Kinematic and kinetic features of normal level walking in patellofemoral pain syndrome: More than a sagittal plane alteration

Marco Paoloni a, b, *, Massimiliano Mangone b, Giancarlo Fratocchi a, Massimiliano Murgia a, b, Vincenzo Maria Saraceni a, b, Valter Santilli a, b

a Physical Medicine and Rehabilitation Unit, Azienda Policlinico Umberto I, Rome, Italy
b Board of Physical Medicine and Rehabilitation, Department of Orthopaedic Science, “Sapienza” University, Piazzale Aldo Moro 3, 00185 Rome, Italy

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1. Introduction

Patellofemoral pain syndrome (PFPS) is a term used for a variety of pathologies or anatomical abnormalities leading to a type of anterior knee pain (Witvrouw et al., 2005) that typically occurs with activity and is exacerbated by stair climbing and prolonged sitting. Alterations in knee kinetics and kinematics remain controversial in people affected by PFPS. Reduced knee flexion during loading response phase (LR) of walking has been found in some studies (Dillon et al., 1983; Nadeau et al., 1997), though not in others (Heino Brechter and Powers, 2002). From a kinetic point of view, PFPS patients generally display a reduced knee extensor moment during the LR (Besier et al., 2009; Heino Brechter and Powers, 2002), and a reduced peak vertical ground reaction force (GRF) (Powers et al., 1996, 1997, 1999). Moreover, women with PFPS exhibit different lower extremity mechanics in a variety of activities with progressive knee loading when compared with controls (Willson and Davis, 2008). From a kinetic point of view, PFPS patients generally display a reduced knee extensor moment during the LR (Besier et al., 2009; Heino Brechter and Powers, 2002), and a reduced peak vertical ground reaction force (GRF) (Powers et al., 1996, 1997, 1999). Heino Brechter and Powers (2002) found no difference in the patellofemoral joint (PFJ) forces between subjects with and without PFPS. They did, however, establish that the contact area between the femur and patella was reduced in subjects in the PFPS group, who consequently displayed increased PFJ stress. The study of the kinematics and kinetics involved in the frontal and transversal planes has not been considered a major goal of biomechanical research in the field of PFPS, largely because measurement of the sagittal plane alone may yield an indirect evaluation of patella functioning. Determination of kinetic and kinematic changes that occur in the knee joint in both the frontal and transversal planes may, however, be relevant to the biomechanical analysis in the clinical setting. Indeed, it has recently been suggested that increased knee abductor and knee external rotator moments during the stance phase of stair climbing and locomotion up an incline may be considered as biomechanical markers in the assessment of mechanisms involved in the development of knee osteoarthritis (OA) in the elderly (Karamanidis and Arampatzis, 2009). It is also suggested that kinematic and kinetic changes in the transversal plane at the knee joint play a specific role in the initiation of local degenerative cartilage alterations by shifting the mechanical load within the load-bearing regions of the knee (Andriacchi et al., 2004). This fact supports the numerous reports of an increased incidence of knee OA in patients who have experienced abnormal joint motion and...
mechanical load, such as those with anterior cruciate ligament injury or generalized joint laxity (Andriacchi et al., 2004).

We hypothesized that PFPS subjects may display abnormal knee joint moments in the frontal and transversal planes during gait due to a neuromuscular dysfunction that normally occurs in such patients. Subjects with PFSP, in fact, display a dysfunction of PFJ neuromotor control as a result of an imbalance of vastus medialis obliquus (VMO) and vastus lateralis (VL) activity (Cowan et al., 2001; Witvrouw et al., 1996), there being a significant delay in the electromyographic onset of the VMO when compared with that of the VL (Cowan et al., 2001). This fact may lead to abnormal patellar tracking within the trochlear groove. It should be considered, furthermore, that the quadriceps muscle, whose function is altered in PFPS subjects, provides the most knee stability on the frontal plane (Shelburne et al., 2006) and may influence tibial rotation (Li et al., 1999).

We therefore designed an explanatory (Bender and Lange, 2001), cross-sectional trial to investigate the kinetic and kinematic features on the transversal, frontal and sagittal planes of the walking pattern in PFPS subjects by means of instrumental gait analysis and to compare these features with those of a control group of healthy subjects.

