Motor Control of the Knee
Kinematic and EMG studies of healthy individuals and people with patellofemoral pain

Ann-Katrin Stensdotter

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In memory of

Professor H.T.A. (John) Whiting
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PAPER I – IV

Dissertations written by physiotherapists, Umeå University 1989-2005
ABSTRACT

Motor Control of the Knee
Kinematic and EMG studies of healthy individuals and people with patellofemoral pain

Patellofemoral pain (PFP) is believed to be associated with deficits in coordination between the different heads of the quadriceps muscle; however, considerable debate exists in the literature regarding the presence of such a deficit. Discrepancies between studies may be explained by differences in experimental tasks, such as whether the task is performed with open (OKC) or closed kinetic chain (CKC), or whether the activity is voluntary or triggered. Particular interest has been directed toward the function of the vastus medialis obliquus (VMO), which is a short muscle with limited ability to exert torque across the knee joint, but probably has a particular role in controlling patellofemoral joint position. Another short muscle that may influence knee joint position control is popliteus (POP), which is located in the back of the knee.

This thesis investigates task specific activity of quadriceps in CKC versus OKC and studies the relative activity between the four heads of the quadriceps in PFP subjects compared to controls without knee pain in voluntary activity (CKC and OKC) and postural responses to balance perturbations. In addition, this thesis investigates the presumed function of POP for control of joint position in postural tasks in healthy individuals.

All subjects were of normal weight and height and between 18 and 40 years. Quadriceps activity was tested for isometric with identical joint configuration in CKC and OKC, and it was performed as a reaction time task. Balance perturbations were elicited by unpredictable anterior and posterior translations of the support surface. Function of POP was investigated in unpredictable support surface translations and in self induced provocations to balance by moving the arms. Muscle activity was recorded with electromyography (EMG). Optic kinematic analysis was used to obtain specific movement responses to perturbations of balance.

The quadriceps muscles were activated differently in CKC and OKC. VMO was activated earlier and to a greater degree in CKC. Rectus femoris was activated earlier and to a greater degree in OKC. PFP subjects reacted slower in both CKC and OKC, but there was no difference between groups in the relative activity between the different heads of the quadriceps. In the unpredictable support surface translation in the anterior direction, PFP subjects responded with earlier onset of VMO and with greater trunk and hip flexion in the anterior translation. POP activation in response to support surface translations in both directions occurred before all other muscles measured. In the self-initiated provocations of balance, POP was activated after the initiation of the balance provocation.

This thesis concludes that quadriceps activity was task specific. The lack of difference between groups in OKC and CKC, and the difference between groups in postural responses suggest that variations in motor behaviour may occur only in tasks habitually performed. Differences in muscle activation patterns may be related to compensatory strategies to unload the quadriceps muscles and the patellofemoral joint. Furthermore, this thesis suggests that POP muscle may have a particular role in active control of the knee joint.

Keywords: Kinematics; Kinetic chain tasks; Knee; Motor Control; Muscle activity; Patellofemoral pain; Unpredictable perturbations
SVENSK SAMMANFATTNING

Motorisk kontroll av knäleden
Kinematik och EMG studier av friska individer och individer med patellofemoral smärta

Det antas finnas ett samband mellan främre knäsmärta, sk. patellofemoral smärta (PFP) och brister i koordination mellan de olika delarna av den stora lärmuskeln, quadriceps. Det är dock omdelbar huruvida detta är fallet. Studiers olika resultat kan kanske förklaras med skillnader i den experimentella uppställningen, om exempelvis muskelaktiviteten sker i slutet (CKC) eller öppen (OKC) ledkeda, eller om aktiviteten är egeninitierad/viljemässig eller utfört av påverkan utifrån. Speciellt intresse har riktats mot funktionen i vastus medialis obliquus (VMO), som är en kort muskel med begränsad förmåga att utverka vridmoment över knäleden, men som sannolikt har en särskild uppgift att kontrollera knäledens position. En annan kort muskel som kan ha betydelse för kontroll av knäledens position är popliteus (POP) som är belägen bakåt i knäet.

Syftet med denna avhandling var att undersöka uppgiftsspecifik muskelaktivitet i quadriceps i CKC jämfört med OKC och att studera aktiviteten i de olika bukarna av quadriceps hos personer med PFP jämfört med personer utan knäsmärta vid viljemässig aktivitet (CKC och OKC), samt vid postural respons vid balansstörningar. Syftet var vidare att undersöka den specifika funktionen hos POP för kontroll av knäledens position.


Quadriceps aktiverades olika vid CKC och OKC. VMO aktiverades tidigare och i högre grad i CKC. Rectus femoris, den centrala delen av lärmuskeln aktiverades tidigare och i större grad vid OKC. Personer med PFP reagerade långsammare i både CKC och OKC, men det var ingen skillnad mellan grupperna i aktiveringens mel i quadriceps olika delar. I den oväntade balansstörningen i riktning framåt, svarade personer med PFP med en tidigare aktivering av VMO och större framåtbojning av överkroppen och i höftleden. POP aktiverades före alla andra uppmätta musklar vid både främre och bakre glidning av underlaget. Som svar på störning av balansen som personen själv åstadkom aktiverades POP efter initiering av balansstörningen.

Aktivitet i quadriceps är uppgiftsspezifik. Avsaknaden av skillnad mellan grupperna i CKC och OKC och skillnaden mellan grupper som svar på balansstörning kan tolkas som att variationer i motoriken endast uppstår vid aktiviteter som ofta upprepas i vardagen. Skillnader i muskelaktiveringssmönster kan vara relaterade till kompensatoriska strategier för att avlasta quadricepsmusklerna och den patellofemorala leden. Vidare konkluderar denna avhandling att POP sannolikt har en särskild funktion för kontroll av knäledens position.
**ABBREVIATIONS**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-D</td>
<td>three dimensional</td>
</tr>
<tr>
<td>AT</td>
<td>anterior translation</td>
</tr>
<tr>
<td>BF</td>
<td>biceps femoris</td>
</tr>
<tr>
<td>CKC</td>
<td>closed kinetic chain</td>
</tr>
<tr>
<td>COM</td>
<td>center of mass</td>
</tr>
<tr>
<td>DA</td>
<td>deltiodeus anterior</td>
</tr>
<tr>
<td>EMD</td>
<td>electromechanical delay</td>
</tr>
<tr>
<td>EMG</td>
<td>electromyography</td>
</tr>
<tr>
<td>GM</td>
<td>gastrocnemius medialis</td>
</tr>
<tr>
<td>MVC</td>
<td>maximum voluntary contraction</td>
</tr>
<tr>
<td>n</td>
<td>number of</td>
</tr>
<tr>
<td>OKC</td>
<td>open kinetic chain</td>
</tr>
<tr>
<td>PFP</td>
<td>patellofemoral pain</td>
</tr>
<tr>
<td>PJRF</td>
<td>patellofemoral reaction forces</td>
</tr>
<tr>
<td>POP</td>
<td>popliteus</td>
</tr>
<tr>
<td>PT</td>
<td>posterior translation</td>
</tr>
<tr>
<td>RMS</td>
<td>root mean square</td>
</tr>
<tr>
<td>RF</td>
<td>rectus femoris</td>
</tr>
<tr>
<td>RT</td>
<td>reaction time task</td>
</tr>
<tr>
<td>SD</td>
<td>standard deviation</td>
</tr>
<tr>
<td>SEM</td>
<td>standard error mean</td>
</tr>
<tr>
<td>TA</td>
<td>tibialis anterior</td>
</tr>
<tr>
<td>VL</td>
<td>vastus lateralis</td>
</tr>
<tr>
<td>VML</td>
<td>vastus lateralis longus</td>
</tr>
<tr>
<td>VMO</td>
<td>vastus medialis obliquus</td>
</tr>
<tr>
<td>Q-angle</td>
<td>quadriceps angle</td>
</tr>
</tbody>
</table>
ORIGINAl PAPERS

This thesis is based on the following papers and are referred to by their Roman numerals:


II Stensdotter AK, Hodges PW, Öhberg F, Häger-Ross C. Quadriceps EMG in open and closed kinetic chain in women with patellofemoral pain. In manuscript.

III Stensdotter AK, Grip H, Hodges PW, Häger-Ross C. Quadriceps activity and movement reactions in response to unpredictable sagittal support-surface translations in women with patellofemoral pain. In manuscript.

IV Stensdotter AK, Holmgren C, Dalén T, Häger-Ross C. The role of m. popliteus in unpredictable and in self-initiated balance provocations. Accepted for publication August 10, 2005 in Journal of Orthopaedic Research, predicted publication 24(3) or 24(4) 2006.

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INTRODUCTION

This thesis is written with regard to muscle coordination and task specific function with special attention paid to the control of joint position. To investigate this problem, a model was needed on which to apply the hypothesis. For this, the knee was chosen. Certain muscles around the knee are believed to be particularly concerned with control of joint position. Task specific activation of these muscles was investigated in healthy subjects. In order to examine task specific muscle coordination and how it was associated with joint pain, persons with patellofemoral joint complaints were (in addition to healthy individuals) included in the study. The reason behind the choice was that joint pain with unknown etiology is a common complaint among patients who are referred to a physiotherapist and that these problems appear to be associated with changes in muscle function that are often treated with exercise intervention.

The need for evidence based knowledge

A main issue in physiotherapy is movement. Various concerns associated with movement and movement disorders challenges the physiotherapy profession, and the intervention method is often itself associated with movement in some form of physical activity. In some cases, the physical activity intervention is rather general, whereas other circumstances may require more specific exercise. In order to aim a specific exercise, a target has to be defined. That is, this question must be asked: What mechanisms do the exercises affect? As long as the target remains undefined or obscure, several exercises and other intervention methods are often used to ensure a positive outcome. In order to justify the methods used in the physiotherapy profession and cater to the patient, an evidence-based approach is needed. An evidence-based study means that the efficacy of the intervention is scientifically proven. The outcome, however, of such intervention can be explained in terms of a multitude of underlying mechanisms, but the specific knowledge of the effective agent(s) often eludes the investigator. In order to understand the efficacy of a particular intervention method, the character and underlying mechanisms of the assessed problem needs to be known.
Musculo-skeletal pain that apparently is neither caused by trauma nor by diagnosed pathology is a common complaint. Many of these complaints are related to the musculoskeletal system and often to a joint. Whereas the etiology may reside in any number of unknown factors, the answer is often sought in biomechanical explanations since pain often appears to be triggered in association with loading. For a joint to withstand the forces it is exposed to, proper loading conditions needs to be secured. This requires control of position both in maintaining and in changing joint configuration. This is secured by passive and active factors. The passive factors consist of bone and cartilage that decides the congruence of the joint surfaces. Ligaments and capsule provide passive support for the joint. Muscles actively control both position and movement by exerting force across the joint. For proper sensory-motor control of the joint, the central nervous system needs sensory information. This is provided by muscle spindles and Golgi tendon organs that convey impulses from the muscle-tendon unit. In addition, proprioception is provided by receptors within the joint capsule, ligaments, and skin. Input from vestibular and visual sources provides additional information.

Musculo-skeletal problems are often characterized by complicated combinations of symptoms and clinical findings, which give rise to a multifactorial explanation. One such problem is patellofemoral pain (PFP). This thesis addresses muscle coordination, which has become one of the key factors believed to be associated with PFP. In order to develop a better understanding of the issue of muscle coordination in PFP, the muscle activity will be described in a context with regard to task specific conditions.

Short muscles are biomechanically suited for joint control purpose, which is a main issue in the studies on PFP, where vastus medialis obliquus (VMO) has drawn special attention. Therefore, the studies on muscle coordination will therefore have particular focus on that muscle. Of particular interest with regard to the role of short muscles for knee joint control is also the normal function popliteus muscle (POP).
Patellofemoral pain

Definition of patellofemoral pain

In this thesis I have chosen to use the term PFP (which only refers to the symptom and which states that there is pain in the patellofemoral joint) without reference to pathology or etiology. Other names one may find in the literature are patellofemoral pain syndrome (PFPS), anterior knee pain, patellar pain, patellofemoral arthralgia, or chondromalacia patella. Chondromalacia patella was used for a while, because the pain was believed to originate from pathological changes in the retro patellar cartilage (Aleman 1928). Later, it was discovered that there were more often than not an absence of pathological changes to the retro patellar cartilage (Kelly and Insall 1992). Although a number of suggestions with regard to the pathology or etiology of PFP has been made (cf. Juhn 1999), the literature provides little consensus in the matter. This is probably why no consistent term is used.

Prevalence and characteristics

Pain from the patellofemoral joint is the most common type of knee pain without known previous injury or disease (Grabiner et al. 1994), and it is most frequently observed in young physically active females (Almeida et al.1999). Ten percent of young boys and girls complain about pain in the patellofemoral joint, and by age twenty almost half of them have stopped being physically active (Fairbank et al. 1984). Six percent are affected in their working life (Blond & Hansen 1998). A reduced activity level (Thomeé et al. 1995a) or a compensatory movement pattern aimed to unload and protect the painful knee (Brecher and Powers 2002) may occur and less reliance may be placed on that limb. Weakness and wasting of the muscles of the affected limb—in particular the quadriceps—is often the found (cf. Thomeé et al. 1995b).

Patellofemoral pain is characterized by an insidious onset of pain, which is not explained by trauma or diagnosed pathology. The symptoms are characterized by intermittent periods of pain triggered by conditions that increase the compression in the joint (Insall et al. 1982) such as long term sitting with the knees in flexion (Percy and Strother 1985), running, negotiating stairs, and squatting (Devereaux and Lachmann 1984; Jacobson
and Flandry 1989). The magnitude of increased compression that the joint is subjected to during normal activity does not hurt the healthy knee. Pain caused from normal activity suggests that the PFP-joint is excessively sensitive to stress (Biedert and Gruhl 1997), presumably due to unfavorable loading conditions. This, in turn, could be caused by anatomical mal-alignment (Elias et al. 2004; Jones et al. 1995a; Witonski & Goraj 1999) and/or muscular imbalance (Cowan et al. 2001, 2002b; Taskiran 1998).

**Anatomical features**

Anatomical mal-alignment is most often referred to in terms of an excessively large quadriceps angle (q-angle) because a large q-angle indicates increased lateral pull on the patella (Elias et al. 2004). The angle is measured between a line from the superior anterior iliac spine to the center of the patella and a line form the center of patella to the tibial tuberosity (Fig. 1). A great q-angle is often associated with increased valgus of the knee because the valgus position will move the tibial tuberosity laterally. However, a large q-angle can be present in the absence of excessive valgus caused from outward tibial rotation (Sanfridsson et al. 2001) or a laterally placed tibial tuberosity (Jones et al. 1995a).

