CLINICAL SCIENCE

Influence of patellofemoral pain syndrome on plantar pressure in the foot rollover process during gait

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BACKGROUND: Patellofemoral Pain Syndrome is one of the most common knee disorders among physically active young women. Despite its high incidence, the multifactorial etiology of this disorder is not fully understood.

OBJECTIVES: To investigate the influence of Patellofemoral Pain Syndrome on plantar pressure distribution during the foot rollover process (i.e., the initial heel contact, midstance and propulsion phases) of the gait.

MATERIALS AND METHODS: Fifty-seven young adults, including 22 subjects with Patellofemoral Pain Syndrome (30 ± 7 years, 165 ± 9 cm, 63 ± 12 kg) and 35 control subjects (29 ± 7 years, 164 ± 8 cm, 60 ± 11 kg), volunteered for the study. The contact area and peak pressure were evaluated using the Pedar-X system (Novel, Germany) synchronized with ankle sagittal kinematics.

RESULTS: Subjects with Patellofemoral Pain Syndrome showed a larger contact area over the medial (p = 0.004) and central (p = 0.002) rearfoot at the initial contact phase and a lower peak pressure over the medial forefoot (p = 0.033) during propulsion when compared with control subjects.

CONCLUSIONS: Patellofemoral Pain Syndrome is related to a foot rollover pattern that is medially directed at the rearfoot during initial heel contact and laterally directed at the forefoot during propulsion. These detected alterations in the foot rollover process during gait may be used to develop clinical interventions using insoles, taping and therapeutic exercise to rehabilitate this dysfunction.

KEYWORDS: Patellofemoral pain syndrome; Biomechanics; Gait; Plantar Pressure; Lower extremity.

INTRODUCTION

Patellofemoral Pain Syndrome (PFPS) is one of the most common knee dysfunctions among physically active young women. Despite its high incidence, rehabilitation is challenging, as the multifactorial etiology of this syndrome is not fully understood.[1-3]

PFPS is believed to originate from a combination of extrinsic and intrinsic risk factors.[1,4,5] The most commonly described extrinsic risk factors related to PFPS include the surface used for running or physical activity practice, sport shoes and the volume and intensity of training.[5] The most frequently cited intrinsic factors include femoral trochlear anatomic alterations, weakness and/or imbalance of the quadriceps, peripatelar soft-tissue tightness and lower extremity dynamic misalignments.[1,4] The most commonly cited lower extremity dynamic misalignments are excessive hip adduction and internal rotation as well as excessive and/or prolonged rearfoot pronation during locomotion.[6,7]

PFPS is believed to be related to a reduction in the contact area in the patellofemoral joint; this reduction occurs due to alterations in the dynamic alignment of the tibiofemoral joint.[8] One theory states that excessive and/or prolonged pronation of the rearfoot leads to excessive medial rotation of the tibia in a closed kinetic chain.[7] This medial rotation of the tibia would induce a compensatory medial rotation of the femur to maintain the relative lateral rotation of the tibial plateau in relation to the femoral condyles, which are associated with knee extension during the midstance phase of gait. When the femur medially rotates, the compression

between the lateral surface of the patella and the lateral femoral condyle rises. As a result, patellofemoral joint stress increases.[6,9]

Kinematic studies that have investigated the relationship between excessive /prolonged foot pronation and rearfoot eversion with PFPS have produced controversial findings. Some authors observed greater pronation in subjects with PFPS during locomotor activities,[13-15] while others could not confirm the coexistence of excessive rearfoot pronation and PFPS.[5,16] One of the potential limitations of these studies was that rearfoot motion could not be differentiated from forefoot motion. Total foot pronation is composed of two events, rearfoot eversion during weight acceptance and midfoot/forefoot loading during early midstance. Models that show the foot as a rigid segment may miss information related to its flexibility during the foot rollover process in locomotor tasks.[16]

