing extent. Distally the superficial medial vastus intermedius aponeurosis and the deep gliding aponeurosis of the vastus medialis fused with the tendon of the rectus femoris and the patella. Together with parts of rectus femoris tendon the vastus medialis occupied the supero-medial half of the upper semi-circle of the patella (Fig. 4). Remainder of the aponeurosis of the rectus femoris continued superficial to the patella to join the patellar ligament.

**Table 1**

Fusion points of the two-layered intermediate layer of the quadriceps tendon

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**Table 1** indicates the individual data (n = 10) of the fusion points (distances to the patella in millimeters) of the two-layered intermediate layer of the quadriceps tendon. The medial deep layer of the vastus intermedius aponeurosis fused with the aponeurosis of the tensor vastus intermedius (deep intermediate layer). The medial superficial layer of the vastus intermedius aponeurosis fused with the aponeurosis of the vastus lateralis (superficial intermediate layer). The meeting point of the superficial intermediate layer was always distal (23 mm, range 12 to 41 mm, SD +/- 0.9) to the meeting point of the deep intermediate layer. All elements of the quadriceps tendon fused over a region proximal to the patella ranging from 13 to 90 mm (Fig. 3b)

In three cases the superficial intermediate layer separated from the deep intermediate layer more proximal. The former again fused further distally with the deep gliding aponeurosis of the vastus medialis and the tendon of the rectus femoris.

The strong muscle belly of the vastus lateralis inserted at the supero-lateral semi-circle of the
patella (Fig. 4). In a fully extended knee joint, fibers of the lateral components of the extensor apparatus were oriented towards the medial superior border of the patella and subsequently towards the medial femoral condyle. Fibers of the medial components of the extensor apparatus were oriented towards the lateral superior border of the patella and subsequently towards the lateral femoral condyle (Figs. 2, 3 and 4).

In four cases an independent and strong aponeurosis of the tensor vastus intermedius was found (n = 4 independent type) (Grob et al.). In one case the aponeurosis of the tensor vastus intermedius was rather weak and greater portions of the lateral vastus intermedius aponeurosis divided into two layers. An identical pattern was found in three cases where the aponeurosis of the tensor vastus intermedius emerged from the lateral part of the vastus intermedius (n = 4 vastus intermedius type) (Grob et al.). In these situations, the anterior part of the lateral vastus intermedius aponeurosis fused with the deep medial vastus intermedius aponeurosis forming the deep intermediate layer of the quadriceps tendon. In two other cases the aponeurosis of the tensor vastus intermedius arose from the vastus lateralis (n = 2 vastus lateralis type) (Grob et al.). Thus the vastus lateralis contributed to both layers of the intermediate layer of the quadriceps tendon (Fig. 5).
Fig. 5 Schematic drawing of the three-layered architecture of the quadriceps tendon. The superficial layer (I) of the quadriceps tendon is formed by the tendon of the rectus femoris (R). The intermediate layer (II) is further sub-divided. The tendon of the vastus intermedius (VI) itself shows a complex multi-layered structure consisting of the lateral part of the vastus intermedius aponeurosis (lateral VI) and the medial deep and medial superficial layers of the vastus intermedius aponeurosis. The medial superficial and the medial deep layer of the vastus intermedius aponeurosis fuse with the aponeurosis of the tensor vastus intermedius (TVI) and vastus lateralis (VL), respectively. The lateral part of the vastus intermedius aponeurosis forms the deepest layer (III) of the quadriceps tendon. In some cases, the aponeurosis of the tensor vastus intermedius emerges either from the lateral part of the vastus intermedius (bended blue arrow) or vastus lateralis (bended orange arrow) (Grob et al.). The vastus medialis (VM) is not directly involved in the architecture of the quadriceps tendon. It inserts into the aponeurosis of the vastus intermedius and tendon of the rectus femoris on its anterior and posterior side (indicated by the red dots and lines).

Discussion
Published data about the structure of the quadriceps tendon are diverse. While some authors observed three layers (Andrikoula et al. 2006; Iriuchishima et al. 2012; Sonin et al. 1995; Warwick & Williams 1973; Yablon et al. 2014), others report two, three or more layers (Waligora et al. 2009; Zeiss et al. 1992). Anatomy textbooks often give no special attention to the structure of the quadriceps tendon and state briefly that the four muscular elements of the quadriceps muscle group fuse in the quadriceps tendon (Moore et al. 2014; Netter 2011; Pabst 2008; Platzer 2013; Schünke et al. 2011). In the present dissections a consistent tri-laminar structure of the
quadriceps tendon was found. However, the intermediate layer could be further sub-divided. Besides this description of the laminar organization the present findings provide information about the fiber orientation and the insertion of the different components of the extensor apparatus of the knee joint into the patella.

The present study differs from traditional anatomic descriptions in as much as it adds the tensor vastus intermedius to the architecture of the extensor apparatus (Grob et al.; Rajasekaran & Hall 2016).

Our dissections revealed that the fibers of the aponeurosis of tensor vastus intermedius have their own position in the deep intermediate layer of the quadriceps tendon and insert into the medial superior border of the patella (Fig. 3).

Similar to previous reports (Andrikoula et al. 2006; Iriuchishima et al. 2012; Sonin et al. 1995; Waligora et al. 2009; Warwick & Williams 1973; Yablon et al. 2014; Zeiss et al. 1992) the present study found variations in the structure of the quadriceps tendon. However, the variability was restricted to the fusion point rather than the number or structure of the individual layers (Fig. 3). In four cases an independent aponeurosis of the tensor vastus intermedius could be traced. In five cases the aponeurosis of the tensor vastus intermedius either arose from the vastus intermedius or the vastus lateralis. In one case an independent but weak aponeurosis of the tensor vastus intermedius was observed. However, these variations did not change the general architecture of the quadriceps tendon.

In contrast to textbooks of anatomy (Moore et al. 2014; Netter 2011; Pabst 2008; Platzer 2013; Schünke et al. 2011) we found a two-layered medial aponeurosis of the vastus intermedius. Thus, it contributed to the deepest as well as to the intermediate layer of the quadriceps tendon. The vastus medialis, as an important dynamic stabiliser against laterally directed forces, inserted in all layers of the vastus intermedius aponeurosis (Figs. 2, 3a and 5). Hence, not only the vastus medialis, but also the vastus intermedius represents a dynamic restraint to lateral tracking of the patella. In contrast to some publications (Andrikoula et al. 2006; Iriuchishima et al. 2012; Sonin et al. 1995; Warwick & Williams 1973; Yablon et al. 2014) the vastus medialis is not directly involved in the architecture of the quadriceps tendon. It inserts into the aponeurosis of the vastus intermedius and tendon of the rectus femoris on its anterior and posterior side.

We postulate six elements of the multi-layered quadriceps tendon based on the current dissection (Fig. 5): Lateral aponeurosis of the vastus intermedius, deep and superficial medial aponeurosis of the vastus intermedius, vastus lateralis, tensor vastus intermedius and rectus femoris. All these elements – with differences in fiber direction - join each other a certain distance proximal to the patella (Fig. 3). Despite the complex structure of the quadriceps tendon and individual differences its anatomic arrangement is well structured.