2. Methods

2.1. Subjects

The experimental group (EG) was composed of 9 patients (2 men, 7 women) affected by PFPS (mean disease duration: 9.5 ± 1.5 months). In order to be included, patients had to report anterior or retropatellar knee pain in at least two of the following activities: prolonged sitting, climbing stairs, squatting, running, kneeling, and hopping or jumping. In addition, they had to have good palpatory palpation of the patella, to have a pain level of 3 cm or more on a 10-cm visual analogue scale (VAS) while stepping down from a 25-cm step or during a double leg squat, to have had symptoms for at least 1 month, to have an average pain level of 3 cm or more on a 10-cm VAS, and to have had an insidious onset of symptoms unrelated to a traumatic incident. Participants were excluded if they had the following: a recent history (within 6 months) of knee surgery or of patellar injury or generalized joint laxity (Andriacchi et al., 2004).

Subjects with PFJS generally have anterior knee pain that is exacerbated by knee loading activities. It has been hypothesized that the load exerted by walking upon the PFJ is not sufficient to reveal consistent biomechanical alterations, it being suggested that stair ambulation is a more appropriate means of eliciting such changes since the latter activity loads the PFJ to a greater degree (Costigan et al., 2002). Strategies that tend to minimize knee loading during gait have been widely described in PFPS patients with gait limitations (Nadeau et al., 1997; Powers et al., 1997). Moreover, as walking is the most important loading activity performed on a daily basis, any factors involved in gait that may explain joint pathology progression warrant investigation.

The results of our study confirm our initial hypothesis, i.e. that altered knee joint moments may be observed not only on the sagittal plane but also on the transversal and frontal planes. It is noteworthy that the present study shows, to the best of our knowledge, that the swing phase was analyzed in the EG, while either the right or left side was randomly used for the analysis in the CG.

Mean velocity (m/s) was assessed to ensure that any kinetic and/or kinematic differences between groups were not due to differences in gait speed. Swing velocity (distance travelled in the swing/swing duration) was also assessed.

Three-dimensional marker trajectories during walking were obtained by means of a frame-by-frame tracking system (Tracklab, BTS, Milano, Italy) and joint angular excursion, defined as a rotation of the distal segment relative to the proximal segment in our biomechanical model (Vaughan et al., 1999), was calculated; joint excursion data were normalized to the stride duration and reduced to 100 samples over the gait cycle. The following parameters were considered for the kinematic evaluation: (i) knee flexion angle at heel contact (HC), (ii) knee flexion range of movement (ROM) during the LR defined as the first sub-phase from initial contact until contralateral toe-off, i.e., 0–12% of the gait cycle (Vaughan et al., 1999), (iii) hip and knee abduction peak during the LR and (iv) hip and knee rotation ROM during the whole gait cycle.

Net internal joint moments were calculated in means of an inverse dynamics approach. Joint moments were normalized to the subject’s body weight. We considered the following parameters for the kinetic analysis: (i) in the LR, we assessed the hip and knee extensor, abductor and external rotator moment peaks and (ii) in the terminal stance sub-phase (TS), we assessed the hip flexor, abductor and internal rotator moment peaks, as well as the knee extensor, abductor and internal rotator moment peaks. We also considered the peak values of the vertical GRF curve.

2.3. Statistical analysis

Statistical analysis was performed using the SAS8.2 (SAS Institute Inc., Cary, NC, USA). Data normality was verified by means of the Shapiro–Wilk test. The mean ± standard deviation of each parameter was calculated in both the EG and CG. The unpaired t-test or Mann–Whitney test was used to evaluate the significance of differences between the EG and CG. A p value of less than 0.01 was considered statistically significant.

3. Results

No significant differences were observed between PFPS subjects and controls in mean age [EG: 28.1 ± 8.1 (range 19–45) years; CG 28.3 ± 5.9 (range 21–38) years], in mean height [EG: 1.71 ± 0.09 (range 1.60–1.82) m; CG: 1.70 ± 0.09 (range 1.60–1.86) m] or in mean body weight [EG: 64.4 ± 0.95 (range 55–80) kg; CG: 64.2 ± 10.8 (range 53–83) kg]. The mean velocity did not differ significantly between groups [EG 1.1 ± 0.15 m/s; CG 1.15 ± 0.16 m/s; p=0.5]. Patients in the EG, however, displayed a significantly slower swing phase velocity than those in the CG [EG 2.44 ± 0.28 m/s; CG 2.95 ± 0.46 m/s; p=0.01]. The kinematic results are summarized in Table 1. A greater degree of adduction was observed during the LR in the knee of PFPS patients than in that of controls. The kinetic results are provided in Table 2. During the LR, patients in the EG exhibited an increase in knee external rotator moment associated with a marked reduction in the knee extensor moment, when compared with subjects in the CG. Increased hip and knee abductor moment was also noted in EG. In the TS, knee extensor moment was significantly lower in the EG than in the CG. Hip abductor moment in the TS was also significantly greater in the EG than in CG. The results of the GRF analysis are provided in Table 3. The vertical GRF peak at HC was significantly lower in the EG than in the CG (Fig. 1), whereas no differences were observed between the two groups in any of the other parameters analyzed.