Alternatively, an indirect way of evaluating the kinetic chain results of the foot rollover process during gait is to assess plantar pressure distribution during the gait subphases. Higher pressures on the medial areas of the plantar surface as well as excessive pronation during running were associated with the development of lower limb injuries.[17]

Thijs et al.[18] evaluated plantar pressure in soldiers during barefoot gait and observed a relationship between PFPS and lateralized support of the feet, suggesting that individuals who developed PFPS exhibited a heel strike in a less-pronated position and a foot rollover that was more directed toward the lateral side of the foot. This study evaluated a specific military population that was going through an intense training period, and the authors commented that caution should be used when generalizing these findings. The plantar pressure distribution findings and their relationship to lower limb injuries and pain suggest that there is not a consensus in the literature and more investigation is needed.

To our knowledge, no studies have investigated plantar pressure distribution during the subphases of the foot rollover process in a PFPS population. This investigation may identify the phases of the foot rollover process during which plantar loading and foot contact alterations occur and may contribute to elucidating foot mechanics in PFPS individuals.

This study aimed to investigate the influence of Patellofemoral Pain Syndrome on plantar pressure distribution during the initial heel contact, midstance and propulsion phases of gait.

MATERIALS AND METHODS

Subjects

Fifty-seven adults of both sexes volunteered for the study and were divided into two groups: the control group (CG) (n = 35; 29 ± 7 yrs; 164 ± 8 cm; 60 ± 11 kg; 32 women) and the PFPS group (PFPS) (n = 22; 30 ± 7 yrs; 165 ± 9 cm; 63 ± 12 kg; 20 women). The sample power calculation was based on the primary outcome (the pressure variables) with an expected proportion of PFPS development of 30%, a power of 80% and an alpha error of 5%.[19,20] The groups did not differ in mean age (p = 0.698), height (p = 0.935), or body mass (p = 0.734). All participants gave their written informed consent, and the Local Ethics Committee approved the study (protocol n.1237/05).

The PFPS subjects experienced pain in the patellofemoral joint region for at least two months (4 ± 3 years). Their pain occurred during at least one of the following situations: resisted contraction of the femoral quadriceps, squatting, prolonged sitting and descending or ascending stairs. Subjects were excluded from the study if they had undergone any previous knee surgery, had a history of patellar dislocation or had any other limitations that would influence gait. The control subjects had no history or diagnosis of knee pathology or trauma, no knee pain with any of the activities mentioned and no limitations that would influence gait.

Overall exclusion criteria for both groups were a discrepancy of 1 cm[21] or greater in lower leg length and major foot deformities. The arch index was evaluated to exclude major arch alterations (planus, equinus planus and extra cavus feet) that could interfere with gait mechanics.[22]

Knee pain intensity in individuals with PFPS was measured with a Visual Analogue Pain Scale (VAS), in which subjects rated their current pain on a 10-cm horizontal scale that ranged from ''no pain'' on the left to ''worst pain imaginable'' on the right. The VAS was shown to be a reliable, valid and responsible means of assessing pain in studies of PFPS.[23-25] The intensity of knee pain in the PFPS group was 1.7 ± 2.3 cm, and the control subjects presented a knee pain intensity equal to 0.0 cm. To better characterize knee function in PFPS and CG subjects, each individual was evaluated with the Lysholm Functional Knee Scale; the average (median) Lysholm score was 70 for the PFPS group and 98 for the CG.[24,25]

As PFPS is common in physically active individuals, the subjects in both groups answered a questionnaire about how many time they have been physically active, frequency and duration of physical activity; they were considered physically active when their physical activity frequency was at least three times a week.[26] Both groups had similar scores for physically activity (GC = 51.3%, PFPS = 40.0%; p = 0.422), practice time (GC = 5 ± 5 years, PFPS = 5 ± 2 years; p = 0.330), frequency (GC = 3 ± 1 days/week, PFPS = 2 ± 1 days/week; p = 0.246) and duration (GC = 85 ± 30 min, PFPS = 68 ± 22 min; p = 0.534).