The situation becomes complex and confusing when the quadriceps tendon is viewed at differ-
ent cross sections. There is a high variability regarding the fusing point of the superficial and deep intermediate layer (between 13 and 90 mm proximal to the superior base of the patella). This and the oblique orientation of the two-layered intermediate layer appear to be the major reasons for the published diversity of the architecture of the quadriceps tendon (Waligora et al. 2009; Zeiss et al. 1992). Depending on the level of transection or MRI cut one finds two, three or four layers (Fig. 3b). Additionally, depending on the direction of the plane the corresponding layers can be complete or incomplete. An oblique transection or MRI cut could easily lead to the impression of a complex multi-layered arrangement of the quadriceps tendon. Furthermore, the aponeurosis of the vastus lateralis, can separate into two or three fiber bundles (Fig. 4) causing additional confusion. Zeiss et al. studied the MRI appearance of 52 knees with normal tendons. They described that the interpretation of the architecture of the quadriceps tendon is especially difficult in its intermediate layer. They found that the number of laminations was variable, with either two (30 %), three (56 %) or four layers (6 %). In 8 % of the knees, the laminations were barely visible (Zeiss et al. 1992).

In contrast to previous investigations, the present study traced all components of the extensor apparatus from the origin to insertion (Figs. 1 and 3). This enabled us to outline the different layers over the whole expansion of the muscle components. The architecture of the quadriceps tendon based on cross- and longitudinal transections (Waligora et al. 2009; Zeiss et al. 1992) is limited and makes an interpretation difficult or even impossible.

The components of the extensor apparatus are arranged like the layers of an onion or the «layered husk of corn» (Fig. 1). A similar view of the anatomy was expressed as early as 1912 by Poirier (Poirier & Charpy 1912).

The medial and lateral muscle fibers of the extensor apparatus lie opposite each other and join 5 to 10 mm medial to the mid-line of the tendon. This arrangement and its orientation towards the medial and lateral femoral condyles support the view that medial and lateral forces of the quadriceps muscle group balance each other. The vastus lateralis, the tensor vastus intermedius and the lateral part of the vastus intermedius counterbalance the medial parts of the vastus intermedius (superficial and deep layer) and the inserting vastus medialis. The rectus femoris also predominantly inserts into the medial aspect of the superior border of the patella. The vastus intermedius and rectus femoris provide an extensive area for the attachment of the vastus medialis (Fig. 3a).

A quadriceps tendon graft may be used to reconstruct the anterior cruciate ligament (Crall & Gilmer 2015; Geib et al. 2009; Lee et al. 2016; Lee et al. 2007; Marshall et al. 1979; Slone et al. 2015), the posterior cruciate ligament (Chen et al.; Chen et al. 2004; Wu et al. 2007), the medial patellofemoral ligament (Lenschow et al. 2015; Steiner et al. 2006), the lateral collateral ligament (Chen et al. 2001) and the Achilles tendon (Arriaza et al. 2016). This autograft shares bio-
logical and mechanical properties with other grafts such as the patellar ligament or hamstrings, sometimes with superiority (Han et al. 2008). Harvesting the quadriceps tendon (with or without patellar bone) might have an impact on the function of the extensor apparatus of the knee joint as a whole. The removal of a tendon graft probably alters the delicate interplay between different layers of the extensor apparatus. Chen et al. reported that 9% of subjects exhibited donor site pain after quadriceps graft harvesting, and the risk of occult partial rupture of the remaining quadriceps tendon may exist. Late quadriceps tendon rupture at the donor site following harvesting of a quadriceps tendon graft has been reported (Pandey et al. 2015). Loss of quadriceps muscle strength of 20% after harvesting the quadriceps tendon graft for anterior cruciate ligament reconstruction and prolonged weakness of knee extension strength, predominantly in women, have also been reported (Chen et al. 2006; Yasuda et al.). However, others report low donorsite morbidity when using a quadriceps tendon graft compared to a bone tendon bone graft of the patellar ligament (Gorschewsky et al. 2007; Han et al. 2008; Lund et al. 2014). The harvesting technique may also impact the outcome. For example, if the quadriceps tendon is harvested at the fusing points (Fig. 3b) it is questionable that such a graft is suitable as a firm graft. A harvest of the quadriceps tendon medial to the fusing points of the intermediate layers violates the insertion of the vastus medialis with potential consequences on the terminal phase of extension and patellar stability (Lieb & Perry 1971; Pocock 1963; Toumi et al. 2007). On the other hand a lateral harvest of the quadriceps tendon compromises the insertion of the vastus lateralis and the tensor vastus intermedius. Based on the present anatomic findings it can be assumed that a harvest of a tendon graft lateral of the fusing points of the two-layered intermediate layer would be of better quality than a medial graft removal (Fig. 3a). Questions arise whether a partial- or full-thickness graft should be harvested and how closure of tendon defects should be performed. Latter questions also arise with regards to parapatellar approaches to the knee joint.

Conclusion

In conclusion, the findings of the present study revealed a complex but constant architecture of a three-layered quadriceps tendon which is formed by six elements. These are 1. lateral aponeurosis of the vastus intermedius, 2. deep and 3. superficial medial aponeurosis of the vastus intermedius, 4. vastus lateralis, 5. tensor vastus intermedius and 6. rectus femoris. These elements of the extensor apparatus join each other proximal to the patella in a complex onion-like architecture. Its two-layered intermediate layer shows variable fusions points. The vastus medialis contributes to the quadriceps tendon with its medial insertion into all layers of the quadriceps tendon. Further studies are needed to translate the anatomical findings into clinical rele-
vance in patellofemoral pathology or knee surgery.

Our study has few limitations. Inter individual differences between specimens’ height were not considered in the present study. An other important limitation is that the quadriceps tendon was investigated in embalmed cadaveric specimens from elderly donors. Age-related muscle atrophy may well have distorted some results. In addition, embalmed tissue has been reported to shrink by 2.2 to 12 % (Cutts 1988; Friederich & Brand 1990). This could have affected absolute values for variables such as measured fusing points of each layer, their distance to the patella and the distances between the fusing points of the quadriceps tendon and therefore are not likely to be representative of normal healthy adults. Nevertheless, the fundamental architecture of the quadriceps muscle group is likely to have been preserved. Considering the complexity of the quadriceps tendon further investigation of its morphology in healthy young individuals is warranted.
References

The interaction between the vastus medialis and vastus intermedius and its influence on the extensor apparatus of the knee joint. An anatomical investigation

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Purpose
Although the vastus medialis (VM) is closely associated with the vastus intermedius (VI) there is a lack of data regarding their functional relationship. The purpose of this study was to investigate the anatomical interaction between the VM and VI with regard to their origins, insertions, innervation and function within the extensor apparatus of the knee joint.

Methods
Eighteen human cadaveric lower limbs were investigated using macro-dissection techniques. Six limbs were cut transversely in the middle third of the thigh. The mode of origin, insertion and nerve supply of the extensor apparatus of the knee joint were studied. The architecture of the VM and VI was examined in detail, as was their anatomical interaction and connective tissue linkage to the adjacent anatomical structures.