Another typical feature that is recognized is excessive hyperextension of the knee (Thomeé et al. 1995a). Habitual loading of the knee in hyper extended position presumably obviates the use of quadriceps activity in quiet stance, and reliance rests instead on the passive components. However, a number of studies have failed to demonstrate any significant differences in anthropometric measures between persons with PFP and individuals without knee pain (e.g. Thomeé et al. 1999). Thus, the literature does not
provide a consensus with regard to these variables. A third cause of mal-
alignment, which is difficult to detect clinically, is incongruence in the
patellofemoral interface. Only computed tomography or magnetic
resonance imaging may yield high enough quality pictures and has
confirmed lateral tracking and tilt of the patella in persons with PFP (e.g.
Grabiner et al. 1994; Dupuy et al. 1997). One cause of lateral tracking of the
patella that resides in the patellofemoral interface is a shallow trochlea and
flattened lateral condyle (Senavongs and Amis 2005).

*Muscle activity*

It is suggested that failure to properly activate the quadriceps leads to
decreased or erroneous control the knee joint position (Taskiran et al. 1998;
Witonski and Goraj 1999). The effects of the spatial and temporal
components of dys-coordination have been demonstrated in biomechanical
models. Temporal dys-coordination of a merely 5 ms delay of the medial
aspect (vastus medialis obliquus (VMO)) of the quadriceps relative to the
lateral aspect (vastus lateralis (VL)) results in lateral patellar tracking
(Neptune et al. 2000). Similarly, patellar lateralization occurs as an effect of
spatial dys-coordination where the force production in the medial aspect of
the quadriceps is decreased relative to the lateral aspect (Sakai et al. 2000).
Failure to properly activate the quadriceps will probably influence patellar
tracking in the presence of anatomical mal-alignment as well as in the
absence thereof. Evidence that dys-coordination of the quadriceps is
associated with PFP has been shown in several studies. Electromyography
(EMG) is a method that records the electrical activity in the muscle and has
been used to determine onset of muscle activity and the degree to which the
muscle is active, i.e., the amplitude of activity. Decreased activity in VMO
relative to VL has been shown both in functional daily living tasks such as
negotiating stairs (Souza & Gross 1991), and other voluntary, but less
functional activities such as open (Boucher et al. 1992; Souza & Gross
1991) and closed kinetic chain tasks (Taskiran et al. 1998, Table 1).
Evidence of delayed activity in VMO relative to VL has been shown in
negotiating stairs (Cowan et al. 2001), in a toe rise task (Cowan et al. 2002b),
and in the quadriceps stretch reflex triggered by patellar tendon tap (Voight
et al. 1991; Witvrouw et al. 1996, Table 2). The reflex studies are, however,
subject to discussion due to the remarkably short reflex latencies reported
(as short as 2 ms, Voight et al. 1991), as well as short onset time differences
between muscles (∼ 5 ms, Witvrouw et al. 1996) that are within the margin of anatomical variation (DeLuca 1997). The reflex latency for the patellar reflex (nerve conduction velocity 72-120ms⁻¹) is measured to ∼ 20-30 ms (Brodal 2004, Frijs et al. 1997). In this perspective, a 5 ms delay is substantial, but due to technical reasons, the validity of such measures may be questioned.

However, evidence of temporal and spatial deficits in VMO activation is not found in all studies. A number of studies have not been able to demonstrate any differences between individuals with and without PFP. Tables 1 and 2 give an overview of the studies done on PFP to establish the order of EMG onset and/or EMG amplitude of activity in the different heads of the quadriceps muscles. The variations between studies in terms of differences between test protocols, the application of EMG, EMG signal analysis, and potential differences between subjects, as well as the authors own interpretation of results make comparison between studies difficult.
## Table 1. Studies on quadriceps EMG amplitude in persons with PFP

<table>
<thead>
<tr>
<th>Authors</th>
<th>Participants</th>
<th>Task</th>
<th>Variable</th>
<th>Type of contraction</th>
<th>Initiation</th>
<th>Muscle task</th>
<th>VMO deficit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Souza &amp; Gross</td>
<td>9 PFP 7</td>
<td>Knee extension, OKC, stair walking</td>
<td>Ratio VMO/VL</td>
<td>Maximal and sub maximal isometric and dynamic (concentric and eccentric) contraction</td>
<td>Voluntary</td>
<td>Prime mover</td>
<td>Yes</td>
</tr>
<tr>
<td>et al. (1991)</td>
<td>controls</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Taskiran et al.</td>
<td>10 (12 knees)</td>
<td>Knee extension (0, 15, 30, 45°) OKC</td>
<td>Ratio VMO/VL</td>
<td>Maximal dynamic contraction</td>
<td>Voluntary</td>
<td>Prime mover</td>
<td>Yes</td>
</tr>
<tr>
<td>et al. (1991)</td>
<td>8 (12 knees)</td>
<td>instability 9 (16 knees) controls</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Boucher et al.</td>
<td>18 PFP</td>
<td>Knee extension, OKC</td>
<td>Ratio VMO/VL</td>
<td>Maximal isometric contraction</td>
<td>Voluntary</td>
<td>Prime mover</td>
<td>Yes</td>
</tr>
<tr>
<td>et al. (1992)</td>
<td>controls</td>
<td></td>
<td></td>
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<tr>
<td>Cerny et al.</td>
<td>10 PFP 21</td>
<td>Knee extension, OKC. Stance and &quot;wall slide&quot;</td>
<td>Ratio VMO/VL</td>
<td>Sub maximal and dynamic (0-30°) isometric (15, 45, 60°) in OKC. Dynamic (0-45°)</td>
<td>Voluntary</td>
<td>Prime mover</td>
<td>No</td>
</tr>
<tr>
<td>et al. (1995)</td>
<td>controls</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Sheehy et al.</td>
<td>13 PFP 15</td>
<td>Ascending and descending stairs</td>
<td>Ratio VMO/VL</td>
<td>Dynamic concentric and eccentric</td>
<td>Voluntary</td>
<td>Prime mover and postural</td>
<td>No</td>
</tr>
<tr>
<td>et al. (1998)</td>
<td>controls</td>
<td></td>
<td></td>
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<tr>
<td>Tang et al.</td>
<td>10 PFP 10</td>
<td>Knee extension, OKC. Squats</td>
<td>Ratio VMO/VL</td>
<td>Dynamic concentric and eccentric</td>
<td>Voluntary</td>
<td>Prime mover</td>
<td>No</td>
</tr>
<tr>
<td>et al. (2001)</td>
<td>controls</td>
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<tr>
<td>Owings et al.</td>
<td>20 PFP 14</td>
<td>Knee extension (80-60°).OKC</td>
<td>Ratio VMO and VL amplitude</td>
<td>Dynamic</td>
<td>Voluntary</td>
<td>Prime mover</td>
<td>No</td>
</tr>
<tr>
<td>et al. (2002)</td>
<td>controls</td>
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</table>
Table 2. Studies on quadriceps EMG onset in persons with PFP

<table>
<thead>
<tr>
<th>Authors</th>
<th>Participant s</th>
<th>Task</th>
<th>Variable</th>
<th>Type of contraction</th>
<th>Initiation</th>
<th>Muscle task</th>
<th>VMO deficit</th>
</tr>
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<tbody>
<tr>
<td>Voight &amp; Weider (1991)</td>
<td>16 PFP 41 controls</td>
<td>Patellar tendon tap</td>
<td>VMO and VL, reflex latency</td>
<td>Reflex, spinal</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>Grabiner et al. (1992)</td>
<td>8 PFP 15 controls</td>
<td>Knee extension, 20°, OKC</td>
<td>VMO and VL excitation</td>
<td>Isometric ramp contraction</td>
<td>Voluntary</td>
<td>Prime mover</td>
<td>No</td>
</tr>
<tr>
<td>Karst &amp; Willet (1995)</td>
<td>15 PFP 12 controls</td>
<td>Knee extension, 90-0°, OKC</td>
<td>VMO-VL time-difference, time to initial</td>
<td>Dynamic concentric</td>
<td>Voluntary</td>
<td>Prime mover</td>
<td>No</td>
</tr>
<tr>
<td>Karst &amp; Willet (1995)</td>
<td>15 PFP 12 controls</td>
<td>Lateral step up (8cm)</td>
<td>VMO-VL, time-difference, time to initial</td>
<td>Dynamic concentric</td>
<td>Voluntary</td>
<td>Prime mover and postural</td>
<td>No</td>
</tr>
<tr>
<td>Karst &amp; Willet (1995)</td>
<td>15 PFP 12 controls</td>
<td>Patellar tendon tap</td>
<td>VMO and VL, reflex latency</td>
<td>Reflex, spinal</td>
<td>Yes</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Witvrouw et al. (1996)</td>
<td>19 PFP 80 control</td>
<td>Patellar tendon tap</td>
<td>VMO-VL, time-difference, reflex latency</td>
<td>Reflex, spinal</td>
<td>Yes</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Sheehy et al. (1998)</td>
<td>13 PFP 15 controls</td>
<td>Knee extension, 0°</td>
<td>VMO-VL, time-difference, time to max amplitude</td>
<td>Isometric</td>
<td>Voluntary</td>
<td>Prime mover</td>
<td>No</td>
</tr>
<tr>
<td>Powers et al. (1996)</td>
<td>26 PFP 19 controls</td>
<td>Functional</td>
<td>VMO-VL, time-difference, time to initial and cessation</td>
<td>Dynamic</td>
<td>Voluntary</td>
<td>Prime mover</td>
<td>No</td>
</tr>
<tr>
<td>Cowan et al. (2001)</td>
<td>33 PFP 33 controls</td>
<td>Ascending and descending stairs</td>
<td>VMO-VL, time-difference, time to initial</td>
<td>Dynamic concentric and eccentric</td>
<td>Voluntary</td>
<td>Prime mover and postural</td>
<td>Yes</td>
</tr>
<tr>
<td>Cowan et al. (2002b)</td>
<td>37 PFP 37 controls</td>
<td>Rising onto toes</td>
<td>VMO-VL, time-difference, time to initial</td>
<td>Dynamic concentric</td>
<td>Voluntary</td>
<td>Postural</td>
<td>Yes</td>
</tr>
<tr>
<td>Owings et al. (2002)</td>
<td>20 PFP 14 Controls</td>
<td>Knee extension (80-60°), OKC</td>
<td>VL-VMO, time-difference, time to initial</td>
<td>Dynamic</td>
<td>Voluntary</td>
<td>Prime mover</td>
<td>No</td>
</tr>
</tbody>
</table>
The discrepancies found in the literature with regard to a deficit in VMO activity may be due to the variations in study design and test protocol. It is quite possible that the observed delay in onset of VMO activity is task specific and possibly limited to some functional tasks. Habitually performed activity may form a certain strategy in accord with the present constraints such as muscle weakness and/or fear of pain (Thomeé et al. 1999). As a consequence, altered movement strategies may emerge in persons with PFP (Grossley et al. 2004; Powers et al. 1999a; Salsich et al. 2001). This may be reflected in the observed alterations in muscle activity observed in voluntary and functional tasks (Cowan 2001, 2002b). In contrast, no delay of VMO EMG activity has been found in PFP in voluntary non-functional activities such as exercise performed in open (OKC, distal end of the limb is free) and closed kinetic chain (CKC, distal end of the limb is fixed) (Sheehy et al. 1998; Grabiner et al. 1992) and in lateral stair stepping (Karst and Willet 1995). Because exercises in a training apparatus may be novel in character, a habitual strategy has not been developed under constraints that would influence timing.

The division into functional and habitual tasks contra non-functional and novel tasks is appealing, but the reported delay in VMO reflex activity (Voight and Weider 1991; Witvrouw et al. 1996) appears to disrupt this idea. However, as mentioned above, the validity of these data may be discussed. Other studies on the patellar reflex have not shown a delay in VMO EMG onset (Karst and Willet 1995). A patellar tendon tap will only involve a spinal response and leave no opportunity for choice of strategy that would adapt the reflex response. However, there is evidence that learning and experience with voluntary and habitual tasks can modulate alpha motor neuron output in a simple reflex (Nielsen et al. 1993). This would partly give some credit to the suggestion provided by Witvrouw and colleagues (1996) that longer reflex latency in VMO in PFP subjects would be explained by reflex inhibition.

In a similar manner as suggested above for EMG onset, discrepancies between studies on EMG amplitude may be explained partly by task specific adaptations. Decreased VMO activity has been found in both open and closed kinetic chain (Souza and Gross 1991; Boucher 1992; Taskiran 1998) and stair walking (Souza and Gross 1991). Again, other studies have not
found a decrease in VMO activity (Cerny 1995; Sheehy et al.1998; Tang et al.2001; Owings et al. 2002).

In addition to differences in various test protocols, the method of determining EMG onset and amplitude and the interpretation of the results may contribute to the explanation why results differ between studies. Analysis of onset of EMG activity and EMG amplitude can be executed according to different methods, which are not always specified in the literature. Furthermore, potential differences between samples may contribute to the discrepancies between the various study results. The subjects included are seldom described in detail. It is important to note that PFP only refers to pain between the patella and the femur and describes a symptom, not pathology. Consequently, the subjects form a rather heterogeneous group (Thomeé et al. 1999) where duration and severity of pain among other things may vary between the participants in the different studies.