Gait Measurement

The contact area and peak pressure were evaluated during barefoot gait using the Pedar-X System (Novel, Munich, Germany) synchronized to the ankle sagittal angular variation. This variation was evaluated by an electrogoniometer that was instrumented with a strain gage (model SG110/A, Biometrics, Gwent, England) and fixed to the ankle joint according to the manufacturer's instructions (Goniometer and torsiometer operating manual. Gwent: Biometrics Ltd; 2002).

The insoles of the Pedar-X System were 2.5 mm thick and contained a matrix of 99 capacitive pressure sensors with a spatial resolution of 1.6 to 2.2 cm;[2] the insoles were placed inside an anti-skid sock.[27] Prior to the tests, the insoles were calibrated according to the manufacturer's instructions, and the zero setting procedure was performed as recommended by Novel prior to data acquisition.[28]

The electrogoniometer was calibrated with the ankle in its mechanically neutral position while the subject stood in a relaxed posture with his or her body weight equally distributed in both feet and in stationary equilibrium; the output value was defined as the zero angle of the

goniometer. Forward motion of the lower segment was regarded as flexion (positive values) and backward motion as extension (negative values).

Before data acquisition, the subjects were instructed to walk freely in a self-selected cadence on a 10-meter walkway to reproduce their daily gait and adapt to the lab environment and to the equipment attached to their feet. The self-selected cadence was converted into an audible digital signal using a metronome. The participants kept a similar cadence between trials based on the audio feedback provided by the metronome; this procedure helped avoid great differences in gait cadence between trials. The cadences performed during the gait trials did not differ between the groups (CG = 108 ± 3 steps/min; PFPS = 107 ± 3 steps/min; p = 0.871). A total of 15 steps were recorded, and the mean was used for statistical purposes.

Pedar and electrogoniometer data were acquired and synchronized using a 12-bit analog-to-digital converter (AMTI, DT3002) at a sampling rate of 100 Hz. Both signals were synchronized by a TTL (transistor-transistor logic) signal that was emitted by the Pedar Sync Box. This box emitted 0 volts (V) when at least 20 kPa was detected by the Pedar System while the foot was in contact with the surface and 5 V when the pressure was lower than 20kPa while the foot was in the swing phase.

Although the Pedar-X system is most appropriate for evaluating shod gait, we used the insoles to evaluate barefoot gait as reported by Nurse and Nigg.[29] Barefoot gait analysis was performed because our intention was to investigate the complex behavior of the foot-floor interaction[30,31] without any other interference such as the subject's shoes. Additionally, the Pedar-X system could acquire multiple steps without requiring the subject to alter their gait to make contact with any platform.[32]

The contact area (cm^2) and peak pressure (kPa) were evaluated in six plantar areas that were adjusted proportionally to the length and width of each subject's foot with the Novel Multiprojects software (Novel, Munich, Germany). The plantar surface was first divided into three larger areas, the rearfoot (30% of the foot length), midfoot (30% of the foot length) and forefoot (40% of the foot length), according to the scheme established by Cavanagh and Ulbrecht.[33] The rearfoot was subdivided into the medial (30% of the rearfoot width), central (40% of the rearfoot width) and lateral rearfoot (30% of the rearfoot width) areas, and the forefoot was subdivided into the medial (55% of the forefoot width) and lateral forefoot (45% of the forefoot width).[34]