4. Discussion

Subjects with PFJS generally have anterior knee pain that is exacerbated by knee loading activities. It has been hypothesized that the load exerted by walking upon the PFJ is not sufficient to reveal consistent biomechanical alterations, it being suggested that stair ambulation is a more appropriate means of eliciting such changes since the latter activity loads the PFJ to a greater degree (Costigan et al., 2002). Strategies that tend to minimize knee loading during gait have been widely described in PFPS patients with gait limitations (Nadeau et al., 1997; Powers et al., 1997). Moreover, as walking is the most important loading activity performed on a daily basis, any factors involved in gait that may explain joint pathology progression warrant investigation.

The results of our study confirm our initial hypothesis, i.e. that altered knee joint moments may be observed not only on the sagittal plane but also on the transversal and frontal planes. It is noteworthy that the present study shows, to the best of our knowledge, that the swing phase was analyzed in the EG, while either the right or left side was randomly used for the analysis in the CG.

knowledge for the first time, that such alterations are likely to occur during walking.

Particularly, PFPS patients in our sample displayed a markedly increased knee external rotator moment in the LR. One possible causative mechanism for this increased knee external rotator moment may be found in the altered VL and VMO function. Indeed, the delay in VMO activation often described in the literature may determine an initial isolated VL contraction that creates an external rotator moment. One obvious limitation of the present study is that we did not perform an EMG evaluation of VMO/VL function in our sample of patients. We may assume, however, that a delay in VMO activation did occur because it is a typical feature of PFPS patients, as has been extensively described in the literature (Cowan et al., 2001; Witvrouw et al., 1996). Further researches, specifically aimed at analyzing the quadriceps muscular function and its relationship with transversal plane knee kinetics, are however warranted to confirm this hypothesis. Another possible explanation may lie in the abnormal patellar tracking observed in PFPS subjects. An in vivo evaluation during squatting recently demonstrated that the patellae of subjects with PFPS were subject to progressive lateral spin during knee flexion, with the difference between PFPS and control subjects becoming evident from as little as 30° knee flexion (Wilson et al., 2009). In contrast to findings by Willson and Davis (2008), we did not detect knee or hip joint rotation alterations in the EG. Since we considered gait alone in our study, we cannot rule out that such alterations may emerge during activities requiring a greater degree of loading.

On the frontal plane, our patients displayed a greater knee adduction peak than controls, which is associated with a significantly increased knee abductor moment peak in the LR, though not in the TS. The combination of increased frontal plane kinetics and kinematics is interesting from a biomechanical perspective. It may be argued that these changes determine alterations in the direction and magnitude of the muscle forces on the patella. Worthy of note is the fact that our PFPS patients

### Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Experimental group</th>
<th>Control group</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knee flexion angle at HC (deg.)</td>
<td>8.17 (5.15)</td>
<td>6.78 (7.59)</td>
<td>0.65a</td>
</tr>
<tr>
<td>Knee flex-extension ROM during LR (deg.)</td>
<td>6.62 (4.24)</td>
<td>6.62 (4.34)</td>
<td>0.99a</td>
</tr>
<tr>
<td>Knee adduction peak during LR (deg.)</td>
<td>2.12 (1.4)</td>
<td>0.09 (1.5)</td>
<td>0.009a</td>
</tr>
<tr>
<td>Knee rotation ROM (deg.)</td>
<td>16.86 (5.9)</td>
<td>18.73 (8.6)</td>
<td>0.60b</td>
</tr>
<tr>
<td>Hip adduction peak during LR (deg.)</td>
<td>6.42 (3.9)</td>
<td>6.53 (2.5)</td>
<td>0.94b</td>
</tr>
<tr>
<td>Hip rotation ROM (deg.)</td>
<td>13.04 (5.0)</td>
<td>11.82 (3.7)</td>
<td>0.57b</td>
</tr>
</tbody>
</table>

Mean values (SD) of kinematic parameters. Significant differences are in bold. ROM=range of movement; HC=heel contact; LR=loading response.

a Unpaired t-test.  
b Mann–Whitney test.