**Movement strategies**

Kinematic analysis of gait and stair walking suggest that persons with PFP have adapted a different movement pattern (Dillon et al. 1983). For example, preferred gait velocity is decreased and during fast walking knee flexion is smaller (Powers et al. 1997b, 1999a). In negotiating stairs, PFP subjects appear to walk slower (Salsich et al. 2001) and with less knee flexion (Crossley et al. 2004; Salsich et al. 2001). Stair walking increases patellofemoral compressive forces up to eight times compared to normal walking (Costigan et al. 2002). Slower velocity will lessen the impact at ground contact and smaller knee joint flexion will decrease knee joint torque, which in turn requires less quadriceps force. Both these strategies reduce patellofemoral compression, which suggests that task specific adaptive strategies are taking place to minimize loading (Brechtner and Powers 2002). An overview of kinematic studies on PFP is presented in Table 3.
<table>
<thead>
<tr>
<th>Author</th>
<th>Participants</th>
<th>Task</th>
<th>Method</th>
<th>Variables</th>
<th>Results (only sign. Differences reported)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dillon et al. (1983)</td>
<td>19 PFP</td>
<td>Gait</td>
<td>2-D video</td>
<td>Gait pattern</td>
<td>Gait pattern</td>
</tr>
<tr>
<td>Powers et al. (1997b)</td>
<td>15 PFP</td>
<td>Gait</td>
<td>Force platform, 3-D kinematics</td>
<td>Stride, joint angles</td>
<td>Reduced walking speed</td>
</tr>
<tr>
<td>Salsich et al. (2001)</td>
<td>10 PFP</td>
<td>Ascending and descending stairs</td>
<td>3-D kinematics, inverse dynamics</td>
<td>Cadence; joint angles; joint moments</td>
<td>Cadence slower (descent) in PFP; knee extension moments reduced in PFP (ascent and descent)</td>
</tr>
<tr>
<td>Brechter et al. (2002)</td>
<td>10 PFP</td>
<td>Ascending and descending stairs</td>
<td>3-D kinematics, MRI</td>
<td>Cadence; knee kinematics; joint moments; PJRF; patellofemoral joint contact area; patellofemoral joint stress</td>
<td>Cadence slower in PFP; PJRF and PJRF-time integral (ascent) less in PFP</td>
</tr>
<tr>
<td>Anderson &amp; Herrington (2003)</td>
<td>20 PFP 20 controls</td>
<td>Descending stairs</td>
<td>2-D kinematics, isokinetic concentric and eccentric quadriceps sub maximal and maximal torque</td>
<td>Isokinetic torque curves, knee angular velocity curve</td>
<td>Break in eccentric torque curve in PFP; break in knee angular velocity curve in PFP</td>
</tr>
<tr>
<td>Crossley et al. (2004)</td>
<td>48 PFP</td>
<td>Ascending and descending stairs</td>
<td>2-D kinematic</td>
<td>Stance phase knee flexion; heel-strike knee flexion</td>
<td>Stance phase knee flexion and heel-strike knee flexion was less in PFP</td>
</tr>
</tbody>
</table>
Treatment

The mainstay treatment for PFP is conservative with respect to referral to physiotherapy, which involves various interventions based on seemingly sound theoretical rationale. The most common interventions are general quadriceps muscle strengthening and exercises specifically focused on VMO. A number of realignment procedures are used, such as stretching, knee braces, orthotics, or tape that are aimed to normalize lower limb biomechanics and to optimize knee joint loading. These treatments are used to restore function, improve performance, and alleviate pain. Other physiological outcome measures that affect treatment are EMG onset and amplitude, various force measurements, patellar position, and knee or lower limb kinematics. Various strength training routines have generally shown positive results on strength, pain, and physical function (Bennet and Stauber 1986; Clark et al. 2000; McMullen et al. 1990; Werner and Eriksson 1993). Likewise, exercise programs that have been particularly focused on VMO function have been reported to successfully facilitate earlier onset in that muscle (Cowan et al. 2002a; Cowan et al. 2003). Taping of the patella was used in these studies. Gilleard et al. (1998) showed that taping of the patella facilitated an earlier VMO EMG onset in activation of the quadriceps. An increase in VMO activity as a result of taping has been demonstrated by several authors (Christou 2004; MacGregor et al. 2005), and positive outcome on physical function, performance, and pain has been reported by others (Bockrath et al. 1993; Ernst et al. 1999; Powers et al. 1997a; Werner et al. 1993b; Christou 2004). Thus, with some exceptions (cf. Cerny 1995), taping is reported to facilitate VMO activity and have a positive effect on PFP (for a critical review see Crossley et al. 2000). Knee splints do not appear to have been used as extensively as tape, but positive outcomes are reported on physical function, strength, muscle activity, knee kinematics, and pain (Timm 1998; Powers et al. 1999b; Schneider et al. 2001). Whereas some methods have targeted the patella itself, other physiotherapy interventions have taken a wider perspective and focused on the entire lower limb kinetic chain. Foot orthotics have been used to correct valgus position of the calcaneus with positive effects on knee biomechanics, physical function, and pain (Eng and Pierrynowski 1994; Gross and Foxworth 2003). Mascal et al. (2003) have successfully taken whole body biomechanics into consideration when correcting anomalies in the lower extremity in PFP.
Exercises can be performed either in CKC or OKC. Good results have been demonstrated with CKC (Clark et al. 2000; McMullen et al. 1990) as well as OKC exercise protocols (Werner and Eriksson 1993a). CKC exercises are often recommended rather than exercises in OKC because many physiotherapists consider CKC exercises safer and more functional (Augustsson and Thomeé 2000; Fitzgerald 1997). However, studies comparing the efficacy of CKC and OKC exercises show no differences between protocols (Colón et al. 1988; Gaffney et al. 1992; Steine et al. 1996; Witvrouw et al. 2000, 2004). Although most studies on exercise treatment for PFP claim successful results, the evidence to support the use of physical intervention is limited because of study design and power (Crossley et al. 2001; Heintjes et al. 2005). The multitude of approaches to PFP may, according to Thomeé et al. (1999), is because the lack of evidence with regard to the etiology of patellofemoral pain.

Occasionally, surgery is performed. The most common type of surgery is lateral retinacular release. This is advocated only in severe cases and is indicated only if there is excessive lateral compression or lateral patellar tracking and/or tilting with tightness of the lateral retinaculum (Fulkerson and Schutzer 1986). Medial or anteromedial transfer of the tibial tubercle is seldom performed in PFP, unless persistent patellar pain with lateral patellar tracking and tilt or lateral subluxation of patella is present or in the case of failed lateral release (Fulkerson 1983).

Short muscles and control of joint position

**Biomechanical principles of muscle function**

One of the key issues in this thesis is whether there are muscles particularly suited for control of joint position. At least biomechanically, one can be tempted to think in these terms. Bergmark (1989) investigated the function of short spinal muscles (such as the deep multifidus) and found that due to their short lever, they were unable to exert great moment across the joint. Instead these muscles increased segmental stability by inducing compression between adjacent vertebrae. Studies on the function of the deep multifidus appear to confirm that they are independently controlled for that purpose.
In a voluntary task, these muscles are activated in an anticipatory fashion regardless of the direction of force (Moseley et al. 2002). A similar functional principle applies to transversus abdominis, a muscle that controls spinal stability by increasing abdominal pressure. In addition, it is anticipatory active regardless of external force direction (Hodges and Richardson 1999). In persons with low back pain, EMG onset in both the deep multifidus and the transverse abdominis is delayed (Hodges and Richardson 1999). This reduces spinal stability by increasing the neutral zone; i.e., it allows larger crude movement before segmental stability is secured (Panjabi 1992).

There are other short muscles in the body that may have a particular function in control of joint position; however, biomechanical circumstances are dissimilar for different joints and muscles that are in a neutral anatomical position. The spine has large degrees of freedom in all directions (around the vertical, transverse, and sagittal axes). The knee, on the other hand, is restricted to small movements around the vertical and sagittal axes, and around the transverse axes movement is restricted basically to one direction, flexion. The transverse abdominis has a dual function: stabilizing the spine and expiration. The muscles around the knee need only affect the joint. The anatomical construction of the knee and origin and insertion of the short knee muscles precludes that they may be direction specific. Examples of short muscles for the knee that may be identified biomechanically as selectively suited for joint control are VMO for control of the patella and popliteus (POP) for stabilization of the posterior aspect knee and control of rotation between tibia and femur (Mann and Hagy 1977).

**Anatomy and function of short knee muscles**

VMO is innervated by the femoral nerve (L2-S3) and consists of the oblique fibers of the vastus medialis. In contrast to the longitudinal fibers, these fibers are less suited to create extension torque across the knee (Lieb and Perry 1968). Instead, they exert a medial pull on the patella, producing a counter force to the cranio-lateral force vector produced by VL (Oarris 2004).

POP is innervated by the tibial nerve (L4, 5 and S1) and consists of a tendinous and a muscular part. The tendinous part originates from the
lateral aspect of the lateral epicondyle of the femur, composes the arcuate ligament of the knee joint, attaches with the postero-medial aspect of the lateral meniscus and runs from the head of the fibula and blends with the vertical capsular fibers. This provides the origin of the muscle itself that covers the popliteal fossa and inserts along the proximal postero-medial border of the tibia above the soleal line (Lovejoy & Harden, 1971). The passive role of the muscle-tendon complex provides dorso-lateral stability of the knee, stabilizes the lateral meniscus, and prevents excessive tibial outward rotation (Ullrich et al. 2002).

Human tissue preparations of the POP muscle has provided information on muscle spindles, which are found, located mainly along the upper border and in the distal two thirds. The density averages 6.5 g⁻¹ muscle (Amonoo-Kuofi 1989), which according to Cooper’s classification (1960), belongs to the low-density category for muscle spindles. Studies on cat preparations have demonstrated that stretch applied to the muscle by outward tibial rotation augments receptor activity (McIntyre et al. 1978).

Functional studies on POP activity in human beings have demonstrated that the active role of the muscle is to internally rotate the tibia on the femur (Mann and Hagy 1977). In initial flexion, POP retracts the lateral meniscus (Jones et al. 1995b) and unlocks the knee joint by inward rotation of the tibia. The locking mechanism is provided by the larger medial condyle of the femur, placing the tibia in an externally rotated position in extension (Basmajian and Lovejoy, 1971). In a crouching posture, POP is constantly active and contributes to prevent anterior dislocation of femur. Popliteus is also active in a number of postural tasks with the knee in extension as well as in flexion (Reis et al. 1973). In the studies on postural tasks, no other muscle activity was recorded along with POP. Therefore, it was neither possible to distinguish if POP activation was of anticipatory nature or occurred before other muscles, nor to determine whether the activity was primarily related to postural control or control of joint position. In the erect quite stance with the knee in full extension, POP is not active (Barnett and Richardson 1953).
Rationale for this thesis

Patellofemoral pain is a common orthopedic problem found most often in young people, particularly women. Many people have reduced their level of physical activity some time after their twentieth birthday. For a few, this inactivity will have consequences in their working life. The obscurity surrounding etiology and pathology of PFP results in a variety of interventions. There are many potential causes and therapeutic approaches, mostly with regard to biomechanical dysfunction. The constraints most commonly regarded target the knee joint in isolation and focus on structural problems or the dynamical control provided by the surrounding muscles, in particular VMO. In varying degrees, a more global perspective focuses on the biomechanics of the kinetic chain from the perspective of the passive structures and the dynamics of muscle.

From this view, the first rationale for this thesis is to contribute to find a consensus with respect to etiology and pathology of PFP in order to better understand the problem, and thereby provide aid to develop more targeted intervention approaches to benefit the patient.

The PFP problem and other related problems (such as lower back pain) focus on muscles particularly suited for the control of joint position from a biomechanical perspective. Studies on the control of the lumbar spine have shown that there is also a neural basis for the idea. Using this as a starting point, the cause and remedy for functional instability and pain of the joints have tended to be adopted in principle from studies on low back pain. Because the different joints in the body are subjected to different demands, the structure as muscles associated with a particular joint will differ. In addition, biomechanical constraints will vary with the task as well as the type of the task (e.g., voluntary versus reflex), the psychological constraints (e.g., the nature of a given command) and the purpose of the task.

Therefore, the second rationale of this thesis is to contribute to a critical investigation of the principle of how (and if) short muscles control joint position in different joints and under different conditions.
AIMS OF THE THESIS

This thesis investigates task specific differences in quadriceps activity in persons with and without PFP, analyzes differences in kinematics, and explores correlations between muscle activity and kinematics. In addition, this thesis investigates the potential function of the popliteus muscle as a specific controller of knee joint position.

Specific research questions:

- Are the four heads of quadriceps activated differently in terms of onset and amplitude of EMG activity in CKC and OKC in healthy subjects without knee pain? (Study I)
- Are the four heads of quadriceps activated differently in persons with PFP compared to controls with healthy knees in terms of onset and amplitude of EMG activity in CKC and OKC? (Study II)
- Do differences in CKC and OKC in quadriceps control between persons with PFP and controls with healthy knees explain inconsistent findings in the literature of quadriceps control deficits in persons with PFP? (Study II)
- Are the four heads of the quadriceps activated differently in persons with PFP compared to controls with healthy knees in terms of onset and amplitude of EMG activity in a triggered postural reaction? (Study III)
- Is the kinematic pattern in response to a triggered postural reaction different in persons with PFP compared to control persons with healthy knees? (Study III)
- Are there any correlations between potential differences in quadriceps EMG activity and kinematic responses to a triggered postural reaction between persons with PFP and controls with healthy knees? (Study III)
- Does the popliteus muscle specifically control knee joint position? (Study IV)
- Is the popliteus muscle active in an anticipatory manner in self-induced provocation of standing balance? (Study IV)
METHODS

Subjects

Study I

Study I was executed in Australia at Division of Physiotherapy, The University of Queensland, Brisbane. Ten healthy subjects, all recruited among students and staff, 3 males and 7 females, (mean age 28.5 ± 0.7, mean height 171 cm ± 8.5, mean weight 64 kg ± 15.6) participated in the study. Subjects were excluded if they had any record of knee pain, trauma, surgery or other joint disease or were involved in competitive sports.

Study II and III

Studies II and III were executed in Umeå at Department of Community Medicine and Rehabilitation, Physiotherapy. Only women were asked to participate in the study because it is among females that PFP is reported to be most common (Almeida et al. 1999). Participants aged between 18 and 40 were chosen to include only those who were fully matured and past puberty, and those not old enough for age related arthritic changes to be potentially present. Seventeen women (age 27.7 ± 6.6 years, height 167 ± 8 cm, and weight 63 ± 9 kg – means ± SD) with patellofemoral pain were referred from their physician or physiotherapist in the Community Based Health Clinics in the Umeå area. They were clinically diagnosed with PFP and had pain when negotiating stairs, running and sitting with bent knees for long periods of time. Since the aim of the study was to examine the long term effect of pain and the potential compensatory strategies that might have developed, rather than the effect of acute and present pain, only subjects that had experienced knee problems for at least one year were chosen (77.1, ± 7.8 years). Eleven subjects had bilateral knee pain, and six had unilateral pain. On the day when entering the laboratory tests, the patient had to be free of pain on a level of severity that interfered with daily living activity, since pain may directly interfere with the task performance in the tests. Pain was rated prior to, during and after the test. All participants rated pain to one a scale were 1 = no pain, 2 = moderate pain, and 3 = severe pain. All patients underwent a second examination by a physiotherapist (= author of the thesis). As a descriptive background assessment of experienced symptoms and pain, all patients completed a self-
administered questionnaire including Knee Injury and Osteoarthritis Outcome Score (KOOS) (Roos et al. 1989); Lysholm Knee Score; pain assessment on a visual analogue scale (VAS, Scott and Huskisson 1976) and a chart where pain was described in terms of markings on a figure (modified from McGill in Wall and Melzack 1999) and some additional questions with regard to sick leave and problems in other joints. No one was or had been on sick leave due to knee pain. A couple reported problems with other joints. Those problems were judged to be independent from the knee pain. For KOOS the answering rate was 100%. On a scale of 0-100 (0 indicating extreme symptoms, and 100 indicating no symptoms), the mean scores in the 5 subcategories were as follows: pain = 51.2 ± 3; other symptoms (such as swelling and stiffness) = 24.4 ± 2; function in daily living = 52.6 ± 3; function in sport and recreation=51.5 ± 2; knee related quality of life = 47.0 ± 2. Lysholm Knee Score was completed by all but one participant and showed that all participants had problems with more than one of the following: long term sitting; negotiating stairs; squatting and walking or running. The problems were rated moderate to severe. Only a few reported problems with swelling and catching which was rated to occur only occasional. Twelve patients completed the pain questionnaire and rated on the VAS (0 = no pain, 10 = the worst conceivable pain) the worst knee pain they ever experienced to 6.7 ±1.8, and the average pain they usually experienced from their knees to 2.6 ±1.0. The pain chart indicated that pain was usually experienced as dull and throbbing in the patellar region. Occasional sharp and cutting pains were described as coming from under the patella and sometime around the edges. Most patients experienced that it was difficult to recall and describe the pain. This was probably the reason why five patients did not complete the pain questionnaire.