Results
The VM originated medially from a broad hammock-like structure. The attachment site of the VM always spanned over a long distance between: 1. patella, 2. rectus femoris tendon, and 3. aponeurosis of the VI; with the insertion into the VI being the largest. VM units inserted twice - once on the anterior and once on the posterior side of the VI. The VI consists of a complex multi-layered structure. The layers of the medial VI aponeurosis fused with the aponeuroses of the tensor vastus intermedius and vastus lateralis. Together they form the two-layered intermediate layer of the quadriceps tendon. The VM and medial parts of the VI were innervated by the same medial division of the femoral nerve.

Conclusions
The VM consists of multiple muscle units inserting into the entire VI. Together they build a potential functional muscular complex. Thereby, the VM acts as an indirect extensor of the knee joint regulating and adjusting the length of the extensor apparatus throughout the entire
range of motion. It is of clinical importance that, besides the VM, substantial parts of the VI directly contribute to the medial pull on the patella and help to maintain medial tracking of the patella during knee extension. The interaction between the VM and VI, with responsibility for the extension of the knee joint and influence on the patellofemoral function, leads readily to an understanding of common clinical problems found at the knee joint as it attempts to meet contradictory demands for both mobility and stability. Surgery or trauma in the antero-medial aspect of the quadriceps muscle group might alter a delicate interplay between the VM and VI. This would affect the extensor apparatus as a whole.

**Keywords:** Vastus medialis, vastus intermedius, extensor apparatus of the knee joint, quadriceps muscle group, extensor mechanism of the knee joint.

**Introduction**

The vastus medialis (VM) and vastus intermedius (VI) muscles are part of the extensor apparatus of the knee joint. Both muscles are situated close to each other on the anterior and medial aspect of the femur. The VM and VI work together with the other components of the quadriceps muscle group (rectus femoris, vastus lateralis and tensor vastus intermedius) to produce knee extension torque when knee joint action is performed. However, anatomical properties such as muscle volume, origin of the muscle and fiber type composition seems to be inconsistent among the components of this muscle group. These variations may be attributed to different functional roles or contributions among synergists of the extensor apparatus of the knee joint.

There is a large quantity of literature regarding the importance of the VM as a medial stabiliser of the femoropatellar joint. In contrast, very little has been written about the VI and its anatomic interaction with the VM. Traditionally, the VM is described as largely separated from the anterior and the medial side of the femur by the VI. It arises from the lower portion of the intertrochanteric line, spiral line, medial lip of the linea aspera, upper part of the medial supracondylar line, the tendons of the adductor longus and magnus, and the medial intermuscular septum. It has been proposed that the fibres of VM pass downwards and forward, and end in the common tendon of the quadriceps muscle, which inserts into the patella and becomes connected with the capsule of the knee joint. In addition to this classic description, great variation in the distal part of the VM has been found.

According to anatomy textbooks, the VI arises from the anterior and lateral surfaces of the
upper two-thirds of the femoral shaft, and from the lower part of the lateral intermuscular septum. The VI inserts into the posterior surface of the upper border of the patella, posterior to the VM, through tendon fibres that make up the deep part of the quadriceps tendon. Although the VM and VI course adjacent to each other, there is a lack of data regarding their functional relationship or interaction. According to many textbooks, atlases of anatomy and journals, the VI and VM are separated by an intermuscular space or septum. However, previous anatomical dissections revealed that the interaction between the components of the quadriceps muscle group is more complex and intricate than was initially described. Furthermore, dissections revealed different morphological findings between the VI and VM compared to classic descriptions in the literature. Loss of knee extension occurs most rapidly due to inactivity of the VM. Patellofemoral pain syndrome is thought to be associated with lateral malalignment of the patella. Possible causes of this malalignment include a hypotrophy or atrophy of the VM, which might affect the VI and other components of the quadriceps muscle group indirectly. The purpose of this study was to investigate the anatomical connection between the VI and VM, as well as their innervations, origins, insertions, and contributions to the function of the extensor apparatus of the knee joint.

Material and Methods
Eighteen cadaveric lower limbs from 12 specimens (6 paired and 6 unpaired), from eight males and four females, with a mean age at death of 77 years (range = 67 to 86 years), were investigated using macro-dissection techniques. The cadaver parts were obtained from the institutional body donation program (http://www.anatom.uzh.ch/Bodydonation.html) following the ethical guidelines «On the use of cadavers and parts of cadavers in medical research and for pre-, postgrad and continued education and research with human subjects» by the Academy of Medical Sciences (SAMS). All lower limbs were embalmed in a formalin based solution. The thighs were examined by a standardized dissection protocol. Each lower limb was placed supine on a dissection table and an anterior approach to the hip joint was performed. Resection of the joint capsule followed and the proximal border of the muscle bellies of the quadriceps muscle group were localized. After an additional incision proximal to the inguinal ligament, the femoral nerve was dissected and traced distally. All the muscle branches of the femoral nerve to the sartorius and the different components of the quadriceps muscle were identified. Finally, the sartorius and the rectus femoris muscles were transsected distally and elevated proximally. All nerve branches to the VI and VM were carefully dissected. The saphenous nerve was traced separately until it exited the adductor canal. VM was released from its medial attachment to the intermuscular septum. Six limbs from four specimens (two paired and two un-
paired) were cut transversely in the middle third of the thigh. The origins, insertions, nerve supply and the architecture of the VM and VI were examined. Attention was paid to the anatomical interaction between the VM and VI, as well as their connective tissue linkage to the adjacent anatomical structures.

Results

Origin, course and insertion of the vastus medialis
The VM originated medially and dorsally from a broad hammock-like structure composed of the medial intermuscular septum and its great expansion between the distal continuation of the intertrochanteric line, the spiral line, the medial lip of the linea aspera down to the proximal part of the medial supracondylar line, the tendon of the adductor magnus, the adductor canal, the aponeurosis of adductor longus and to the periarterial connective tissue of the groove for the femoral vessels (Fig. 1). The medial aponeurosis of the VM was always tightly bound to the aponeurosis of the adductors.

The insertion of the VM always spanned over a long distance in three sections (Fig. 1, Fig. 2 and Fig. 3), being:

1. Section 1 – the entire aponeurosis of the VI;
2. Section 2 – the distal tendon of the rectus femoris; and
3. Section 3 – the medial border of the patella and joint capsule.

The first section of this VM insertion was the largest and expanded over the whole length of the VI aponeurosis. It had a fleshy double insertion - a strong and large insertion on the anterior side and a weaker insertion on the posterior side of the VI aponeurosis. VM clamps the VI aponeurosis like a clip holding a sheet of paper (clip-type double insertion) (Fig. 2, Fig. 3 and Fig. 4). This part of the VI insertion is broad and strong especially on its anterior side (Fig. 2 and Fig. 3). Distally, as more muscle fibres of the VM blended into the VI aponeurosis, its medial part divided into deep and superficial layers. These two layers finally crossed over the lateral part of the VI aponeurosis (Fig. 2 and Fig. 3).

The second section of VM insertion occurs on the medial edge of the most distal 52 mm of the rectus femoris tendon (range = 40-61mm, SD = 0.7) where the VM blends its fibres on its upper and lower side (Figs. 2, 3). Distally, this attachment continues into the third section of the VM insertion at the medial border of the patella. An aponeurotic expansion of this section rein-
forces the capsule of the knee joint (Fig. 2 and Fig. 3). Proximally, the muscle fibres of VM are aligned almost longitudinally to the axis of the femoral shaft. Distally, the fibres run in an oblique direction and near the end are almost transverse in orientation. The VM consists of multiple muscle units, which become more oblique in direction from proximal to distal (Fig. 1).