DATA ANALYSIS

The stance phase of the gait was divided into three subphases using a customized mathematical function developed using Matlab software (v.7.1). The initial heel contact phase was defined as the time interval between the first foot contact with the ground (as seen in the pressure data) and the deflection instant in the transition from extension to flexion of the ankle angular variation curve. The midstance phase was defined as the time interval between the prior ankle deflection instant (extension to flexion) and the deflection instant in the transition from the flexion to extension of the ankle. The propulsion phase was the interval between the last deflection instant from flexion
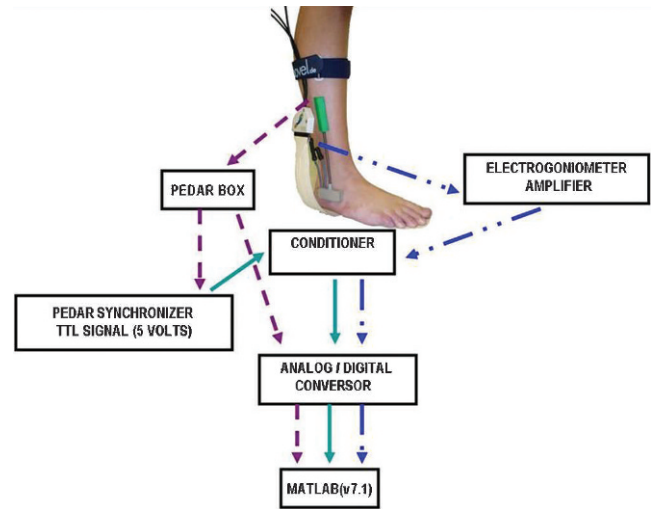

Figure 1 - Synchronization between the Pedar-X System and the ankle electrogoniometer through the synchronizer box of the Pedar-X System.

to extension of the ankle and the toe-off instant (as seen in the pressure data).

Statistical inferential analysis was performed with Statistica v.7 software (Statsoft Inc.). For statistical purposes, pressure data from only one foot per subject were analyzed and compared. In the control group, a foot was randomly chosen for analysis, while in the PFPS group, the chosen foot corresponded to the painful knee in subjects with unilateral pain and the most painful knee in subjects with bilateral pain.