Seventeen controls matched for gender, height, and weight (age 26.0 ± 4.6 years, height 167 ± 4 cm, and weight 61 ± 4 kg) without any record of knee pain, were recruited from university staff and students. As a descriptive background assessment, anthropometric features were clinically estimated for both groups. The quadriceps angle (q-angle) was measured between a line from the superior anterior iliac spine to the center of patellae and a line form center of patella to the tibial tuberosity (Fig. 1). A large q-angle indicates increased lateral pull on the patella (Elia et al. 2004). Hyperextension angle of the knee was measured using the greater trochanter, the midpoint of the lateral knee joint line and the lateral malleolus as reference points. These measures were chosen on the basis that
increased q-angle and hyperextension of the knee is often reported for PFP subjects (Reid et al. 1993; Thomec et al. 1995a). PFP subjects had a significantly ($F = 20.0; p<0.001$) greater q-angle ($17.4\degree \pm 4.5$) than the controls ($10.6\degree \pm 4.2$). PFP subjects also had a significantly ($F = 10.6; p<0.003$) greater hyperextension angle ($7.3\degree \pm 3.7$) than the controls ($3.0\degree \pm 3.1$). Subjects and controls were excluded if they had any history of trauma or joint surgery to the lower extremity, diagnosed joint- or neuro-motor pathology, or were involved in elite competitive sports. Normal height and weight were inclusion criteria, since very tall or greatly overweight persons may have knee problems caused by their anthropometrics. In addition, very tall persons would not fit into the measurement volume for kinematics, and EMG recordings are difficult on overweight persons were subcutaneous adipose tissue obscures detection of muscle activity. All but one of the PFP subjects was found to qualify for the study. The reason for exclusion was that the person had undergone knee surgery as a child.

**Study IV**

Ten healthy female medical students and staff at the radiological clinic (age 25.2 ± 4.5 years, height 169 ± 4 cm, weight 61 ± 6 kg, - means and SD) volunteered for this study. No one reported any record of knee pain, trauma, surgery, joint- or neuro-motor pathology, or involvement in competitive elite sports. The reason for including only women was to create a baseline for potential future studies on popliteus muscle function in PFP.

| Table 4. View over subjects participating in the studies |
|-----------|-----------|-----------|-----------|-----------|-----------|
|           | Participants | Healthy controls | PFP | Women | Men |
| Study I   | 10         | 10         | -   | 7      | 3    |
| Study II, III | 34       | 17         | 17  | 17     | -    |
| Study IV  | 10         | 10         | -   | 10     | -    |

**Ethics**

All studies were performed in agreement with the Declaration of Helsinki and informed written consent was obtained from all subjects. The study was approved by the Medical Faculty Research Ethics Committee at the Universities of Queensland and Umeå (§245/01, dnr 01-166) respectively.
Methods

Design

All studies were designed as controlled experimental laboratory studies. Studies I and IV were done on healthy subjects, aimed to study normal physiological functions. Study II and III were performed on patients with PFP in order to study anomalies in muscle function and kinematic behavior and compared to matched controls with healthy knees. Although each individual with PFP was matched for age, height and weight, comparisons were made on group level.

Data collection and analyses were performed via different computer aided systems. Thus, blinding of the examiner was in general not needed. Where manual inspection was performed, any identities in the material were hidden from the examiner in order to avoid bias (see the chapter on EMG analysis).

Test procedures

In study I, subjects sat on a firm plinth with the hips flexed to 90° and knee flexion in 30° from full extension. Ankle joint position was kept at 90°. The pelvis was firmly strapped to the plinth. This position was used as it represented a mid range position where the patella is in full contact with the femur condyles without provoking knee pain by increased pressure from greater extension (Oartis 2004). Identical positions were kept in both the CKC and the OKC task in order to control for as many parameters as possible to avoid potential confounders. Knee extension efforts were performed as a reaction-time (RT) task in two different conditions. For OKC, a strain gauge was connected from the plinth to a strap around the ankle, approximately 10 cm proximal to the malleolus and isometric knee extension efforts were made against the resistance of the cable. In the CKC task the strain gauge was incorporated into an inelastic belt that passed around the trunk support of the plinth and under the sole of the foot (Fig. 2). Isometric extension efforts were performed either by pushing up (OKC) or forward (CKC) into the belt, depending on condition. Subjects were instructed to respond as quickly as possible in response to an auditory stimulus and to use a moderate force effort. Twenty repetitions in sets of 10 were performed for each condition and subjects were allowed ~2-30 seconds pause between each repetition and 2-3 minutes rest between sets of 10. Subjects were encouraged to relax their quadriceps between each
Methods

repetition. Experimenters observed EMG activity with sufficient gain to ensure activity was minimal during the pause. The order of task presentation was randomized between sets of OKC and CKC. Subjects performed a single maximal voluntary isometric contraction (MVC) for 5 seconds with loud verbal encouragement for each task (OKC and CKC) after completion of 20 repetitions.

![Figure 2](image1.png)

*Figure 2. Knee extensions in open (OKC) and closed (CKC) kinetic chain. Arrows indicate force direction. Strain gauge indicated by [ ].*

Study II was a replication of study I where patients with PFP were included in addition to the healthy controls. The set up was somewhat different. Instead of a using and strain gauge for force recordings and positioning the subject on a plinth which restricted hip and knee angle position in both sides, an isokinetic dynamometer was used. This provided a different position, but kept the hip and knee angles for the measured limb similar to in study I. For OKC, the resistance was provided by a 10 cm wide brace clasped around the ankle, immediately proximal to the malleolus. In the CKC task, the resistance was provided by a plate placed under the foot (Fig. 3).

![Figure 3](image2.png)

*Figure 3. Knee extensions in open (OKC) and closed (CKC) kinetic chain. Arrows indicate force direction. Force production was viewed on line by the subject for feedback purpose.*
Methods

An advantage with the setup used in study II was that force production could be monitored on line and provided visual feedback for the subject of the force. The response to generate moderate force resulted in 143 ± 43 N, being the average for both groups and tasks together. The auditory signal which provided the trigger for muscle contraction in the reaction time task was recorded together with EMG and force data. In all aspects with regard to randomization of OKC and CKC, number of sets and repetitions, and manner of task execution, study II was performed in accordance with study I. In study III and IV, unpredictable perturbations to standing balance were evoked by sagittal plane support-surface translations. The subject stood barefoot on a sliding platform with the back turned to the experimenter to assure that clues would not be observed in terms of time and direction of platform movement. In order to standardize the standing position, the feet were placed shoulder width apart (within markings on the platform) and the malleoli over the transverse center line marked on the platform. The subject held the arms folded across the chest to limit upper extremity movement for balance reactions (Fig. 4).

Prior to the test, the subjects were given visual feedback of muscle activity by viewing on-line EMG signals when trying to stand completely relaxed and when activating the muscles. In the test situation the subjects were encouraged to remain relaxed and to try not to prepare for the perturbation. To release muscle tension and facilitate relaxation the subjects briefly stepped off the platform between each trial. The test was initiated with one perturbation performed backward for half the group, and forward for the
other half. This was done in order to eliminate expected initial excessive or strange reactions. After that the platform was moved either anterior (5 times) or posterior (5 times) in a pre-determined pseudo-randomized sequence of 10 perturbations that were identical for all subjects. In study III, after the perturbations, the subjects performed MVC of the quadriceps for ten seconds, in a standing position with straight legs. The verbal command was: “tighten your thigh muscles as hard as you can”, with loud and repeated emphasis on as hard as you can. The MVC was performed last in case the effort would cause pain or discomfort that may have interfered with the task performance.

In study IV, a second test session involved self-initiated provocation of balance (Fig. 5). The subjects were standing in the same position but with their arms resting along the sides of the body. An RT task was preformed in response to an auditory stimulus. The subject was asked to reached forward, as rapid as possible, to grip with both hands, a small stick (10 cm long) hanging slightly out of reach (20 cm in front of the outstretched hands at shoulder height, when the subject was standing upright). The same EMG feedback process and facilitating of muscle relaxation was performed as in the support surface translation protocol.

Figure 5. Reaction time, reach and grip task. Small and large circles illustrate reflex markers. Crossed circle = center of mass (COM). Long vector projects COM-force. For camera placement, see figure 4.
Methods

Equipment

*Electromyography recording*

EMG records the depolarization of the muscle fibers in the immediate area around the electrodes and is commonly used to determine onset of muscle activity as well as to which degree a muscle is active. In this thesis EMG has been used to determine onset of muscle activity in all four studies and analyses of degree of muscle activity has been recorded in all but study IV. EMG activity of VMO, (vastus medialis longus) VML, rectus femoris (RF) and VL was recorded from the right quadriceps in study I. In study II and III, EMG was recorded from the same muscles for the most painful leg in the PFP group (nine right legs and eight left legs). In the control group, EMG was recorded from the leg corresponding to the most painful leg in the PFP subject that they were matched to. Matching was made relative to leg preference i.e., a painful preferred leg could be matched to a preferred right leg. Leg preference was determined in relation to the foot normally used to kick a ball (Beling et al. 1998). All subjects preferred the right leg. In study IV, EMG was recorded from the preferred leg for VMO, RF, VL, biceps femoris (BF), gastrocnemius medialis (GM), tibialis anterior (TA), and deltoideus anterior (DA). In all surface recordings Ag/AgCl electrodes were used (study I: 5 mm discs, Grass, USA and study II -IV: pre-gelled self adhesive, Ag/AgCl, 5 mm rectangles, Blue Sensor, Medicotest, Helsingborg, Sweden), which have the advantage to reduce electric noise and minimizes the effect of the over potential created by alternate currents generated by fluctuations in impedance between gel and electrode (Gerdle et al. 1999). The electrodes were placed in bipolar configuration which functions as a filter as the difference of the currents measured under the two electrodes is registered and amplified and signals common for both electrodes are suppressed (Gerdle et al. 1999).

To achieve a valid representation, electrode placement is important. The electrodes were placed approximately in parallel with the muscle fibers over the muscle bellies, with an inter-electrode distance of 20 mm, measured center to center. The positioning of the bipolar electrodes in line with the muscle fiber is done to limit recordings to the same fibers for both electrodes, thus reducing the risk for cross-talk from other muscles (Hermens et al. 1999). The location off the motor point where the motor nerve enters the muscle is generally found in the centermost part of the
muscle. Over the motor point, the electrical current propagates in opposite directions, and the EMG signal may be weak or absent (DeLuca 1997). The standardized placements that were used in the studies in this thesis (Hermens et al. 1999; Zipp 1982) are aimed to reduce this problem. Quadriceps placements were based on a modification of standard proposed by Zipp (1982, Fig. 6). Other placements were made in accordance with recommendations in SENIAM (Hermens et al. 1999, Fig. 7). In all studies prior to applying the electrodes, the skin was thoroughly cleansed, shaved and wiped with rubbing alcohol (study II-IV) or treated with liquid abrasive (study I) to provide optimal electrode contact and minimize impedance. The skin and adipose layer functions as a low pass filter, the thickness increasingly attenuating high frequencies (DeLuca 1997) which increases the risk of cross talk form other muscles (Solomonow et al. 1994). This was one reason for excluding severely over weight persons from the study.

In study IV activity in POP was recorded using indwelling fine wire electrodes (single strand, size 0.05 mm, Alumel TC type K, HPN insulated, California Fine Wire Company, Grover Beach, CA, USA), with 1 mm bared tips arranged in bipolar fashion with 3 mm inter-electrode distance. The electrodes were inserted into a hypodermic needle (80 mm, 21G) and applied through a 4 mm incision medial of the tibia and approximately 12
cm distal of the knee joint line (under local skin anesthetics, Citanest 5 mg ml\textsuperscript{-1}) and guided in a cranio-lateral direction aimed toward the head of the fibula (Fig. 8). Positioning in the centre of the muscle was aided by ultrasound guidance (Fig. 9), 8 MHz, range 5 cm (8L5) (Acuson Sequia 512), and anchored by hook-shaped electrode endings. The end of the protruding wires were bared 3 mm and attached to conducting silver crocodile clips.

Figure 8. Bipolar fine wire EMG electrodes were placed into the popliteus muscle (arrow pointing at the site).

Figure 9. Ultra sound picture of application of fine wire EMG electrodes. Medial perspective of left leg. Top arrow shows the tibia plateau. Bottom arrow shows the tip of the hypodermic needle used for insertion of fine wires.

In study I, a standard system with lead connections was used. Therefore only one ground electrode was needed, which was placed over the proximal part of tibia. The raw EMG signals were amplified 2000 times, band pass filtered between 20 to 1000 Hz (Neurolog, UK) and sampled at 2 kHz using a Power 1401 and Spike2 software (CED, UK). In study II – IV, a telemetric system which utilizes an active ground electrode (placed ~12 cm from the recording site) in connection with a preamplifier (x 1000) for each bipolar electrode, was used. EMG data was transmitted via an analogue telemetric system (MEGA 6000, Kuopio, Finland). The signal was then again amplified times 2 (total amplification = x 2000) and band pass filtered between 15 and 750 Hz (Bessel). In study II, the EMG data was sampled and digitally stored at 2000 Hz (12 bits, Mysas, Dept. of Biomedical Engineering & Informatics, University Hospital, Umeå, Sweden) (Karlsson
et al. 1994). In study III and IV the EMG signal was sampled and stored at 2160 Hz (12 bits, Pro Reflex, Qualisys Gothenburg, Sweden).

**Electromyography analyses**

EMG analyses were made for onset in all studies. In study I onset of EMG activity of each muscle (VMO, VML, RF and VL) and the onset of force measure were identified visually for each trial. To remove observer bias, data were presented for each individual trial in random order with no reference to muscles or order of repetition. The time of onset of force was identified in a similar manner. Data were presented as the difference between EMG onsets of muscle pairs (VMO:VML, VMO:VL, VMO:RF, VML:VL, VML:RF, VL:RF) and the difference between onset of force and onset of EMG for each muscle.

In study II-IV, onset of EMG activity was first determined using an autoregressive algorithm (e.g., Merletti and Parker 1999). Based on the algorithm, a pre-whitening filter was applied to remove any existing correlation within the signal. As a next step, a cumulative sum was applied to the filtered signal giving the signal g(t). Any existing linear trend in g(t) was removed before setting a threshold for onset detection at 3 standard deviations. To increase onset time resolution the first local minimum before the detected onset was determined. The algorithm determined onset served as a guide for visual inspection and correction (Staude and Wolf 1999). Similar to study I, visual inspection and correction was blinded.