The medial surface of the shaft of the femur is bare and overstretched once by the medial part of the VI aponeurosis and once by the inserting muscle fibres of VM (Fig. 1 and Fig. 2B). The VM units, arising from the hammock-like origin (as described above), are fleshy except for their lowest part, where they run over the medial condyle of the femur and the thin muscle sheet of the articularis genus. Here the VM consists of a gliding aponeurosis that generally merges with the superficial layer of the medial VI aponeurosis and laterally from the aponeurosis of the vastus lateralis. Both build the superficial part of the intermediate layer of the quadriceps tendon (Fig. 3).

**Origin, course and insertion of the vastus intermedius (VI)**

The fibres of the VI arise from the anterior and lateral aspects of the proximal two thirds of the femoral shaft, including the lateral lip of the linea aspera. Its attachment to the medial femur is restricted to an area proximally and is very close to the intertrochanteric line. The VI is a complex multi-layered structure; the distal two thirds of the VI is covered by a strong aponeurosis which continues into the quadriceps tendon. The medial part of this VI aponeurosis is divided into a superficial and deep layer (Fig. 2 and Fig. 3) and, together with the lateral part of the VI aponeurosis, provides a wide area for the double insertion of the fleshy fibres of the VM as described above (clip-type double insertion of the VM into the VI) (Fig. 2, Fig. 3).

The thickness of the medial part of the VI aponeurosis increases steadily from proximal to distal as more muscle fibre units of the VM insert on both sides. Superficial and deep layers of the medial VI aponeurosis fuse with the aponeuroses of the tensor vastus intermedius and vastus lateralis respectively (Fig 2 and Fig. 3). Together they form the two-layered intermediate layer of the quadriceps tendon. Therefore, the VI contributes firstly to the deep layer of the quadriceps tendon through its lateral part of the VI aponeurosis and secondly to the intermediate layer of the quadriceps tendon by its two-layered medial VI aponeurosis (Fig. 2 and Fig. 3). In two specimens, some distal fibres of the superficial layer of the medial part of the VI aponeurosis featured a completely separate aponeurosis, which fused with the posterior gliding aponeurosis of the VM. It emerged as the superficial sheet into the middle layer of the quadriceps tendon. Multiple muscle bundles, up to six in number, below the VI aponeurosis continued distally as the articularis genus and did not merge into the quadriceps tendon.
Innervation of VM and VI

In all specimens, the VM was innervated by the same medial division of the femoral nerve. One long, thick branch coursed distally in a fibrotic tunnel along the antero-medial border of the muscle giving up many side branches to and between the muscle portions of VM (Fig. 1 and Fig. 5). A second branch, which divided from the same medial division of the femoral nerve, gave branches to the proximal parts of the VM and to the medial parts of the VI (Fig 5). These branches had a short course and were often hidden by branches of the lateral circumflex femoral artery.

In contrast to the medial part of VI, the lateral part was innervated proximally by multiple short nerve branches from the lateral division of the femoral nerve. The same division supplied branches to the tensor vastus intermedius (TVI) and the vastus lateralis (Fig. 5).

Discussion

An important finding of the present study is that the insertion of VM is not limited to the distal end of the quadriceps tendon and the patella, as has been described in many textbooks of anatomy. In contrast, the insertion of the VM expands from the joint capsule and the patella to the medial edge of the rectus femoris and the aponeurosis of the VI (Fig. 2, Fig. 3 and Fig. 6). The fleshy muscle units of the VM hold and pull the VI aponeurosis medially like a clip holding a sheet of paper (Fig. 4). It could be said that the VI aponeurosis is enclosed by the muscle fibres of the VM and, therefore, is located deep to the muscle surface of the VM (Fig. 2 and Fig. 4). This leads to the impression, as described in the literature, of the existence of an aponeurosis belonging to the VM on its deep surface which is attached to the medial border of the patella. The present dissections revealed that this aponeurosis, which is located in the interior of the VM muscle, in reality belongs to the VI muscle (Fig. 2 and Fig. 4).

The dilemma about the meaning of this «deep aponeurosis» is highlighted by descriptions in the ancient literature. Gegenbaur (1899) stated that in the upper part, VM muscle fibres either merge in a terminal aponeurosis inside the muscle that finally fuse with the lower third of the VI aponeurosis, or the muscle fibres of the VM insert directly in the terminal tendon of the VI. Henle (1855) illustrated that medial portions of the extensor cruris (i.e. VM) blend in a vertically oriented aponeurosis that belongs to the vastus anterior (i.e. VI). An attachment of the VM muscle fibres into the VI has also been mentioned by others. Modern textbooks of anatomy do not show these findings (Fig. 6).
The present results demonstrate that not only the VM, but also substantial parts of the VI, insert into the medial aspect of the extensor apparatus of the knee joint (Fig. 3) and, therefore, build strong counterparts to the lateral-acting forces on the patella. This functions as a dynamic medial stabilizer of the patella and is supported by the existing aponeurotic connections between the VM, VI and the medial patellofemoral ligament33,42 – the primary, static, medial restraint of the patella. Together, these structures are activated during contraction of the quadriceps, making the whole system of fundamental importance for the stability of the medial patellofemoral joint47. In view of the considerable interaction between VM and VI, the importance of the VM as medial-acting force is by no means restricted to the distal part of its muscle fibres (Fig. 4 and Fig. 6). These findings are in contrast to previous reports19,26,27,29.

These investigations revealed that the patellar insertion of VM is very small compared to the distinct attachments into the rectus femoris and, above all, into the aponeurosis of the VI (Fig. 2, Fig. 3, Fig. 4 and Fig. 6). Thus, the angle of the distal fibres, which directly insert into the medial aspect of the patella does not place the muscle in a position to act as a strong medial stabilizer27,31,32,41.

With regard to the orientation of its muscle fibres, the direct force supplied by VM for extension of the knee joint is limited27. In an in-vitro study, Sakai et al.49 studied the influence of weakness of the distal part of the VM muscle on patellar tracking and reported that simulated VM pull had little influence on patella tracking. Their finding suggested that another factor must regulate or resist the lateral displacement of the patella (Fig. 3). A biomechanical study of the quadriceps using amputated specimens to test the extensor capacity of the different components of this muscle showed that all the long components were able to extend the knee fully. However, the knee could not be extended by the oblique fibres of the VM27.

Little attention has been given to the proximal part of the VM, in particular, its interaction with the VI. Most investigations deal primarily with the distal part of the VM, which is also termed vastus medialis obliquus (VMO) (Fig. 6)27,35,40,44,51,60. We were not able to find a separate innervation to the different sections of VM, nor a clearly distinct fascial plane between the two heads. All the muscle fibres of the VM were supplied by the same medial division of the femoral nerve (Fig. 5). There is evidence that the more distal fibres, because of their lever arm arrangement, help to maintain patellar alignment. However, the cross-sectional area of the proximal VM, where it inserts into the aponeurosis of the VI, is much larger and could, therefore, contribute as a strong stabilizer against the lateral patellar forces. We propose that the VM consists of multiple muscle units, with each muscle unit having its specific orientation. The VM inserts through the VI along the longitudinal components of the extensor apparatus at three
sections (Fig. 4 and Fig 6). Based on these findings, the VM exerts a predominantly medial pull on the longitudinal component of the quadriceps muscle group («medial pull-mechanism»).