Plantar pressure variables followed a normal distribution (Shapiro-Wilk's Test), and variances were homogeneous (Levene's Test). Groups and areas were compared using 2 three-way ANOVAs (2X3X6) that considered the gait
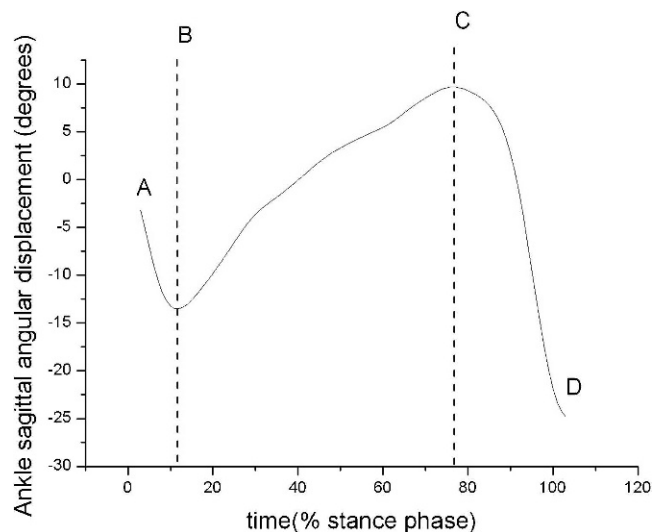
Figure 2 - Subphases of the gait stance obtained from ankle sagittal angular variation: the initial heel contact occurred between A and B, the midstance phase occurred between B and C, and the propulsion phase occurred between C and D. Positive values denote ankle flexion, and negative values denote extension.
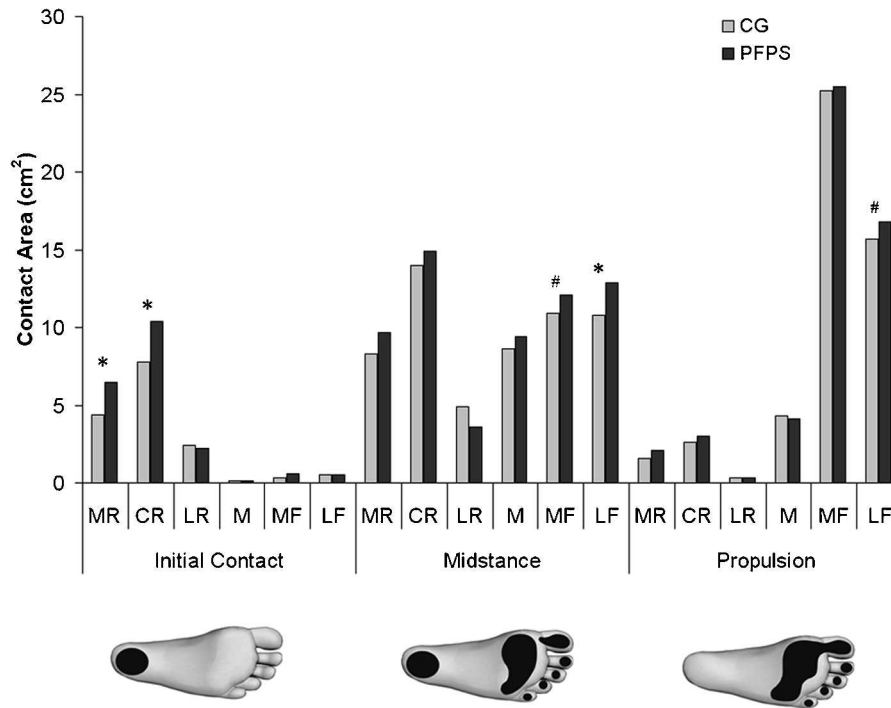
Figure 3 - Mean values of the contact area (cm^2) in six plantar areas (MR = medial rearfoot, CR = central rearfoot, LR = lateral rearfoot, M = midfoot, MF = medial forefoot and LF = lateral forefoot) during initial contact, midstance and propulsion. (CG = control group, PFPS = patellofemoral pain syndrome, * p<0.05, # p < 0.1).
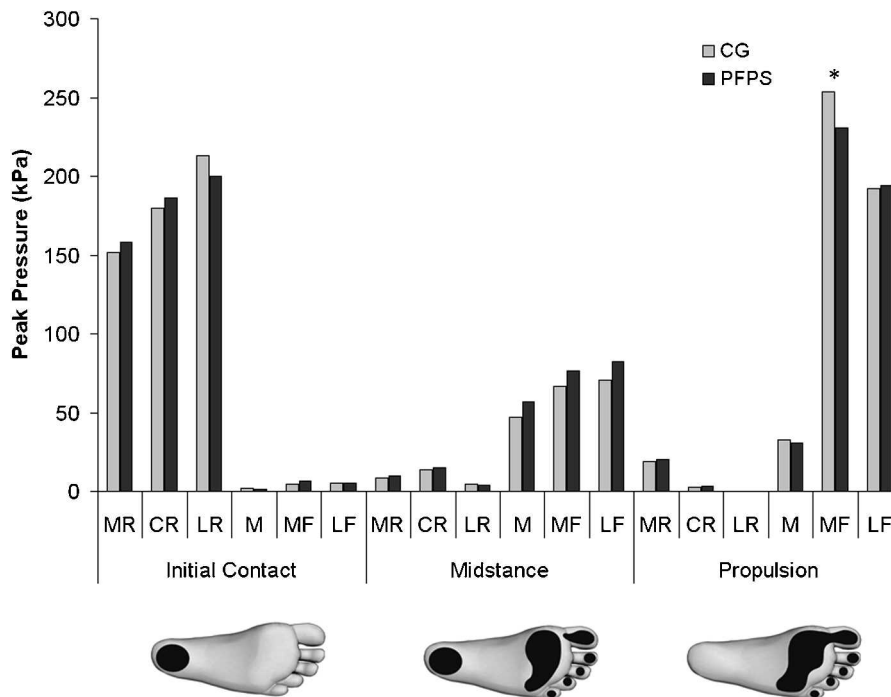
Figure 4 - Mean values of the peak pressure (kPa) in six plantar areas (MR = medial rearfoot, CR = central rearfoot, LR = lateral rearfoot, M = midfoot, MF = medial forefoot and LF = lateral forefoot) during initial contact, midstance and propulsion. (CG = control group, PFPS = patellofemoral pain syndrome, * p<0.05).

subphases (3) and the plantar areas (6) as repeated measurements; these analyses were followed by a Newman-Keuls post-hoc test. The level of significance was set at $\alpha = 5\%$ and marginal significance was set at $1\% < \alpha < 5\%$.