In study II, EMG onsets were identified for each of the VMO, VL, VML, and RF muscles and presented as the difference between EMG onsets of muscle pairs (VMO:VML, VMO:VL, VML:VL, VMO:RF VML:RF, VL:RF) and relative to the auditory signal. To enable comparison with earlier studies that have showed delayed VMO relative to VL, the EMG onset time difference for VMO-VL was stratified and categorized into 3 intervals (VMO onset ≥ 10 ms before VL, VMO onset ≥ 10 ms after VL, and VMO onset between 10 ms before and 10 ms after VL onset) to determine in which order the muscles were activated. The 20 ms interval was chosen as minimum level for specificity on the basis of algorithm and visual inspection of EMG onset (Cowan et al. 2001). One subject from each group who had a reaction time > 1 s, was considered to have failed to perform the task adequately and was removed from the analyses of onset time of EMG.
Methods

In study III, EMG onsets were identified for the same four heads of the quadriceps and similarly presented as relative differences between EMG onsets for muscle pairs and relative to onset of motion of the sliding platform. In this study only the long loop reflex was of interest. The average postural response latency is 70-100 ms (Horak and Nashner 1986), but sometimes, a stretch reflex is elicited in a postural reaction (Nashner 1976). The stretch reflex latency for the quadriceps is described in the literature to approximately 20-30 ms (Brodal 2004; Frijns et al. 1996). Occasional EMG onsets shorter than 50 ms were therefore discarded in order to exclude any muscle activity from spinal origin. In study IV, EMG onsets were identified for VMO, RF, VL, POP, GM, BF, AT, and DA. EMG onsets for the muscles of the lower limb were presented relative to onset of motion of the sliding platform. In this study both the short and long loop reflexes were of interest. With respect to the stretch reflex latency, occasional EMG onsets for postural reactions < 25 ms relative to platform motion, were discarded (n = 5). Shorter latencies were either attributed to artifacts or voluntary muscle activity initiated prior to perturbation. In the self induced provocation of balance, start of the activity in was denoted by EMG onset in DA i.e. initiation of shoulder flexion. Onsets for the lower extremity muscles were presented relative to DA (DA: VMO, etc). EMG onsets of the quadriceps, hamstrings and muscles of the leg were also presented relative to POP (POP: VMO, etc), in order to compare the relative order of muscle activation between the different directions of perturbation and the RT task. Furthermore, physiological considerations were made with regard to how long a latency that is feasible for EMG onsets between heads of the same muscle. The limit was set to 40 ms. Time differences > 40 ms between the different heads of the quadriceps were discarded (~ 2 %).

Peak EMG root mean square (RMS) amplitude was analyzed in study I – III. Since absolute values of amplitude can not be directly compared between subjects or between different muscles, all peak EMG amplitudes were normalized to the maximum EMG RMS value in the MVC effort. All MVC efforts were performed in a manner similar to the specific task for each test, as described in test procedures. In study I, peak EMG amplitude was determined for each muscle (VMO, VML, RF and VL) for the initial 200 ms. In study II, in addition to determine peak amplitude, an attempt to find the time to peak amplitude was made. Therefore the peak EMG amplitude was averaged for each subject over each series of ten trials. The average peak was defined at 90% of the absolute average peak to remove artifacts,
Methods

and then normalized to MVC. From the normalized peak EMG amplitude, the ratio of muscle activity for each specific muscle pair (VMO/VML; VMO/VL; VML/VL; VMO/RF; VML/RF; VL/RF), and for CKC/OKC for each muscle (VMO, VML, RF and VL) was calculated. In study III, similar to in study II, both peak EMG amplitude and time to peak EMG amplitude was of interest. EMG amplitude in response to perturbation was determined from the peak EMG amplitude during the first second after initiation of platform motion, estimated in a sliding time window of 100 ms. Peak EMG amplitude was identified at 90% and then normalized to MVC. EMG amplitude ratio for each specific combination of muscle pairs (VMO/VML; VMO/VL; VML/VL; VMO/RF; VML/RF; VL/RF) was computed. A ratio of activity between the anterior and posterior direction of translation (anterior/posterior) was computed for each muscle (VMO, VML, RF and VL).

Kinematic capture

Kinematics was used in study III and IV. Three-dimensional (3-D) kinematics was captured at 240 Hz using a five camera system based on infra-red light reflected by spherical markers (Pro Reflex, Qualisys Gothenburg, Sweden). A calibration measure (150 frames) was performed by moving a wand (with two 19 mm markers, distance 74.9 cm) in the measurement volume, giving a standard deviation for the marker distance of 3.2 mm.

Figure 10. Twenty spherical reflex markers (19 mm) were placed bilaterally over the 5th metatarsal joint, midpoint of the 3rd metatarsal, lateral malleolus, tibial tuberosity, midpoint of lateral knee joint line, one cm proximal of basis patellae, anterior superior iliac spine, greater trochanter and one cm inferior of acromion. One marker (30 mm) was placed on symphysis of sternum manubrium and one on sacrum between the posterior superior iliac spines (not shown on figure).
Twenty spherical passive reflective markers (19 and 30 mm diameter) were placed bilaterally over anatomical landmarks (Fig. 10). A rigid six degrees of freedom segment model was created to identify movements (Buczek et al. 1994, Fig. 11).

Position and orientation of segments were determined using an optimal algorithm (Cappello et al. 1997). Markers were positioned on anatomical landmarks to define local reference systems for each of the 6 segments used in the model (i.e. trunk, pelvis, thighs, and shanks). Joint movements were calculated as rotations around the three axes according to the Cardan/Euler representation $X, y', z''$, and COM shifts along the y axis of the global coordinate systems. (Small spheres = reflex markers, large center sphere = COM.)

Figure 11. A rigid six degrees of freedom 6-segment model (trunk, pelvic, thighs and shanks) was created to identify movements Joint movements were identified around the three axes of the local coordinate system according to the Cardan/Euler representation $X, y', z''$, and COM shifts along the y axis of the global coordinate systems. (Small spheres = reflex markers, large center sphere = COM.)
converted (i.e. multiplied by -1), yielding valgus and external rotation as positive, whereas varus and internal rotations were denoted by a negative value. Center of mass (COM) was calculated as the center of body with arms excluded according to the segment model. Anterior shift of COM relative to the lateral malleoli, was denoted by an increasing value and posterior shift by a decreasing value. All kinematics data were low pass filtered at 6 Hz, 4th order Butterworth filter, and analyzed in Visual3D software (C-Motion, Rockville, Canada) and MATLAB (version 6.5 for Windows, MathWorks Inc®, Natick, MA, USA).

Kinematic analysis

In study III, the true joint positions (degrees) were of interest and kinematic data were therefore identified as absolute values (i.e. not normalized to zero for the starting position). Joint angle in quiet stance (calculated as the median value during the period from start of sampling until start of platform motion, ~3 s) served as reference value to determine the extent of shift in joint angle. For postural response to balance perturbation, maximum flexion and extension (transverse axes) relative to the reference values, were presented for the trunk segment, the combined left and right hip joints, and for the left and right knees separately (Fig. 11). For the sagittal and vertical axes, maximum rotation was presented as total range of motion (maximum value minus minimum value). This was presented only for the knee joints. The reference value for COM (cm) was calculated as COM position relative to the lateral malleolus according to the same procedure as above for joint angles. Maximum initial shift of COM was calculated relative to the reference value. In response to anterior translation, posterior shift of COM always occurred first. In response to posterior translation, anterior shift of COM always occurred first. Maximum angular velocity (degrees s⁻¹) was calculated for movement around the rotational axes as outlined above and maximum linear velocity (m s⁻¹) was calculated for the initial shift of COM in response to perturbation.

In study IV, maximum knee joint movement (degrees) and shift of COM (cm) was calculated for the first joint movement that occurred in response to platform translation or self-initiated provocation on balance. Initial maximum angular velocity (degrees s⁻¹) was calculated for the corresponding initial angular shift. Maximum linear velocity (m s⁻¹) was calculated for the initial shift of COM in response to perturbation.
Methods

Kinetics

As a reference point for onset of EMG activity in study I, onset of force at knee extension was measured (1 kHz) with a strain gauge (Validyne, USA). For OKC, the strain gauge was connected from the plinth to a strap around the ankle. In the CKC task the strain gauge was incorporated into an inelastic belt that passed around the trunk support of the plinth and under the sole of the foot (Fig. 2). In study II, level of force was used as a control variable, and was provided by an isokinetic dynamometer (Kin Com®, Chattanooga, Illinois) that provided resistance in OKC and CKC (Fig. 3). The dynamometer was adjusted to accommodate identical joint angles in both tasks, and was therefore modified in manner that did not allow exact torque calculations with reference to length of moment arm, to be made in the KintCom software. Produced force was therefore taken at face value, without consideration to moment arm influence.

Balance perturbation

Support surface translations in the anterior and posterior direction were employed for balance perturbations in study III and IV. The perturbation device consisted of a spring loaded sliding platform mounted on rails. The platform could be moved (3 cm, acceleration 10 m s⁻², average speed 1 m s⁻¹) in either anterior or posterior direction, without providing any prior clues for direction. The stop was sudden. The tension of the spring was blocked at a given length in order to provide equal horizontal force for each trial. A potentiometer signal indicated the start and stop of the platform motion.

Statistical analysis

Repeated-measures ANOVA were used in all studies. It allows comparison of performance between tasks for each individual. These results are then compared on group level. Sphericity corrections were performed in all studies. Greenhouse-Geisser was used in study I and Huynh-Feldt was used in study II-IV. In all studies the level of probability chosen as statistically significant was \( p < 0.05 \). Means ± SD are presented in the text, means and SEM are presented in the figures. All statistics in study I was performed in
Methods

Statistica. In study II-IV, all statistical analyses were performed using SPSS (11.5 for Windows).

In study I, differences in EMG onset latency for muscle pairs and EMG amplitude between OKC and CKC tasks were evaluated with a repeated-measures ANOVA two factors; condition (OKC and CKC) and muscle portion (n=4) or muscle pairs (n=6). Paired t-tests were used to evaluate specific differences.

In study II, a three factors repeated-measures ANOVA was used to examine effects of group (n = 2; PFP and control), task (n = 2; OKC and CKC) and muscle (n=4) for EMG onset time. Effect of group (n=2; PFP and control), task (n = 2: OKC and CKC) and muscle pair (n = 6) were examined for relative difference in EMG onset time or ratio of EMG amplitude. When a main effect was found a further analysis was performed with single repeated measure ANOVAs to determine main effects of group and condition for each individual muscle or muscle pair. CKC/OKC ratios between groups and force measures between groups within tasks were compared with a one-way ANOVA. A Chi-square test was used to determine statistical difference between groups for onset time-difference between VMO-VL as stratified in three categories. Correlations between EMG amplitude and force were tested using Pearson’s correlation coefficient.

In study III, a three factors repeated-measures ANOVA was used to examine the effect of group (n=2; PFP and control), perturbation (n=2; anterior and posterior translation) and muscle (n=4) on EMG onset time. Effect of group, perturbation, and muscle pairs (n=6) on EMG onset time-difference and amplitude ratio were examined with a 2 x 2 x 6 repeated-measures ANOVA. Single repeated measure ANOVAs were used to test main effects of group and perturbation on onset time-difference and ratio for each muscle or muscle pair. Ratio of EMG amplitude for each muscle (n=4) between the anterior and posterior translations, were compared between groups (n=2) with one way ANOVA. Correlations (Pearson’s) were tested between EMG and kinematic variables that were significantly different between groups.

In study IV, comparison between conditions for EMG onset time of POP relative to each one of the other muscles was examined with a 3 x 6
repeated-measures ANOVA: with condition (n=3: AT, PT and RT) and muscle pair (n=6) as factors. Comparison between directions of support-surface translations on EMG onset time was examined with a 2 (AT and PT) x 7 (muscles) repeated measures ANOVA. Differences in EMG onset time between muscles within each condition of perturbation was examined with a repeated measures ANOVA with muscles as factors (n=7), and pairwise comparisons of main effects.
RESULTS

Task specific muscle activity

In study I, EMG was used to investigate task specific muscle activation in the four heads (VMO, VML, VL and RF) of the quadriceps in OKC versus CKC in healthy persons without knee pain. When subjects performed rapid knee extension efforts in response to an auditory stimulus, there were differences in onset time and amplitude of muscle activation between OKC and CKC.

EMG onset of activation in the different heads of the quadriceps was more simultaneous in the CKC task than in OKC (condition x muscle interaction: p<0.001, Fig. 12). Figure 13 illustrates EMG onset time expressed relative to the initiation of the force for each muscle and shows that there was no difference between muscles for CKC, that is, the onsets of EMG of all muscles were approximately simultaneous. In contrast, for OKC, there were differences between muscles in latencies for EMG onset times relative to onset of force. The latency was greatest for RF (mean 62 ms±20) and shortest for VMO (mean 55 ms±22). The data indicate that for the OKC task the EMG onsets of all muscles occurred before that of VMO. The relative latency for EMG onset time was significantly different between tasks for all muscle pairs (RF:VML p<0.05, for all the rest p<0.001), except for VMO:VL.

Figure 12. Representation of EMG raw data for muscle activity in CKC) and OKC from one trial in a single healthy subject. Activation was more simultaneous in CKC than in OKC. RF was activated first and VMO last in OKC. (Some amplitudes are clipped).
The amplitude for the normalized EMG was significantly larger for RF (p<0.001) in the OKC task compared to CKC, whereas the amplitude for VMO was significantly larger (p<0.05) in the CKC task compared to in OKC. Amplitude of activity was not significantly different between the tasks for other muscles (Fig.14).

Study II showed that differences between CKC and OKC in terms of task specific muscle activity were similar for persons with PFP and healthy controls without knee pain. There was a significant main effect of muscle pairs for relative EMG onset time-differences as illustrated in Fig. 15 (F_{3,0.930} = 8.2; p = 0.02). Single comparisons for muscle pairs showed that VL was activated before VML in CKC and almost simultaneous OKC (main effect: task, F = 4.2; p = 0.05), VMO was active before RF in CKC, and almost simultaneously in OKC (main effect: task, F = 17.1; p < 0.001), and VML was active before RF in CKC and almost simultaneous in OKC (main effect: task, F = 10.8; p < 0.002). There was no difference between CKC and OKC tasks for VL-RF (Fig. 15).
Figure 15. Group means and SEM for EMG onset time-differences between muscle pairs in open [○] and closed [●] kinetic chain for PFP subjects and in open [△] and closed [▲] kinetic chain for controls. A negative value denotes that the first muscle in the pair is active first, and a positive value denotes that the second muscle in the pair is active first.

Note that the most significant differences between CKC and OKC exists for VMO and RF, which is similar to in study I, i.e. VMO is activated earlier than RF in CKC. However, in contrast to study I, the heads of the quadriceps are activated more simultaneous in OKC than in CKC.

Figure 16. Group means and SEM for ratio of peak EMG amplitude between muscles in open [○] and closed [●] kinetic chain for PFP subjects and in open [△] and closed [▲] kinetic chain for controls. A higher value denotes greater activity in the first muscle in the pair. * = p <0.05.