Patients with lesions that affect the knee commonly demonstrate visible atrophy of the VM prior to causing any measurable decrease in the circumference of the thigh\textsuperscript{27}. These patients also lack active full extension. This supports the assertion by many authors and clinicians that the VM is mainly active during the terminal range of extension, and many exercise programs to strengthen the knee extensor muscles are based on this interpretation. However, there is continued activation of VM throughout the range of motion from 0 - 90° of flexion. The function of the interacting VM and VI could also be the reason why electromyography (EMG) studies showed continuous activation of the VM during the entire gait cycle\textsuperscript{15,27,28,42,52,58}. Physical therapists often focus their therapy on enhancement of VM activity over the rest of quadriceps muscles, however this is difficult to achieve\textsuperscript{55}. EMG studies have shown that all components of the quadriceps act in conjunction and that none of the components are predominantly responsible for fully extending the knee\textsuperscript{27,58}.

The EMG observations in the literature, together with findings of the present anatomical study, suggest that the VM acts as an indirect extensor at the knee. It can be hypothesized that by pulling the longitudinal components of VI and rectus femoris medially and dorsally, the VM tightens and shortens these quadriceps muscles, much like a belt around the waist. Obviously, this shortening of the length of the quadriceps (indirect extensor mechanism) is most important during the terminal phase of extension.

It has been shown that nearly twice as much force is needed by the quadriceps group to produce full extension of the knee in comparison to extending the knee to only 15° of flexion\textsuperscript{27}. This explains the importance of the VM in the terminal range of extension where it is mostly active. The VM triggers the longitudinal components of the quadriceps muscle group by creating a pre-strain at the terminal range of extension. Without this «shortening and pre-straining mechanism» in the terminal phase of extension, the quadriceps muscles would be too long and not sufficiently powerful to effect full extension of the knee joint. In other words, the required orchestral shortening of the quadriceps muscle group for full knee extension could not be achieved by contraction of the muscle fibres (direct extensor mechanism) alone. A simplified model of this mechanism is shown in Fig. 8.

Conversely, the length of the quadriceps muscle group has to extend maximally to create full
flexion at the knee. Including the VM, the quadriceps muscle group features an extraordinary mechanism to adjust its length during the entire range of motion. Therefore, any dysfunction of the VM would automatically influence the whole range of motion of the knee joint, which can be observed in daily clinical practice. The regulative function of the VM during the entire range of motion of the knee joint is indispensable and explains why the VM, of all the quadriceps components, atrophies most rapidly due to inactivity, loss of knee extension after trauma or surgery, or after effusion in the joint. Similarly, failure of the VM can lead to restrictions in knee joint range of motion.

The medial surface of the femur is, in contrast to some descriptions in the literature, bare of muscle attachments. This indicates its function as a gliding surface for the mediadorsally contracting VM muscle units (Fig. 1 and Fig. 4).

The results of this study should also influence the radiological interpretation of MRI-transections of the extensor apparatus. The medial aponeurosis of the VI, traditionally regarded as an intermuscular septum or space between the VI and VM, does not correspond to the intermuscular plane between these two muscles (Fig. 7). This is due to the double attachment of the VM into the VI aponeurosis (the clip-type double insertion shown in Fig. 2 and Fig. 4). The VM and VI form a functional connection. This interpretation is supported by the innervation pattern of both muscles (Fig. 5). With regard to its innervation, the VI can also be divided into a medial and lateral section.

The functions of the VM can be summarized as follows.
1. The VM is an effective indirect extensor of the knee joint, mainly important during the terminal phase of extension (Pretension).
2. The VM adjusts the length of the quadriceps muscle group and regulates the knee joint during the entire range of motion.
3. VM (together with the VI) represents a dynamic restraint to lateral tracking of the patella.

Most modern anatomy textbooks do not reflect the complex anatomy and interaction between the different muscle components of the quadriceps group. Classical anatomy has defined each muscle as a separate entity with a unique function at the joint it spans, so it is common to view muscles as mechanically independent actuators. As a result, many musculoskeletal models have been developed based on a simplified view of the human quadriceps anatomy. However, in the last decade, the potential of force transmission between synergistic skeletal muscles through connective tissue linkage has been demonstrated.

The interaction between the VM and VI, with its responsibility for the extension of the knee
joint and influence on the patellofemoral function, leads to a ready understanding of common clinical problems found at the knee joint as the body attempts to meet contradictory demands for both mobility and stability. The results of this study have many implications including the understanding and treatment of patellofemoral instability, therapy for knee malfunction or knee stiffness after trauma or surgery, the choice of surgical approach to the femur and knee joint, treatment of the extensor apparatus in knee revision settings and radiological interpretation of MRI-transections of the extensor apparatus.

The present study has few limitations, although one important limitation is that the quadriceps tendon was investigated in embalmed cadaveric specimens from elderly donors. Age-related muscle atrophy may well have distorted some results. In addition, embalmed tissue has been reported to shrink by between 2-12%\(^8\). This could have affected absolute values for variables such as measured distances. Nevertheless, the fundamental architecture of the quadriceps muscle group is likely to have been preserved. Considering the complexity of the extensor apparatus of the knee joint, further investigation of its morphology in healthy young individuals is warranted.

**Conclusion**

Comprehension of the function and architecture of the quadriceps muscle group is strongly linked with an understanding of the anatomy of the VM and VI. VM consists of multiple muscle units inserting into the entire VI aponeurosis. Together, VM and VI build a potential functional muscular complex. From an anatomical point of view, it can be suggested that the VM acts as an indirect extensor of the knee joint, regulating and adjusting the length of the extensor apparatus throughout the entire range of motion. It is of clinical importance that, besides the VM, substantial parts of the VI directly contribute to the medial pull on the patella and help to maintain medial tracking of the patella during knee extension. Surgery or trauma in the antero-medial aspect of the quadriceps muscle group might alter a delicate interplay between the VM and VI, which would affect the extensor apparatus as a whole.
References

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The interaction between the vastus medialis and vastus intermedius and its influence on the extensor apparatus of the knee joint

Fig. 1 Origin and insertion of the vastus medialis. Medial view of the distal two thirds of a left thigh in slight external rotation is shown. The vastus medialis (VM) is lifted from its hammock-like origin (red transparent surface) and medial lip of the linea aspera and medial supracondylar line (long red dotted line). See also the corresponding femur (on the top) with the marked bony origin of the VM. The insertions of the VM into the patella (P), the quadriceps tendon and the vastus intermedius are marked with blue, red and green dotted lines and arrows. Below the lifted VM, the medial surface of the femur is bare of muscle fibres and, therefore, not an attachment site for the VM. This indicates the function of the medial femur as a gliding surface for the contracting VM muscle units (*). The long nerve branch to the VM (single yellow arrow) courses distally along the anteromedial border of the muscle and remains, in contrast to the saphenous nerve (yellow double arrows), lateral to its superficial aponeurosis in a separate fibrotic tunnel. The nerve branch to the VM becomes gradually thinner as it gives up many side branches (thin yellow arrows) to and between the muscle units (*) of the VM. Sections of the nerves are underlined with black paper for better visualisation. The sartorius muscle (S) is transsected showing the underlying femoral artery.
Fig. 2 Anterior and posterior insertion of the vastus medialis into the aponeurosis of the vastus intermedius. A) The distal right thigh proximal to the knee joint is shown. The vastus medialis (VM) is released from its anterior insertion into the vastus intermedius (VI) and rectus femoris (R) freeing the view to the multi-layered quadriceps tendon. The insertions of the VM into the patella (P), the distal tendon of the rectus femoris (R) reflected laterally and the vastus intermedius (VI) are marked with blue, red and green dotted lines and arrows. The green arrows indicate the anterior insertion of the VM (VM anterior) into the aponeurosis of VI. Vastus lateralis (VL) and tensor vastus intermedius (TVI) are also labelled. The fusing points of the different layers of the quadriceps tendon are underlined with black paper for better visualization. The blue headed needle perforates the medial VI aponeurosis (See the exit point of the needle on Figure 2B). 