### Table 2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Experimental group</th>
<th>Control group</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loading response Hip abductor moment</td>
<td>0.898 (0.24)</td>
<td>0.508 (0.17)</td>
<td>0.001b</td>
</tr>
<tr>
<td>Loading response Hip extensor moment</td>
<td>0.310 (0.19)</td>
<td>0.210 (0.12)</td>
<td>0.20c</td>
</tr>
<tr>
<td>Loading response Hip external rotator moment</td>
<td>0.107 (0.03)</td>
<td>0.09 (0.03)</td>
<td>0.25a</td>
</tr>
<tr>
<td>Loading response Knee abductor moment</td>
<td>0.555 (0.13)</td>
<td>0.398 (0.13)</td>
<td>0.01b</td>
</tr>
<tr>
<td>Loading response Knee external rotator moment</td>
<td>0.071 (0.02)</td>
<td>0.042 (0.02)</td>
<td>0.007b</td>
</tr>
<tr>
<td>Loading response Knee extensor moment</td>
<td>0.027 (0.01)</td>
<td>0.077 (0.025)</td>
<td>0.005b</td>
</tr>
<tr>
<td>Terminal stance Hip abductor moment</td>
<td>0.842 (0.26)</td>
<td>0.450 (0.18)</td>
<td>0.002a</td>
</tr>
<tr>
<td>Terminal stance Hip flexor moment</td>
<td>−0.378 (0.20)</td>
<td>−0.559 (0.18)</td>
<td>0.06a</td>
</tr>
<tr>
<td>Terminal stance Hip internal rotator moment</td>
<td>−0.138 (0.04)</td>
<td>−0.121 (0.06)</td>
<td>0.49a</td>
</tr>
<tr>
<td>Terminal stance Knee abductor moment</td>
<td>0.477 (0.10)</td>
<td>0.376 (0.14)</td>
<td>0.10a</td>
</tr>
<tr>
<td>Terminal stance Knee internal rotator moment</td>
<td>−0.075 (0.02)</td>
<td>−0.100 (0.04)</td>
<td>0.11a</td>
</tr>
<tr>
<td>Terminal stance Knee extensor moment</td>
<td>0.083 (0.06)</td>
<td>0.329 (0.20)</td>
<td>0.003b</td>
</tr>
</tbody>
</table>

Mean values (SD) of kinetic parameters. Significant differences are in bold.

a Unpaired t-test.  
b Mann–Whitney test.  
c Unpaired t-test with Welch correction.

### Table 3

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Experimental group</th>
<th>% of GC</th>
<th>Control group</th>
<th>% of GC</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical force (N/kg)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak at HC (iGRF)</td>
<td>40.7 (15.6)</td>
<td>2</td>
<td>56.7 (9.1)</td>
<td>2</td>
<td>0.01a</td>
</tr>
<tr>
<td>Peak at LR</td>
<td>95.5 (25.0)</td>
<td>16</td>
<td>99.8 (6.6)</td>
<td>17</td>
<td>0.63b</td>
</tr>
<tr>
<td>Peak at TS</td>
<td>98.2 (23.9)</td>
<td>46</td>
<td>110.6 (8.2)</td>
<td>47</td>
<td>0.17b</td>
</tr>
</tbody>
</table>

Mean values (SD) of ground reaction force (GRF) parameters. For each value the percentage of gait cycle (GC) during which the event occurred is shown. HC=heel contact; LR=loading response; TS=terminal stance; iGRF=impact GRF (see text for clarification).