In study II, the ratio for normalized peak EMG activity for muscle pairs showed that the muscles were activated differently in OKC versus CKC (main effect of task: $F = 12.3; p = 0.001$, Fig. 16). The differences between
CKC and OKC in study II were similar to the differences in study I. Single comparisons of muscle pairs between tasks showed that VMO was more active than RF in CKC (main effect of task: \( F = 15.1; p = 0.001 \)) and that VL was more active than RF in CKC (main effect of task: \( F = 13.4; p < 0.001 \)). In study II, ratio between CKC and OKC for each muscle indicated that muscle activity was higher in the OKC task than in the CKC task for both groups (Fig. 17). Level of muscle activity was more equal between CKC and OKC in PFP subjects compared to controls for VML (\( F = 4.6; p = 0.04 \)) and VL (\( F = 4.8; p = 0.03 \)).

![Figure 17. Group means and SEM for ratio of peak RMS EMG amplitude between closed (CKC) and open (OKC) kinetic chain for patellofemoral pain subjects (PFP) (●) and for controls (▲). A lower value denotes more activity in OKC. * = p <0.05.](image)

Force production in CKC was highly correlated with peak EMG amplitude for VMO (\( r = 0.66; p < 0.001 \)), VML (\( r = 0.50; p = 0.001 \)) and VL (\( r = 0.60; p < 0.001 \)) and less correlated with activity RF (\( r = 0.38; p = 0.02 \)). In OKC, force production did not correlate with activity in VMO, but was correlated significantly with activity in VML (\( r = 0.62; p < 0.001 \)), RF (\( r = 0.56; p < 0.001 \)) and VL. (\( r = 0.76; p < 0.001 \)).

Task specific activation of the different heads of the quadriceps was also shown in response to unpredictable balance perturbations elicited by anterior and posterior support surface translations (study III). There was an interaction effect between translation direction and muscle, (\( F_{2,4,85.2} = 3.6; p = 0.01 \)), which indicated that not only are the heads of the quadriceps activated differently, but also that the anterior versus the posterior platform motion affected onset of muscle activation differently (Fig. 18).
The ratio of EMG amplitude varied significantly between the muscle pairs (main effect of muscle pair, $F_{3.0, 80.5} = 7.4; p = 0.01$, Fig. 19). Single tests for the different muscle pairs showed that the VL/RF ratio and VML/RF ratios were closer to one in the posterior direction of translation (main effect of condition, $F = 6.0; p = 0.02$ and $F = 6.6; p = 0.01$, respectively, Fig. 19). The ratio for EMG amplitude between the anterior and the posterior translations, indicated that the muscles were more active in the anterior direction than in the posterior direction (main effect of condition, $F = 27.9; p < 0.001$, Fig. 20).
Results

Differences between PFP and controls

It was hypothesized that persons with PFP would have a delayed onset and decreased amplitude of EMG VMO activity compared to controls with healthy knees. In CKC as well as in OKC there was no difference in quadriceps activation between persons with PFP and controls with healthy knees (study II), neither in terms of relative recruitment order (Fig. 15) nor in terms of relative amplitude of activity (Fig. 16) between the four heads of the quadriceps (VMO, VML, VL and RF).

The CKC/OKC ratio was closer to one in PFP subjects compared to controls for VML ($F = 4.6; p = 0.04$) and VL ($F = 4.8; p = 0.03$) (Fig. 17).
Results

An interesting finding in study II was that onset of EMG activity in relation to the auditory stimulus occurred ~60 ms later in the PFP group compared to the control group in both the CKC and OKC tasks (main effect of group: $F = 4.4; p = 0.04$, Fig. 21). Single comparisons for each muscle showed an effect of group for all muscles (VMO, $F = 4.2; p = 0.05$; VML; $F = 4.5; p = 0.04$; RF; $F = 4.5; p = 0.04$; VL; $F = 4.3; p = 0.04$).

Separation into three strata for EMG onset time (VMO earlier than VL; simultaneous onset of VMO and VL; and earlier onset in VL than VMO) showed no differences between groups in either of the CKC and OKC tasks (Fig. 22).

![Figure 22. Stratified EMG onset time-difference for VMO-VL (simultaneous onset, onset of VMO between <10 ms before VL and <10 ms after VL; VL active ≥ 10 ms before VMO; VMO active ≥ 10 ms before VL).](image)

In study III, when persons with PFP and controls were tested for postural reactions in response to unpredictable perturbations of balance, significant differences between groups were found mainly in the anterior translation.

VMO EMG onset was earlier in the PFP group than in the control group ($F = 5.7; p = 0.02$, Fig. 18). Relative to other muscles, VMO was activated significantly earlier compared to VL (main effect of group, $F = 5.9; p = 0.02$) and compared to RF (main effect of group, $F = 5.2; p = 0.03$) in the PFP group (Fig. 23). When differences between PFP and controls were tested separately for the anterior and posterior directions, VMO EMG onset occurred earlier for the PFP group only with anterior translations ($F = 4.9; p = 0.03$, Fig. 18). Relative onset time differences for muscle pairs...
showed that VMO activity preceded RF significantly in the PFP group in only the anterior direction of translation ($F = 4.3; \ p = 0.05$, Fig. 23).

VML/VL ratio was greater in the PFP group (main effect of group, $F = 11.3; \ p = 0.002$, Fig. 19). There was no significant difference between groups for EMG amplitude ratio between anterior and posterior translation (Fig. 20).

In study III, kinematics was captured in quiet stance and during the perturbation. Lower extremity alignment, estimated in quiet stance, showed that relative to the femur, the tibia was externally rotated in the PFP group ($0.6, \pm 3.4^\circ$), and internally rotated in the control group ($-0.7, \pm 3.5^\circ$) ($F = 4.5; \ p = 0.04$). There were no differences between groups in any other variables measured in quiet stance.

In the anterior translation, the perturbation caused a greater initial posterior shift of COM in the PFP group ($3.1, \pm 0.03$ cm) compared to the controls ($2.9, \pm 0.03$ cm) ($F = 4.4; \ p = 0.045$). The active response that followed the initial perturbation showed larger flexion of the trunk segment in relation to the pelvic segment ($5.5, \pm 4.4^\circ$) ($F = 4.2; \ p = 0.048$) and greater flexion of the hip joints ($8.8, \pm 3.0^\circ$) ($F = 4.8; \ p = 0.037$) in the PFP group compared to in the control group (trunk: $3.1, \pm 1.9^\circ$ and hips: $6.4, \pm 2.7^\circ$) (Fig. 24).
In the anterior translation, there was no difference for knee angular velocity in flexion/extension (right and left sides pooled) between the PFP subjects (80.3, ± 29.9° s⁻¹) and the controls (83.8, ± 31.4° s⁻¹). There was neither a difference for hip angular velocity (PFP; 47.6, ± 14.9° s⁻¹, controls; 48.2°, ± 16.9° s⁻¹), nor for trunk angular velocity (PFP; 34.6, ± 18.7° s⁻¹, controls; 34.4, ± 15.0° s⁻¹). Linear velocity of COM was also similar compared between PFP subjects (0.21, ± 0.03 ms⁻¹) and controls (0.21, ± 0.02 ms⁻¹) in response to anterior translation.

In the posterior translation, trunk extension was larger in the control group (1.8, ± 0.6°) than in the PFP group (1.2, ± 0.8°) ($F = 5.2; p = 0.029$). Linear velocity of COM in response to posterior translation was similar to the response to anterior translation for both groups (PFP, 0.20, ± 0.04 ms⁻¹ and controls, 0.20, ± 0.02 ms⁻¹).

Kinematic and EMG variables that were significantly different between groups were tested for correlation. Only one significant result was found. In anterior platform translation, early onset of VMO relative to VL correlated with increased angular shift in flexion for the combined hip joints ($r = 0.50; p = 0.05$). EMG variables significantly different between groups were also correlated to anthropometrics (q-angle and knee hyperextension) that differed between groups. No other significant correlations were found.
Popliteus function

In study IV, the specific function of POP with regard to joint position control was investigated in postural tasks. In response to unpredictable perturbations elicited by anterior (AT) and posterior (PT) support surface translations, POP was active before all other muscle in response to anterior as well as posterior direction. The POP response was similar regardless of perturbation direction ($F = 2.5; p = 0.15$) (Fig. 25). In the anterior direction, early POP EMG onset was significant compared to all muscles except GM. In the posterior direction, POP was activated significantly earlier compared to all muscles but VL. EMG onset time differed between muscles ($F_{5,9,35.2} = 8.8; p = 0.007$), and was also different between anterior and posterior translations ($F = 16.2; p = 0.007$) (Fig. 25). When all muscles were compared at the same time, anterior and posterior translations influenced the various muscles differently (interaction of direction and muscle; $F_{2.3,14.0} = 1.6; p = 0.046$). However, when single comparisons were made for each muscle, there were no significant differences for EMG onset in AT and PT except for BF ($F = 38.5; p = 0.001$).

![Graph](image)

Figure 25. Group means and SEM for EMG onset time relative to start of platform motion for anterior and posterior support-surface translation in the unpredictable perturbation.

Whether POP was active in an anticipatory manner i.e. prior to initiation of the balance provocation as denoted by EMG onset in the prime mover of the shoulder (DA), was investigated in self induced provocation of balance in the RT reach and grip task. Relative to the auditory trigger signal, activity occurred first in TA. Approximately 50-100 ms later, the quadriceps muscles were activated in the following order: VL, RF, and VMO. Activity in DA, denoting initiation of balance provocation, occurred at 382 ms after the
auditory trigger signal. After DA, activity in POP and GM occurred almost simultaneously, and BF was activated last of all the muscles monitored (Fig. 26).

In order to be able to compare POP activity between tasks, onset was calculated relative to the other muscles. In the response to support-surface translations, POP was active before VMO ($F(1.0, 8.0) = 38.6; p<0.001$); RF ($F(1.0, 8.0) = 37.8; p<0.001$); VL ($F(1.1, 8.6) = 61.2; p<0.001$); and TA ($F(1.0, 5.0) = 167.5; p<0.001$) compared to the RT task, where it was active after those muscles. In relation to GM and BF, POP was active first in all three conditions. The early onset of POP relative to BF was significantly different between conditions ($F(1.1, 5.4) = 160.4; p=0.001$). The early onset time of the POP relative to GM was not significantly different between conditions (Fig. 27).

In order to investigate knee joint movement associated with POP activity, 3-D kinematics was analyzed. Initial knee joint movement response to support-surface translation was in general either extension or external tibial rotation occurring 0-10 ms after start of platform motion. In response to anterior translation, extension dominated (90%, angular shift $2.7 \pm 1.3^\circ$, angular velocity $52.2 \pm 23.9^\circ \text{s}^{-1}$). In response to PT, external tibial rotation was the most common response (68%, angular shift $2.3 \pm 2.6^\circ$, angular velocity $37.3 \pm 46.5^\circ \text{s}^{-1}$). External rotation of tibia in response to anterior translation occurred in 3% of the trials, while knee extension occurred in response to posterior translation in 6% of the cases.
In 7% of the trials data could not be analyzed due to hidden/unidentified markers in the kinematic recording. Posterior shift of COM in AT (2.8, ± 0.4cm) and anterior shift of COM in PT (3.2, ± 0.6cm) were similar, and COM velocity (AT, 0.3, ± 0.0 m s⁻¹; PT, 0.3, ± 0.1 m s⁻¹) was equal in both directions. The RT task generated a more varied array of movements. At times, the first joint movement that preceded onset of EMG in the POP was knee extension and at other times it was external rotation of the tibia. Sometimes, flexion and internal rotation occurred prior to EMG onset in the POP and in some instances COM started to move first before any activity in POP was defined.
DISCUSSION

This thesis shows that quadriceps activation was specific to the task in open and closed kinetic chain in both persons with and without PFP. This task specificity includes both the EMG onset time of muscle activation and the EMG amplitude showing the degree to which a muscle is activated. There was no difference between persons with PFP and control persons with healthy knees in terms of which relative order the four different heads of the quadriceps (VMO, VML, VL, and RF) were activated. In addition, there were no differences in the relative degree of activity that was measured for the four different heads of the quadriceps. Thus, there were no differences between persons with and without PFP in CKC and OKC that could explain the discrepancies between results in earlier studies. Interestingly, persons with PFP reacted significantly slower to the auditory signal with regard to quadriceps activation performed in the RT task in CKC and OKC.

By comparing persons with PFP and healthy controls, this thesis demonstrates that there were differences in postural reactions in response to unpredictable perturbations of balance. This was particularly evident when the balance was perturbed by anterior translation of the support surface. The VMO was activated significantly earlier in persons with PFP compared to controls with healthy knees. This correlated with increased hip flexion in anterior support surface translation, an increase that was greater in persons with PFP.

This thesis suggests that the popliteus muscle has a particular role in the specific control of knee joint position because the activity appears independent of direction of support surface translation in unpredictable balance perturbations. Anticipatory activity in advance of initiation of self-induced provocation of balance could not be shown.

Results

Task specific muscle activity

Two studies (Study I and II) in this thesis show that the heads of the quadriceps muscle are activated differently in CKC and OKC. There are similarities between the results in some aspects. Both studies show that the
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The greatest difference for EMG onset time and amplitude between CKC and OKC exists for VMO and RF. In CKC, VMO is activated before RF and to a greater extent. In OKC, RF is active before VMO and to a greater extent.

Paper I (see “Discussion” in Paper I) suggests that the muscle that is activated first also may be the one that is most active, and early onset and great amplitude may be correlated. However, this may be an artifact created by the additive effect of the rectified EMG. The muscle that first becomes active may due to being active for longer time, build up more energy and therefore in a small time window (200 ms) show the greatest amplitude.

In other aspects, the results in Study I and II are dissimilar. In Study I, the EMG onsets for the four heads of the quadriceps (VMO, VML, RF, and RF) were more simultaneous in CKC than in OKC. In Study II, more simultaneous onsets for the quadriceps occurred in OKC. This contrast may be because of the differences in setup between Study I and II. In Study I, the subject was seated with full support underneath the legs and both legs kept in same position (90° hip angle and 30° knee angle). This restricted the degrees of freedom, particularly rotation at the hip, to a greater extent than in Study II where only the distal end of the test leg was supported either around the ankle or under the sole of the foot. The thigh of the contralateral leg rested on the seat with the lower leg freely hanging without support under the foot. Thus, the arrangement in Study II allowed a variation in the task execution; Study I restricted variation in task execution. The influence of variations of position in OKC as well as CKC is corroborated by O’Sullivan et al. (2005). They found that there is less than a 0.001% (OKC) or 0.005% (CKC) that all positions would activate VMO equally.

In Study II, force production in CKC was highly correlated with peak EMG amplitude for the vastii (VMO, VML, and VL) and less correlated with activity in RF. In OKC, force production did not correlate with activity in VMO, but it was correlated significantly with activity in VML, RF, and VL. Keeping in mind that the relationship between absolute EMG amplitude and force is unreliable when different subjects and muscles are compared, conclusions on the basis of this finding are weak. However, the result corroborates that the main differences in task specific quadriceps muscle activity for CKC versus OKC reside in VMO and RF.
That RF is activated differently in CKC and OKC is probably because it is a two joint muscle. In OKC, where knee extension is isolated, the contribution of RF is increased as a result of its dual function as a knee extensor and hip flexor. In CKC, action in the kinetic chain is coupled, causing the hip to extend together with the knee. RF is then contracting to extend the knee, but simultaneously it is passively stretched across the hip joint. The coupled hip-knee extension in CKC was evident in the test situation where the subjects had to be firmly strapped down during the test in order to prevent extension at the hip. Thus, due to its functional anatomy, RF is different from the vastii. That RF function differs from the other vastii has been observed by other authors that are questioning whether RF even should be considered a part of the quadriceps (Nene et al. 2004).