B) The VM is lifted laterally showing the femoral side of the VI aponeurosis with the posterior inserting VM muscle fibres (green arrow, VM posterior). The medial femur is bare of muscle fibres and not an attachment site for the VM.
**Fig. 3** Insertion of the vastus medialis into the vastus intermedius in relation to the other components and architecture of the extensor apparatus of the knee joint. A cross-section of a right thigh with the extensor apparatus of the knee joint is shown (same specimen as in Figure 2). The vastus medialis (VM) is released from its anterior insertion into the vastus intermedius (VI) and rectus femoris (R), thereby freeing the view to the multi-layered quadriceps tendon. Insertions of the VM into the patella (P), the distal tendon of R (reflected laterally) and the VI are marked with blue, red and green arrows. The VM inserts into the VI aponeurosis on its anterior (VM anterior) and posterior (VM posterior) side. Blue headed needles mark the superficial and deep medial layer of the VI aponeurosis, the tensor vastus intermedius (TVI) and the vastus lateralis (VL). Besides the VM, medial parts of the VI directly contribute to the medial pull on the patella. A corresponding schematic drawing of the three-layered quadriceps tendon is shown at the top right corner.
Fig. 4 Schematic drawing of the interaction between the vastus medialis and vastus intermedius. Schematic drawing of interaction between the vastus medialis (VM) and vastus intermedius (VI). The hammock-like origin (grey) and the fleshy clip-type double insertion (red) of VM into the VI aponeurosis (green) is shown. VM cramps the VI aponeurosis like a clip holding a sheet of paper. The medial surface of the femur is bare of muscle fibres (see also Fig. 1). This indicates the function of the medial femur as a gliding surface for the contracting VM muscle units (red).
Fig. 5 Nerve supply to the extensor apparatus of the knee joint. The anterior view to a left proximal thigh with the nerve supply to the extensor apparatus is shown. For better visualisation of the femoral nerve branches, the sartorius (S) and rectus femoris (R) muscles were transsected and elevated. Some nerve branches are underlined with black paper. The red sticker indicates the middle of the neck of femur on the intertrochanteric line. The vastus medialis (VM) is innervated by the medial division of the femoral nerve; this nerve branch to the VM (yellow arrow) runs along the anteromedial border of the muscle. It separates from the saphenous nerve (double arrow) very proximally. Tensor fasciae lata (T), gluteus medius (G), vastus lateralis (VL) and tensor vastus intermedius (TVI) are also labelled.
Fig. 6 Schematic drawings of the the extensor apparatus of the knee joint. In these schematic drawings the blue, red and green dotted lines indicate the insertion sites of the vastus medialis (VM).

A) As described traditionally in anatomy textbooks and the current literature. Vastus medialis longus (VML) and vastus medialis obliquus (VMO) are labelled.

B) According to the present study, besides the insertion into the patella (P) (blue) and quadriceps tendon (red), the largest insertion expands over the whole length of the vastus intermedius (VI) aponeurosis (green). This insertion has a fleshy double insertion - a strong and large insertion on the anterior side and a weaker insertion on the posterior side (see also Fig. 2, Fig. 3, Fig. 4 and Fig. 7b). Besides the VM, medial parts of the VI insert into the medial aspect of the patella (see also Fig. 3). The VM consists of «multiple muscle units»(*), which are oriented at various angles. Rectus femoris (R), tensor vastus intermedius (TVI) and vastus lateralis (VL) are also labelled.
Fig. 7 MRI cross-section of the extensor apparatus of the knee joint. A) MRI cross-section through the middle third of the right thigh (marked with colour) is shown.

B) The same cross-section as Fig. 7A but marked with colour. The aponeurosis of the vastus intermedius (VI) is labelled green and the tensor vastus intermedius (TVI) blue. Vastus lateralis (VL) is also labelled. Vastus medialis (VM) inserts into the VI aponeurosis (green) on its anterior and posterior side (*), but also into the rectus femoris muscle (R). The thick red dotted line corresponds to the hammock-like origin of the medial intermuscular septum and medial lip of the linea aspera (red dot). The red arrows indicate the direction of VM pull on the longitudinal components of the extensor apparatus of the knee joint (from anterior, lateral and distal to medial, dorsal and proximal).
The interaction between the Vastus Medialis and Vastus Intermedialis and its influence on the extensor apparatus of the knee joint.
Fig. 8 Hypothetic simplified functional model of the extensor apparatus of the knee joint based on the present anatomical findings.

A) In a simplified example, the extensor apparatus of the knee joint works like the conventional brake of a bicycle.

B) Unlike braking, however, the action of the extensor apparatus of the knee joint leads to extension of the knee joint.

C) A side pull (red arrow) on the longitudinal cord, that connects the braking handle with brake shoes, would lead to a pretension of the pulling mechanism and consequently to a more efficient braking action. In other words, the braking action can be controlled by the side pull (red arrow) on the cord.

With regard to the extensor mechanism of the knee joint, this control function is adopted by the vastus medialis (VM) muscle. Due to its medial and dorsal pull (red arrow) on the longitudinal components of the quadriceps muscle group, the VM influences the length, effectiveness and power of the extensor apparatus of the knee joint. This shortening of the quadriceps muscle group is most important during the terminal range of extension (Fig.8-C). Thus the VM regulates the extensor apparatus during the entire range of knee joint motion.
SUMMARY

PART I: Surgical exposure of the hip joint and femur

Recent attention in THA has focused on minimally invasive techniques and their short-term outcomes. Early reports on patient outcome seemed to favour MIS techniques, whereas later reports cautioned against their wide utilization due to increased complications related to femur fractures, implant failures and muscle trauma. These complications may require an extension of the surgical approach. Distal extension of the anterior approach by splitting the interval between the rectus femoris and the VL has been described as being “unproblematic”. Some surgeons favour the distal extension of direct anterior approach even in complex revisions.

The study “Distal extension of the direct anterior approach to the hip poses risk to neurovascular structures: an anatomical study” (Paper 1) demonstrates that carrying out this extension without substantially damaging the lateral portions of the quadriceps muscles is challenging. Neurovascular structures lateral to the incision are endangered directly, affecting the quadriceps muscle group (i.e. VL and lateral portions of the VI). The anterior access is also not ideal for the introduction of a cerclage cable passer at the proximal part of the femur, for example in the treatment of an intraoperative fissure or fracture. The direct anterior approach to the hip joint is best suited for interventions proximal to the intertrochanteric line. As a result of the findings of this study, some textbooks for surgical approaches in Orthopaedic surgery need revision.