a Unpaired t-test.  
b Mann–Whitney test.
displayed a marked reduction in the knee extensor moment in the same gait cycle sub-phases. One appealing hypothesis is that a redistribution occurred among quadriceps moments from the extensor to external rotator and abductor. Indeed, in keeping with previous findings (Heino Brechter and Powers, 2002; Powers et al., 1997, 1999), we did not find any differences in the sagittal kinematic features of the knee joint during stance, with both patients and controls exhibiting a small degree of knee flexion in LR, which is responsible for weight acceptance, during the first phase of gait cycle. We believe that it would be interesting to investigate a detailed muscle model to test this hypothesis in future studies. An alternative explanation for a reduced knee extensor moment may be the need to unload the knee joint to avoid pain. This kinetic feature is associated with a significantly reduced vertical GRF at the HC. The short spike of force in the vertical GRF vector immediately following the HC, which is called the impact ground reaction force peak (iGRF) (Henriksen et al., 2008), is thought to reflect the abrupt vertical deceleration of the center of mass immediately after foot contact with the ground. Reduced iGRF may be determined by altered neuromotor control due to knee pathologies, as the presence of pain alone appears to be insufficient to determine such an alteration (Henriksen et al., 2008). Impact GRF production may be influenced by both walking speed (Voloshin, 2000) and knee joint angle at the HC (Lafortune et al., 1996). In our sample, however, we cannot exclude any such interaction as there was no difference between the EG and the CG in these factors. Interestingly, we observed lower swing velocity in the EG than in the CG. Grenholm et al. (2009) found that women with long-term anterior knee pain, compared with healthy controls, display a reduced knee angular velocity in the stance leg while descending stairs, even though the overall walking speed remains similar. This reduced speed may place less demand on the swing leg, thereby allowing the latter to absorb the impact of foot contact when lowering the body and thus reduce joint reaction forces. One explanation for these findings may be that PFPS patients reduce the swing speed of their symptomatic limb in order to reduce the iGRF and, consequently, also reduce the extensor torque on the symptomatic knee. Future studies specifically designed for this purpose are needed to confirm this hypothesis.

The overall moment redistribution may account for consequences in knee joint pathology progression. As extensively reported in the literature, an increased knee abductor moment is associated with medial knee OA (Maly, 2008), it often being connected with leg axis alterations. It is noteworthy, however, that medications that afford pain relief in symptomatic knee OA concurrently modify the knee abductor moment (Henriksen et al., 2006; Schnitzer et al., 1993), thereby suggesting that gait modifications designed to help loading are likely to occur in people with knee pain. The knee abductor moment appears to be involved in the onset of chronic knee pain (Amin et al., 2004) and radiographic knee OA (Lynn et al., 2007) and is associated with a greater risk of radiographic OA progression (Miyazaki et al., 2002). On the basis of the results of this study, PFPS patients may be considered as a population at risk, from a biomechanical point of view, for the development of medial knee OA due to repetitive altered knee loading. Lynn et al. (2007) recently described, in a prospective case study with long-term follow-up, the differences in the biomechanical profiles of asymptomatic people who subsequently develop medial or lateral knee OA. In particular, an initial increased knee abductor moment and low medial–lateral share force are associated with future development of symptomatic medial knee OA. The increased hip abductor moment observed in our sample of PFPS patients partially counteracts the knee abductor moment. This increased hip abductor moment was, in one study, found to effectively protect against the progression of medial knee OA over 18 months in 57 people with knee osteoarthritis; since few knee muscles specifically provide knee frontal-plane stability, the protection afforded by the hip frontal-plane muscles is likely to play an important role in regulating medial/lateral knee load distribution (Chang et al., 2005).

Interestingly, studies based on principal component analysis (Astephen et al., 2008; Astephen and Deluzio, 2005) demonstrated how the abductor and the external rotator joint moments during the stance phase of gait are the most important discriminatory factors of OA gait patterns. Karamanidis and Arampatzis (2009) found that older adults had higher knee abductor and knee external rotator joint moments during the stance phase of stair ascending and descending. The same authors found that the kinematic and the kinetic changes they detected may be used as biomechanical markers to assess mechanisms involved in the development of knee OA in the elderly, recommending interventions designed to counteract this age-related load redistribution in the knee joint before the onset of knee pain and irreversible degenerative cartilage damage. Our findings in a relatively young population of patients suggest that gait alterations caused by PFPS may be a risk factor for the development of chronic knee pain and knee OA.

One limitation of our study is the possible occurrence of kinematic crosstalk when estimating knee kinematics on frontal planes. Such crosstalk typically results from joint axis misalignment and may cause motion to be measured where it does not exist and vice-versa (Piazza and Cavanagh, 2000). This mistake would have occurred particularly when measurements were made in the presence of large knee flexion angles, e.g. during the swing phase. Caution should consequently be taken when interpreting these kinematic features in PFPS subjects.

Moreover, we cannot rule out the possibility that our study was under-powered to detect differences between the two groups.

5. Conclusions

The PFPS subjects we studied displayed several kinematic and kinetic alterations during gait, detected not only on the sagittal plane but also on the frontal and transverse planes. The relevance

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of our results to clinicians is that these alterations may represent a biomechanical risk factor for the development of chronic knee OA in the future. Further studies are warranted to shed more light on the link between PFPS and gait pattern alterations, particularly as regards the specific role played by pain and quadriceps muscle dysfunction.

Conflict of interest statement

All the authors declare that there are no relationships of a financial nature, or other issues, that might lead to a conflict of interests.

References