VMO activity, it has been claimed, occurs exclusively or mainly in the final degrees of knee extension (Speakman and Weisberg 1977). Therefore, in quadriceps exercises in OKC, full extension and emphasis on final contraction has been advocated. More recent studies on VMO activity, have shown that the muscle is active through out the full range of movement (Mizubayshi et al. 1999). The literature does not describe why VMO would be differently activated in CKC and OKC.

Task specific differences in quadriceps activity were also found in postural reactions in response to anterior versus posterior support surface translation (Study III). The onset of muscle activity was affected differently by directions of perturbation. The greatest difference was (once again) found in RF, which was generally activated later but to a greater degree compared to the vastii in response to anterior platform translation. This difference, similarly to in CKC versus OKC, may be explained by the anatomical differences between the RF and the vastii. In response to anterior platform translation, a relative posterior shift of COM occurred as a result of inertia, preventing initial movement of the pelvic and trunk segments. Consequently, a concomitant and passive hip flexion and knee extension was observed initially when the lower limbs moved forward with the platform translation relative to the trunk. This placed COM posterior to the new area of support, creating a flexion moment across the knee joints. This was followed by active flexion for the hips and trunk and resulted in a bowing motion. The passive shortening of RF in response to anterior platform translation may have decreased motor neuron excitability
(Cresswell et al. 1995). The response to posterior platform motion was exactly opposite. Passive knee flexion was often seen initially. The biggest difference in joint movement occurred as passive extension of the hips and stretching of RF. This may have increased motor neuron excitability (Cresswell et al. 1995). However, initial joint movement is passive, triggered by the horizontal platform forces, and muscle activation follows as a response. It is, therefore, difficult to determine the exact relation between intersegmental dynamics, shift of COM and EMG.

As expected, greater quadriceps activity occurred in response to the greater demands caused by anterior platform translation. The quadriceps muscle must then not only keep the knees extended against the force of gravity, but also counteract the force created by the posterior shift of the body’s COM. When the platform moved posterior, the quadriceps served merely to keep the knees extended against the force of gravity. In both directions of translation, the quadriceps activity contributes to control of knee joint position.

**Differences between PFP and controls**

In this thesis, none of the studies on PFP could prove the hypothesis that persons with PFP have a delayed onset of activation and decreased amplitude in VMO EMG.

There was no deficit in activity of VMO in people with PFP in the CKC and OKC tasks (Study II). This suggests that the discrepancy in the literature with regard to a deficit in VMO activity in PFP subjects, between functional and non-functional tasks, cannot be explained by the nature of closed kinetic chain. A possible explanation for the lack of difference between groups may be the novelty of the task compared to daily life activity. Although the task that was performed in CKC was aimed to mimic a functional weight-bearing situation in contrast to the non-functional OKC task, CKC may not have sufficiently mimicked functionality. Similarly, altered quadriceps activity in PFP subjects could not be demonstrated in lateral stair stepping (Karst and Willet 1995) because a lateral 8 cm high lateral step up may not be considered a habitual every day task.

The discrepancies between studies on functional tasks that show delayed onset in VMO activity relative to VL (Cowan et al. 2001, 2002b) – in
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counter to studies on OKC tasks where no delay in VMO has been found (Karst and Willet 1995; Owings et al. 2002; Sheehy et al. 1998) – might be explained by the differences in the control strategies used by the central nervous system. Many elements of a familiar and functional task are likely to be preprogrammed, but they also depend on feedback for fine-tuning during the execution of the task. Frequent experience with a task may result in a preferred strategy that becomes evident in every day functional tasks. In contrast, activities that have been tested in OKC are often novel and non-functional in daily living activities. This suggests that the absence of a preferred strategy may be due to lack of experience with the task.

Alternatively, the absence of late onset of VMO in the present study could be due to the demand to respond rapidly. The short latency may not have been sufficient to adapt the response, or demands on fast response may have shifted focus and priority, influencing muscular coordination. Differential EMG patterns are evident when demands in regard to execution speed of a task changes (Sliper et al. 2002) that have been identified in postural responses between tasks that are performed as reaction time tasks compared to self-paced tasks (Lee et al. 1987).

In people with PFP, deficits in knee proprioception (Baker et al. 2002) may also contribute to the discrepancy in outcome between studies of stair stepping and OKC tasks. It is plausible that reduced proprioception may affect control of quadriceps activity in frequently used functional tasks. Simple limb movement tasks, such as knee extension, may not be affected by a proprioceptive deficit if they are performed in a feed forward manner without reliance on feedback.

In response to unpredictable perturbations of balance (Study III), there was a difference between persons with PFP and controls with healthy knees. However, in contrast to delayed VMO activity (Cowan et al. 2001, 2002b), VMO was activated earlier in persons with PFP. This was most apparent in response to anterior translation of the support surface, the direction in which the quadriceps was more active. In contrast to the opportunity of choice of strategy in voluntary tasks, an unpredictable balance perturbation rapidly initiates a pre-structured response (Nashner and McCollum 1985), or alternatively, a response controlled by a single feedback control scheme (Park et al. 2004). Although time for a choice of strategy is limited, this does not exclude that the response is modulated over time because postural
responses are learned (Nashner 1976). Earlier experience with a task, such as fear of pain or an overestimation of perceived risk of injury to the knee or falling, might have influenced the postural response. In this study, support of such modulations is the difference in movement response between persons with PFP and healthy controls. In response to anterior translation, PFP subjects reacted with somewhat larger trunk and hip flexion presumably to reduce quadriceps activity and thereby joint loading or alternatively as a modification in response to an overestimation of perceived risk in order to secure a broader safety margin. When the magnitude of perturbation increases, there is a transition toward larger movement at the hip (Runge et al. 1999). This suggests that the PFP subjects reacted as if the perturbation was larger than it actually was.

Another explanation is that PFP subjects were more perturbed than the controls because the larger trunk and hip flexion correlated with a larger posterior shift of COM ($r = 0.5; p = 0.001$). Although the larger posterior shift of COM in PFP subjects was statistically significant, it was very small (approximately 2 mm), and the influence on the biomechanics may be discussed. Arguments against that PFP subjects were more perturbed are that there was no difference between groups in COM linear velocity or joint angular velocity. Movement velocity is the primary source of information that the central nervous system relies on to scale an appropriate correction in response to the coded magnitude of perturbation (Jeka et al. 2004).

There is evidence that leaning is reflected in plastic changes that occurs on several levels in the central nervous system (Nielsen et al. 1993; Perez 2004, 2005). It can be assumed that such modulations occur with habitual and functional activities that are voluntarily initiated as well as functional responses such as to perturbations of balance. These changes are not necessarily primarily issuing alterations in quadriceps activity but may belong to a task specific adaptation of movement initiated by other muscles. Rectus abdominis could for instance, be responsible for the increased trunk and hip flexion seen in the PFP subjects in response to anterior translation.

A similar explanation as above for a modified strategy may apply to the delayed VMO EMG onset in PFP subjects seen in stair stepping, which may be supported by examples of adaptive strategies in persons with PFP when negotiating stairs (Brechter and Powers 2002; Costigan et al. 2002;
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Crossley et al. 2004; Salsich et al. 2001) and in locomotion. These are described in the literature (Powers et al. 1999a).

In this Study (III), the EMG amplitudes of VMO and VML were in general larger than of RF and VL in the PFP group compared to the control group. This was significant for VML relative to VL. In studies on voluntary tasks, either no group differences for ratio between VMO and VL were found (Sheehy et al. 1998), or VMO was less active relative to VL in PFP subjects (Boucher et al.1992; Souza & Gross 1991; Taskiran et al. 1998). The difference between previous studies on voluntary activity and the present study on triggered reactions may be a reflection of task specificity and/or group differences in strategy. It could also be a methodological problem (see Methodological considerations). If this is the case, the validity of all such studies must be questioned.

The relationship between force and EMG amplitude can not be compared between individuals (see Methodological considerations). Therefore, force was measured only as a control variable when comparing EMG amplitudes between PFP subjects and controls in CKC versus OKC (Study II). The ratio of EMG amplitude was closer to one for PFP subjects for all muscles. This was significant for VML and VL. There was no difference in force production between the groups in CKC or OKC neither in MVC nor when performing the RT tasks. However, the muscles were more active in OKC for both groups. This suggests that different strategies are used to generate force in CKC and OKC, which can be compared to the CKC/OKC differences in EMG onset times. In spite of instruction to use the quadriceps to generate force, it appeared that the hip extensors contributed to force production in CKC and that the quadriceps was less engaged than in OKC. The CKC/OKC ratio was closer to one in the PFP subjects, an observation that indicates that they used their quadriceps relatively more than the controls to generate force in CKC compared to in OKC. There are several possible explanations for this. One may be that PFP subjects, due to fear of pain and/or to unload the knee joint, produced less force in OKC and used the hip extensors to generate force in CKC. This would even out the CKC/OKC difference and result in a ratio closer to one.

Interestingly, the PFP subjects had a slower reaction time (i.e., late EMG onset relative to the auditory signal) in both the CKC and OKC (Study II). Slow reaction time has also been observed in patients with lower back pain.
(Luoto et al. 1999) and persons with fibromyalgia (deGier et al. 2003). Fear of pain has been found to be a significant predictor for slower reaction time (deGier et al. 2003) and may be due to slow information processing in the central nervous system (Luoto et al. 1999). In these studies, reaction time is measured in the upper extremity, whereas the study in this thesis regards the lower extremity. This alerts the idea that a presence of slow reaction time in PFP might be related to changes in quadriceps coordination. Whether the problem resides in afferent factors (perception and proprioception), central information processing, or efferent factors, remains unclear. Furthermore, whether the delayed reaction time is a precursor to the development of PFP or a result of pain cannot be determined. Previous studies have suggested that delayed reaction time may increase the risk for development of musculoskeletal pain (Tamiela and Kujala 1992).

This thesis investigates the function of short muscles for specific joint position control. The main result is that POP was activated before all other muscles in response to perturbations to standing balance in both anterior and posterior directions of support surface translations. All onset latencies were shorter than 70 ms. In 80% of the responses, the latencies were shorter than 50 ms. Muscle activity in a postural reaction typically occurs after approximately 70-100 ms and is issued as a pre-structured response to a particular set of cues (Horak and Nashner 1986). To maintain upright posture, the length changes of the thigh and leg muscles are of less concern than the displacement of the trunk and possible counter-productive stretch reflexes are suppressed (Nashner 1976). Therefore, the observed POP activity may be aimed toward control of knee joint position rather than geared to control of posture.

The early contraction of POP is most likely explained by a short latency reflex. The resulting increase of joint stiffness may serve to protect the knee from potential injury when the supra-spinal responses are too slow. The activity may have been triggered by muscle spindle discharge as a result of sudden stretch of POP (Wei et al. 1986) induced by knee extension and/or external rotation of the tibia in response to support surface translations. In comparison, stretch applied to POP in cat preparations evoked discharge from phasic receptors (McIntyre et al. 1978). Johnson and Pope (1978) proposed that the POP, referring to its structure and anatomy, is the most important posterior stabilizer of the knee. This thesis suggests that POP is
important for the integrity of the knee joint also with regard to its particular neuro-motor function.

The fast response from POP, when subjected to stretch in the postural reaction, suggests that the muscle has proprioceptive characteristics important for joint position control. According to Wei et al. (1986), muscle spindles contribute to leg joint position monitoring in cats. In contrast, Vallbo et al. (1981) argued that muscle spindles in the hand do not show explicit responses to active position tracking. However, muscle spindle contribution may differ with regard to muscle function – manipulative versus postural – as well as species divergences. Although the low muscle spindle density in POP (6.5 g⁻¹) (Amonoo-Kuofi 1989; Cooper 1960) implies that it is not under fine neural control, this does not exclude stretch sensitivity because high spindle density may not necessarily enhance stretch sensitivity (Abrahams et al. 1975). Instead, it appears that the location (Meyer-Lohmann et al. 1974) and arrangement (Richmond and Abrahams 1975) of muscle spindles decides the stretch sensitivity. In POP, muscle spindles are located mainly along the upper border and in the distal two-thirds of the muscle. Half of these spindles exist in conjunctive forms (Amonoo-Kuofi 1989). The arrangement of muscle spindles into complexes may enhance their collective ability of response. When fusimotor fibers are shared by two or three spindles, stretch will exert an effect on more spindles than would single unshared fibers (Richmond and Abrahams 1975). Thus, despite low muscle spindle density and because of the pattern and localization of spindles, POP may contribute to motor control of knee joint position.

In the RT task, activity in POP did not precede initiation of activity in the prime mover, but occurred after DA. Instead, anticipatory activity occurred in TA and the quadriceps before the initiation of self-induced provocation to balance. Kinematic data did not show any consistency that indicated whether POP activity was triggered in response to muscle stretch or if it was issued from a feed-forward pre-structured response either for postural or knee joint control purpose.
Methodological considerations

**EMG**

There are a number of considerations to pay attention to both when applying EMG, performing the signal analysis, and interpreting the results. An important notion to keep in mind is that the signal that emerges is not the actual muscle activity, but only a representation of the same.

In all studies, surface electrodes were used. With this technique there is always a risk for cross talk from other muscles. Measures to optimize the EMG recording were taken by careful electrode placement and reduction of impedance by cleaning the skin and excluding severely overweight persons. The best way to reduce cross talk is to use intra-muscular electrodes. However, invasive techniques were not used because that would have reduced the number of subjects willing to participate. Thus intramuscular electrodes were only used in Study IV because it is the only way to record activity from the deeply situated POP.

Although careful electrode placement was adhered to in all studies, this does not rule out the influence on the EMG signal due to individual anatomical differences such as individual variation in muscle shape and localization of the motor point. This will potentially influence EMG onset time. With depolarization velocity (4 m s⁻¹) taken into consideration, individual variances in motor point location may in large muscles account for as much as 10 ms difference for the recorded onset of muscle activity (DeLuca 1997). Inter-individual variances were of less a concern in Study I and Study IV because subjects where compared to themselves between different tasks. In Study II and III, subjects were compared on a group level and the results were interpreted with respect to weakness of the method. In Study III, onset time differences were greater than 10 ms.