The anterior approach remains a standard approach not only for THA but also for paediatric hip surgery. Proximal enlargement is necessary for the treatment of developmental hip dysplasia and to expose the anterolateral aspect of the acetabulum in hip revisions. The anterior approach to the hip joint is the only approach that takes advantage of a so called “internervous plane” (sartorius muscle innervated by the femoral nerve and tensor fasciae latae muscle by the superior gluteal nerve). Therefore, this approach has been considered as muscle saving and advantageous.

The study “Potential Risk to the Superior Gluteal Nerve During the Anterior Approach to the Hip Joint: An Anatomical Study “ (Paper 2) revealed that the anterior approach, while protecting the nerve branches to the gluteus medius and minimus, can affect the innervation of the tensor fasciae latae muscle by the superior gluteal nerve. The importance of preventing injury to the terminal branch of the superior gluteal nerve has been emphasized. Insufficient exposure of the femur during hip replacement might lead to direct damage to the tensor fasciae latae muscle including its motor
For the first time the detailed course of the nerve branch to the tensor fasciae latae muscle, in relation to the ascending branch of the lateral circumflex femoral artery, a reliable landmark during surgery, has been documented. Therefore, the study provides important information to the surgeon on how the superior gluteal and, consequently, tensor fascial latae can be protected during the anterior approach to the hip joint.

Despite the soft tissue-preserving nature of the anterior approach, there is a great danger of damaging the lateral femoral cutaneous nerve; the literature shows diverse rates of injury to the lateral femoral cutaneous nerve of between 0.1% and 81%. Anatomical textbooks do not describe the exact distribution pattern of the lateral femoral cutaneous nerve distal to the superior iliac spine or in the proximal aspect of the anterolateral thigh region, respectively. In other words, there is a lack of detailed information about the distribution and variation in the course of the lateral femoral cutaneous nerve in the proximal aspect of the thigh, the region in which the anterior approach to the hip joint is performed.

The study “The Anatomical Course of the Lateral Femoral Cutaneous Nerve with Special Attention to the Anterior Approach to the Hip Joint” (Paper 3) is the first study that describes the course of this nerve in the proximal aspect of the thigh with respect to the anterior approach to the hip joint. The study provides guidance on how the lateral femoral cutaneous nerve can be protected during surgery. The results of this study suggest that, in approximately one-third of patients in whom an anterior approach to the hip joint is used, certain injury to the lateral femoral cutaneous nerve cannot be avoided. Patients undergoing this approach should, therefore, be informed of the risk.

In contrast to the anterior approach to the hip joint the anterolateral and lateral approaches detach the gluteus medius and minimus insertion from the greater trochanter. If this technique is not performed properly this might be associated with abductor dysfunction and posterior limp. In 2004 the VL muscle as a functional flap was introduced. It was believed that either advancement or rotational transfer of the VL muscle could be used to bridge a discontinuity between the remaining gluteus medius and the proximal femur and that the VL could act as a substitute for lost abductor muscle function. Since 2004, this technique has been performed many times.

When shifting the VL muscle as a functional flap, one has to protect its vascularization as well as its innervation. The study “Limitations of the Vastus Lateralis Muscle as a Substitute for Lost Abductor Muscle Function: An Anatomical Study” (Paper 4) revealed that innervation pattern of the VL and VI muscles exclude a VL muscle transfer without damage to nerve branches of
the lateral components of the quadriceps muscle group. Based on this study, one might question whether it is justified to perform a proximal transfer of the VL for reconstruction of the abductor function. The study above, together with the study “Distal extension of the direct anterior approach to the hip poses risk to neurovascular structures: an anatomical study” (Paper 1) provide fundamental information about the innervation of the different components of the quadriceps muscle group. As a result of the dissections of the innervation of the quadriceps muscle group the TVI muscle was found (see also PART II).

With the lateral approach to the femur, the vessels that perforate the lateral intermuscular septum (LISP-vessels) and the lateral components of the quadriceps muscle group must be ligated. To date, the effect on the blood supply to the femur remained unclear. The study “Effects of ligation of lateral intermuscular septum perforating vessels on blood supply to the femur” (Paper 5) answered this question. The first time, the anatomy of the LISP-vessels and their multiple anastomoses around the femur has been documented. The study revealed that the entire femur is surrounded by a rich and structured network of longitudinal (vertical) and circular (horizontal) running anastomoses on four levels: 1. Direct anastomosis; 2. Periosteal anastomosis; 3. Muscular anastomosis; and 4. Anastomosis on the level of fascia, subcutaneous layer and skin.

PART II: Architecture and function of the quadriceps muscle group

Thanks to the investigations in PART I, the author also focused interest on the architecture and function of the quadriceps muscle group as whole. The quadriceps femoris is traditionally described as a muscle group composed of the rectus femoris and the three vasti (VL, VI and VM), which arise independently and blend into the common quadriceps tendon. Modern anatomy textbooks do not reflect the complex anatomy and interaction between the different muscle components. Classical anatomy has defined each muscle as a separate entity with a unique function at the joint it spans.

In the study “A newly discovered muscle: The tensor of the vastus intermedius” (Paper 6) an intervening muscle, between the VL and VI – named the tensor vastus intermedius - has been described. Depending on the relation to the adjacent VL and VI muscles, different morphological types of TVI were identified. As the TVI was previously attributed to other parts of the quadriceps muscle group, its role in the organization of the quadriceps tendon was unknown. The possibility of a separate intermediate muscle arising proximally between the bellies of the VL and the VI and inserting separately at the medial aspect of the patellar base
has not previously been explored. In view of its course from the anterolateral aspect of the greater trochanter to the medial base of the patella, the TVI appears to be significant in controlling the motion of the patella. Its fibers entering the middle layer of the quadriceps tendon from the oblique lateral aspect counteract the forces of the medial fibers of VM. The steering function of this muscle is also suggested by its rich innervation.

The isolated rupture of the TVI as presented in a case report “Knee Pain Associated with Rupture of Tensor Vastus Intermedius, a Newly Discovered Muscle: A Case Report” (Paper 7) further supports the finding, that the TVI is a distinct anatomical structure independent of the adjacent vasti. However, further research is needed to establish its exact function and clinical relevance.

The TVI fulfils all criteria for an independent muscle: 1. it is innervated by independent branches of the femoral nerve; 2. it is vascularized through separate muscle branches; and 3. it has a defined origin at the anterior aspect of the greater trochanter and inserts in the middle layer of the quadriceps tendon at the medial patellar base. Despite its variable connections with the adjacent muscles and variable volume of its muscle belly in the proximal aspect of the thigh, the TVI can be clearly distinguished in the distal aspect.