Of further consideration for the specificity of determination of onset time is the use of algorithms and visual inspection. To optimize correctness and reliability, a computer aided protocol where algorithm determined onset was visually inspected and corrected was used according to Staude and Wolf (1999). Two algorithms were tried, and the autoregressive algorithm that was finally used in Study II-IV proved better than the min-max algorithm that was tried first. Although an algorithm is reliable because it reproduces the same result each time, it is not always correct. In approximately 20% of
the readings, manual correction was necessary. The visual determination is probably more correct (but less reliable) although it is still considered fair (Hodges and Bui 1996). Best reliability for manual determination of onset is achieved with only one examiner. In all studies, all visual inspections and corrections were made by the same person and in a blinded fashion to avoid examiner bias. Reliability for visual onset determination has been tested by Cowan et al. (2001) and decided to ± 10 ms. Onset time differences between muscles reported in Study I were less than this and in Study III and IV were larger. However, in Study I, variations due to anatomical differences between subjects did not apply, which eliminates one possible source of error. When there was any doubt about the determination point for onset, data were discarded.

The determined onset of EMG activity has to be interpreted relative to a reference point. In Study II and IV, onset was determined relative to the audible signal that served as a trigger for the RT task in OKC and CKC and in the reach and grip task. Onset relative to start of platform motion was determined in Study III and IV. These reference points yielded information in terms of reaction time for voluntary activity and postural response.

In Study I, onset of force was used as a reference point; however, for a number of reasons this point of reference is not stable and should be used with reservation. First, EMG activity precedes the output of force generated by the muscle by 10-100 ms due to fluctuations in the excitation-contraction coupling (Rios et al. 1992). Several muscles contribute to the development of the force across a joint, and force cannot (in vivo) be separately traced to any particular muscle. Therefore, onset of EMG for a particular portion of quadriceps cannot be directly attributed to onset of force. Second, time to onset of force is due to electro-mechanical delay (EMD), depending on muscle length and joint position owing to the degree of laxity in the tissue and the time it takes to gain enough muscle tension for the force to be transferred through tendon to bone (Vos et al. 1991). This poses a validity problem in determination of EMG onset time in Study I.

To solve the problem with unstable points of reference, determination of inter-muscular coordination via direct comparisons of EMG onset times between different muscles were done in all studies. This allowed onsets to be compared without respect to individual differences in reaction time and EMD. However, in Study I, only EMG onset times relative to onset of force were presented in the published paper. (This was done on
recommendation from the reviewer who believed that the presentation of EMG onset relative to force and relative between different muscles was the same thing.) Therefore, relative EMG onsets for muscle pairs were removed from the results in that paper (see Paper 1). Despite the potential fluctuations with EMD, EMG onsets relative to force and relative between muscles exhibited the same inter-muscular order of activation. However, with respect to the inherent fluctuation described by Rios et al. (1992), relative EMG onsets for muscle pairs may have been a more correct presentation.

When interpreting the results of the present studies, EMG amplitude, as with onset, depends on electrode placement and localization of the motor point. The EMG signal diminishes with the distance from the motor point to the electrodes (DeLuca 1997), and the amplitude contains the summated degree of activity from the muscles fibers within the area of detection; i.e., the amplitudes from each individual depolarization are added. It is important to note that amplitudes will sometimes cancel rather than add, depending on coinciding positive and negative charges. This was not controlled for in the present studies. The amplitude of muscle activity increases linearly with the increase or force that is produced. However, this is valid only within an individual for the same muscle when the same joint position and muscle length is kept and with identical electrode placement – the measurement of the same muscle volume. When different individuals, different muscles, or different volumes or parts of the muscle are compared, no correlation between the size of the amplitude and the force production can be guarantied. Inter-individual differences exist also in coordination strategies and muscle anatomy. Despite these problems, comparisons between groups in Study II and III were conducted but with reservation paid to the considerations above with regard interpretation of the results. In Study I, the above considerations were of less concern because comparisons were made within subjects between tasks. To optimize that the same muscle volumes were measured, identical joint configurations were secured in the different tasks that were compared. In Study I and II the same hip and knee joint angles were kept in CKC and OKC, and in Study III and IV all subjects stood in a standardized starting position at the initiation of the different balance perturbations.

In order to compare between subjects and between muscles, the EMG amplitude was normalized to MVC. Values normalized to MVC decide the percent of muscle activity used in the task. This percent can be compared
between muscles and between subjects; however, there is much debate whether this method is valid or good enough. Although all measures were taken to ensure that the MVC efforts were optimally performed, it is still difficult to determine to what degree an individual is able to voluntarily recruit their muscles. In Study II, feedback of force production was used to achieve MVC although force production may not be a valid measure of muscle activation because there are many strategies to produce force by the means of using other muscles. Although the subjects were informed to concentrate on quadriceps muscle contraction rather than force production in CKC, subjects tended to use the hip extensors to push with maximum force into the resistance under the foot. In OKC, isolation of the quadriceps was much easier when movement was restricted to a single joint. This tendency makes clear instructions crucial, but it is not enough to ensure proper technique. The degree to which an individual is able to voluntarily contract a muscle varies (Strojnik 1999), and experience with pain may reduce the voluntary drive of muscle activity further (O’Reilly et al. 1989). Interpretation of the results of EMG amplitude has to be done with these limitations in mind. If a person produces little activity in the MVC, this very little activity may be fully engaged already at a low level of intensity in a task. This may then give a false impression that this muscle is sufficiently engaged when in fact it is quite the opposite. In Study III, PFP subjects activated VMO less relative to VL and RF in MVC, and control subjects activated VMO more than VL. This leads to opposite ratios for MVC values compared to ratios based on values normalized to MVC. In Study III, therefore, the ratio of normalized values show an increased VMO activity in PFP subjects in the postural response, whereas MVC values suggest that the PFP subjects had a decreased ability to activate VMO voluntarily.

In Study II and III, the attempt to find the time to peak amplitude did not succeed to satisfaction. The idea was discarded due to difficulties to create a valid way of determination. One reason for this was that some readings presented multiple peaks and that great variation in strategies made it increasingly complicated to establish a consensus for interpretation of time to peak amplitude. Therefore, in Study II and III, only peak amplitude was considered.
Discussion

Kinematics

Kinematics was used in Study III and IV. The optical kinematic system was based on five cameras detecting motion from spherical reflex markers via infrared light. Although resolution technically is as high as 0.1 mm, the actual resolution depends on the distance between cameras and markers. An initial calibration was always performed ahead of capture by using a wand with spherical markers at each end (74.9 cm between center of markers) (Cappello et al. 1997). The standard deviation for the measured distance between markers was calculated, producing a measure of specificity (3.2 mm). In this thesis, it was not calculated to what extent this standard deviation influenced the values for measured segmental motion and rotation around the axes.

According to recommendations by Qualisys (Pro Reflex, Qualisys Gothenburg, Sweden), markers were placed on designated anatomical positions on the skin or on tight clothing. The disadvantage with this method is that the skin or the clothing slides over the underlying structures. The degree of sliding varies between locations on the body and between individuals. There is no standard for the magnitude of this slide. This decreases to an unknown degree both validity and reliability of the accuracy of the estimated motion around the joint center (Cappello et al. 1997). The use of marker clusters mounted on a firm plate or frame would solve this problem (Cappello et al. 1997). This approach was tried; although the internal constellation between markers in the cluster remained stable, the cluster plates did slide. By the end of one session, the thigh cluster had moved caudally, approximately 4 mm. Thus the skin marker set up was kept.

With regard to how the 3-D motion is calculated, there are other methods than the Cardan/Euler (cf. Woltring 1994) used in this thesis. It needs to be made clear that the analyzed movements are based on algorithms. Thus the use of other methods for analyses may give increased or decreased values for the resulting joint angles. However, with adherence to the same method, the internal validity is not threatened, and the relative differences for the same joint and axes between subjects and tasks should not be affected.
Discussion

**Kinetics**

In Study I, a force transducer (Validyne, USA) was mounted into the resistance for CKC and OKC. Only the onset (not the magnitude of force) was measured in this study. In Study II, force was measured with an isokinetic dynamometer (Kin Com, Chattanooga, Illinois). The apparatus was modified for CKC to permit the same joint angles as in OKC. With this arrangement, computer aided calculations of moment arm in CKC was not possible. With moment arm unknown, the force contributing to the torque could not be compared between CKC and OKC. Force data, however, was compared within tasks between PFP and controls.

**Subjects**

In Study I, both men (n=3) and women (n=7) participated. The aim of the study was to investigate the difference in muscle activity between CKC and OKC. The ideal group would have been half men and half women. Although no difference in performance between men and women was found, the sample may have been too small to show any gender differences.

In the studies on PFP, a homogenous group of subjects was preferred. In spite of measures taken to find a homogenous sample, the group was not perfectly homogenous. A harder screening would probably resulted in too few subjects. Furthermore, the diversity in the sample is a reflection of the diversity in the PFP population at large (Thomeé et al. 1999). The heterogeneity in the PFP population may be a problem in studying the group. Samples may be slightly different in the different studies, which may explain the diversity of findings in the different studies, including this thesis. The duration and severity of pain and whether pain was present at the time of testing may vary between studies, and they are often sparsely described. In the present studies, only subjects with pain for at least one year were chosen, and pain was not present when entering the test in the laboratory. In other studies, the PFP subjects had pain anywhere from one month (Cowan et al. 2001); however, most studies do not state how long the pain had been present. Whether there was pain present during the test was not stated in any study. This makes comparisons between studies difficult. There are many variables not controlled for in studies on PFP that are inherent in the profile of the population. This is difficult to overcome and poses a problem with studies on this population.
Discussion

External validity

Although ten persons (Study I and IV) may seem to be too few to represent the baseline for normality, this is often the number of subjects chosen in EMG studies and studies on kinematics. Numerous repetitions of the same task are performed in order to obtain a reliable measure of variation in performance in the individual as well as in the group. However, this does not necessarily strengthen the external validity.

Similar to the studies on normality, the studies on PFP (Study II and III) involved rather few participants and a large number of trials for each task. When studies are performed on patients, larger variability may be expected than for healthy subjects. Seventeen patients and the same number of controls (matched for age, gender, height, and weight) were tested. Because PFP is characterized by a rather heterogeneous group, it is expected that a larger sample than the 17 included in these studies would change the results. To test this, preliminary analyses were performed halfway through the data collection. The results of those analyses pointed in the same direction as the final results. No significant differences between preliminary and final results were found. Thus the addition of more data strengthened the significance of the preliminary results at the “half time” analysis. This indicates that the sample may be representative for the PFP population. Therefore, it is probable that a larger sample would have further strengthened the final result rather than changed it. On this basis, the external validity appears good as long as the same inclusion criteria are applied.

Clinical implications

Study I suggests that CKC may be a better choice of exercise for persons with PFP, on the basis that training designed to remedy muscular imbalances as described for PFP (cf. Cowan et al. 2001, 2002b) should be particularly aimed at VMO. This was one reason why a similar protocol with CKC and OKC tasks were repeated with PFP subjects. The PFP subjects did not differ from controls with healthy knees in terms of recruitment order or amplitude for the four heads of the quadriceps. It could be expected that the PFP patients in Study II may have delayed VMO activity relative to VL in more functional tasks, such as negotiating stairs. If this is true, the finding that VMO is better activated in CKC may have
implications for clinical practice, but with respect to some reservations. If a VMO deficit emerges in functional tasks such as stair stepping, but not in CKC and OKC exercises using an apparatus, the benefit from training in an apparatus were no VMO deficit is present may be challenged in terms of transfer effects to other tasks. If non-functional training in an apparatus is used, attention should not only be paid to whether training is performed in CKC or OKC, but also to how the specific design of the apparatus, the subject's position in the apparatus, and the manner in which the exercise is performed.

In Study II and III, clinical implications may follow from the results and suggest that focus may be directed toward task specific performance rather than presumptions of deficits in quadriceps coordination. The results in this thesis together with previous studies suggest that differences in quadriceps activity in persons with PFP may depend on the task. The results from the kinematic analyses in this thesis and previous kinematic studies suggest that persons with PFP are using compensatory strategies. The present study suggests that these strategies may be permanent since they did not have pain at the time of testing. The compensatory strategy may be an attempt to decrease the load on the quadriceps as well as the patellofemoral joint due to experience with pain or muscle weakness. Muscle weakness may result from habitual unloading to avoid pain. Differences in quadriceps activation may be a part of or brought about by this compensatory strategy. Because compensation may become a permanent habit, even when the pain is absent, intervention aimed to normalize muscle function should be directed toward task performance as well as general and specific muscle training.

This thesis suggests that POP contributes to the control of the knee joint, at least in unpredictable perturbations of standing balance. This implies that the muscles’ importance for knee joint integrity should be noted. The consequence of injury to the posterior aspects of the knee as well as the knee function after surgical reconstruction involving POP should be considered with this in mind. The passive function of POP can successfully be restored, but there is currently no method that will restore its active function (Wang et al. 2004). In valgus deformities of the knee, a number of structures, including POP contribute to the mal-alignment. Therefore, POP is quite often cut or released in order to correct the biomechanical function. There are, however, techniques that in most cases may obviate the need for release of POP (Politi
and Scott 2004). In order to optimize knee joint control and stability, these techniques should be considered when possible.

Future research

On the basis of the results in this thesis, it is suggested that future research should involve more research on task specific constraints. A better understanding for normal variations in movement performance and the influence of various constraints would make it easier to notice and judge abnormalities in motor behavior. More studies including kinematic analysis and EMG are needed to confirm the correlations and possible causative relationships between quadriceps muscle function and movement strategies. Training studies involving movement analysis and EMG may help discern the existence of cause and effect between muscle coordination and motor behavior. A new line of research involving reaction time may be valuable not only in the research with regard to PFP, but also for other types of pain. Finally, the principle of short muscles’ particular function in joint position control needs to be investigated further, not only for the knee. Other joints, such as the ankle, hip and shoulder are subject to pain and instability where short muscle function may play an important part. Task specific function needs to be related to joint- and muscle-specific biomechanical constraints.
GENERAL CONCLUSIONS

- The four heads of quadriceps are activated differently in terms of onset and amplitude of EMG activity in CKC and OKC in subjects with healthy knees. VMO is activated earlier and to a greater degree in CKC. RF is activated earlier and to a greater degree in OKC. (Study I)
- The four heads of quadriceps are not activated differently in persons with PFP compared to controls with healthy knees in terms of onset and amplitude of EMG activity in CKC and OKC. (Study II)
- There are no differences in quadriceps control between persons with PFP and controls with healthy knees in CKC and OKC that can explain inconsistent findings in the literature of vastii control deficits in persons with PFP. (Study II)
- The four heads of the quadriceps are activated differently in persons with PFP compared to controls with healthy knees in a triggered postural reaction. VMO is activated earlier in persons with PFP, particularly in the anterior translation of the support surface where quadriceps activity is greater (Study III)
- The kinematic pattern in response to a triggered postural reaction is different in persons with PFP compared to control persons with healthy knees. PFP persons responded with greater trunk and hip flexion in response to anterior translation of the support surface. (Study III)
- Early VMO activity correlated with increased trunk and hip flexion in response to a triggered postural reaction. (Study III)
- The popliteus muscle appears to specifically control knee joint position, at least in unpredictable perturbations to balance. (Study IV)
- The popliteus muscle is not active in an anticipatory manner prior to initiation of self-induced provocation of standing balance. (Study IV)
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