The insertion of the quadriceps femoris into the patella is traditionally described as a common tendon with a tri-laminar arrangement, with the most superficial fibers originating from the rectus femoris, the deepest layer from the VI and the intermediate layer from the VL and VM. Other studies have suggested that the quadriceps tendon anatomy is more variable with a two- to four-layered, or even more complex organisation, often with unequal contributions from its tendinous constituents. Considering the components of the quadriceps muscle group, the published variability of the tendon composition seems surprising. As the TVI was previously attributed to the VL, its role in the organization of the quadriceps tendon was unknown. This gave reason to further investigate the multi-layered structure of the quadriceps tendon with special emphasis on all components of the extensor apparatus including the newly discovered TVI. The study “New insight in the architecture of the quadriceps tendon” (Paper 8) revealed a complex, but constant, onion-like architecture of a three-layered quadriceps tendon which is formed by six elements. These are:

- lateral aponeurosis of the VI,
- deep and superficial medial aponeurosis of the VI,
- VL,
- TVI, and
- rectus femoris.
These elements of the extensor apparatus join each other proximal to the patella in a complex onion-like architecture. Its two-layered intermediate layer shows variable fusions points. The VM contributes to the quadriceps tendon with its medial insertion into all layers of the quadriceps tendon.

Modern anatomy textbooks do not reflect the complex anatomy and interaction between the different muscle components. Classical anatomy has defined each muscle as a separate entity with a unique function at the joint it spans. It is common to view muscles as mechanically independent actuators. As a result, many musculoskeletal models have been developed based on a simplified view of the human quadriceps anatomy. However, in the last decade, the potential of force transmission between synergistic skeletal muscles through connective tissue linkage has been demonstrated.

The investigation about “The interaction between the vastus medialis and vastus intermedius and its implication on the function of the extensor apparatus of the knee joint. An anatomical investigation” (Paper 9) focused on the function of the quadriceps muscle group as a whole. Like the other vasti the VM and VI are part of the extensor apparatus of the knee joint. Both muscles are situated close to each other on the anterior and medial aspect of the femur. The VM and VI work together with the other components to produce knee extension torque when knee joint action is performed. However, anatomical properties such as muscle volume, origin of the muscle and fiber type composition seem to be inconsistent among the components of this muscle group. These variations may be attributed to different functional roles or contributions among synergists of the extensor apparatus of the knee joint.

During the dissections, the author observed that the interaction between the VM and VI is more complex and intricate than was initially described. Dissections of the quadriceps muscles also revealed different morphological findings between the VM and VI compared to classic descriptions in the literature. The last study for my PhD thesis investigated the anatomical connection between the VM and VI, their innervations, origins, insertions, and contributions to the function of the extensor apparatus of the knee joint. Based on these findings a simplified mechanical model of the function of the quadriceps muscle group has been developed (see also the video clip added to the appendix).
Appendix A. Ongoing Projects and Papers

Several papers that extend the work outlined in this thesis are currently in preparation for peer review and publication, but are not included in this monograph for examination. These papers are outlined here for the interest of the reader.

1. **Potential risk to the nerve supply of the vastus medialis during the medial subvastus approach to the distal femur**
   Masters thesis by a medical student in the Department of Anatomy, University of Zürich, Switzerland supervised by Karl Grob

Surgical treatment options for distal femur fractures include intramedullary nailing or plating using a lateral subvastus approach. There have been many reports on the good results achieved with minimally invasive plate osteosynthesis in distal femur fractures. In some cases medial plating has been recommended in some fractures such as severely comminuted fractures and periprosthetic fractures for additional stability, or in those for which use of a lateral plate or nail is not appropriate. Electively, the medial subvastus approach is used to perform supracondylar varus osteotomy of the femur to correct a valgus deformity.

There are only a few reports on the medial subvastus approach, and these have discussed the clinical limitations of this approach with respect to the potential risk for the major vessels. However, preliminary dissections of the VM and its nerve supply revealed that it might be difficult to protect its terminal nerve branches (see Paper 9 - Fig. 9). This would result in a partial denervation of the distal muscle units of the VM, which represents a dynamic restraint to lateral tracking of the patella. The purpose of this study was to evaluated the nerve supply to the VM muscle and its potential risk for injury during the medial subvastus approach to the femur.

2. **MR imaging of the tensor vastus intermedius. A study on the basis of an anatomical dissection**
   Principal investigator: Karl Grob

MR imaging has become widely accepted as the imaging technique of choice for evaluating acute musculotendinous injuries, allowing accurate evaluation of both normal anatomy and pathology of virtually any muscle and tendon. The purposes of this study were: (a) to dissect and evaluate the anatomy of the lateral extensor apparatus of the knee joint in a specimen where an independent TVI has been found, with special emphasis on the conjunction between the TVI, VI and VL; and (b) to document the corresponding TVI anatomy on MR imaging. MR images were analyzed from a cadaveric lower leg where the TVI muscle, as part of the extensor apparatus of the knee joint, had been dissected (see Paper 9 - Fig. 10).
3. **The appearance of the tensor vastus intermedius muscle in primates**  
   Principal investigator: Karl Grob

The objective of this study was to evaluate whether the TVI also exists in other primates. Cadaveric legs of two hylobates lar, one orangutan, one chimpanzee, one ceropithecus aethiops and one macaque were dissected. The anatomy of the quadriceps muscle group, with special attention to potential intervening muscle bellies between the VL and VI, were investigated (see Paper 9 - Figs. 11 and 12).

4. **The articularis genus muscle revisited. An anatomical study with special emphasis on its interaction with the vastus intermedius and vastus medialis**  
   Principal investigator: Karl Grob

The anatomy of the articularis genus (AG) muscle has prompted speculation that it elevates the suprapatellar bursa during extension of the knee joint and prevents impingement of the synovial membrane between the patella and the femur. However, architectural parameters of the AG such as the cross-sectional area and the pennation angle indicate that it is not capable of generating enough force to fulfil this function. The purpose of this study was to further investigate the anatomy of the AG with special emphasis on its interaction with the adjacent muscles, VI and VM. The AG muscle was investigated in 18 human cadaveric lower limbs. The mode of origin and insertion of the AG, its nerve supply and specifically its connections with the VI and VM were studied.

5. **The interaction between the vastus lateralis and rectus femoris and its influence on the extensor apparatus of the knee joint. An anatomical investigation**  
   Masters thesis by a medical student in the Departments of Anatomy at the Universities of Fribourg and Zürich, Switzerland supervised by Karl Grob

The VL and rectus femoris muscles are part of the extensor apparatus of the knee joint. Both muscles work together with the other components of the quadriceps muscle group to produce knee extension torque when knee joint action is performed. Although the VL and rectus femoris course adjacent to each other, there is a lack of data regarding their functional relationship or interaction. Interestingly, there is a section of up to 10-14 cm in the distal half of the extensor apparatus where the rectus femoris is held medially on dens aponeurotic track formed by the VL (see Paper 9 - Fig. 13). From an anatomical point of view, it could be concluded that besides the medial pull-mechanism (see also paper 9), a lateral push-mechanism also exists. The latter could be further divided into a superficial push-mechanism (between the VL and rectus femoris) and a deep push-mechanism (between the TVI and VI). The purpose of this study is to further investigate the anatomical and histological interaction between the VL and rectus femoris.
Appendix B. Video Clip

Video Clip added electronically:
“Simplified functional model of the extensor apparatus of the knee joint” based on the study:
“The interaction between the vastus medialis and vastus intermedius and its influence on the
extensor apparatus of the knee joint. An anatomical investigation”. 