RESULTS

The PFPS group showed a greater contact area at the medial (p = 0.004) and central (p = 0.002) rearfoot during initial heel contact, a greater contact area at the medial (p = 0.072) and lateral (p = 0.005) forefoot in the midstance and a greater contact area at the lateral forefoot in the propulsion phase (p = 0.079).

The PFPS group also presented a smaller peak pressure at the medial forefoot during propulsion than the CG (p = 0.003).

DISCUSSION

Our main findings showed that subjects with PFPS presented larger contact areas at the medial and central rearfoot during initial heel contact, at the medial and lateral forefoot in the midstance, and at the lateral forefoot during propulsion. PFPS individuals also presented a smaller peak pressure at the medial forefoot that was followed by a larger contact area at the lateral forefoot during propulsion.

These results suggest that PFPS individuals exhibit a foot rollover process characterized by an initial heel contact that is performed more medially at the rearfoot and a propulsion phase that is performed more laterally at the forefoot. In the midstance, the larger contact area at both the medial and lateral forefoot suggests that PFPS individuals have a greater excursion of the foot during this phase both medially and laterally.

According to Willems et al.,[17] this laterally directed support during propulsion, which causes the terminal push-off to occur laterally rather than predominantly across the hallux as expected, occurs because an increase in eversion during initial heel contact leads to a less stable foot. Consequently, a greater re-inversion is performed to provide a rigid lever for optimal push-off. Willems et al.[17] performed a prospective study of physically active subjects who developed exercise-related injuries. Plantar pressure and rearfoot 3D kinematics were evaluated, and the researchers observed a foot rollover pattern during running that was similar to what we observed during gait. Subjects who developed injuries showed a more central initial contact that was associated with a more everted rearfoot as well as a more laterally directed propulsion. In our study, PFPS individuals presented a more medially directed initial contact and more laterally directed support during propulsion. This result may also be attributed to a greater eversion of the rearfoot at heel strike followed by an increase in supination during the propulsion phase.

The laterally directed propulsion observed in this study, inferred from the larger lateral forefoot contact area and the smaller peak pressure at the medial forefoot during propulsion, is compatible with the pattern reported by Thijs et al.[18] These authors prospectively evaluated plantar pressure during the gait of military subjects who developed PFPS. They observed a more lateralized foot rollover pattern in subjects who developed PFPS than in subjects who did not develop the disorder.

The present study contributes to discussions about the influence of PFPS in the foot rollover mechanism during gait,

revealing changes in this pattern that would be difficult to perceive through a clinical visual observation of gait. The decision to divide the foot rollover mechanism into three phases allowed us to investigate in more detail what was happening at initial contact, midstance and propulsion in this population. The rollover pattern observed in the PFPS individuals was different from that observed in the healthy individuals and could induce alterations in the load attenuation within the kinetic chain of the lower limbs. Plantar pressure that is medially distributed at the initial contact and laterally distributed during propulsion would probably result in torque alterations in the lower kinetic chain.

A plantar contact that is medially oriented in the rearfoot is probably related to an everted rearfoot and could lead to an excessive medial rotation of the tibia. This rotation could induce a compensatory medial rotation of the femur and a lateralization of the patella in relation to the femur, increasing the patellofemoral joint stress.[7] This medially directed contact in the rearfoot has already been detected in individuals with PFPS during stair descent.[34] Plantar pressure that is laterally distributed during propulsion is probably related to a greater re-inversion that is performed to provide a rigid lever for push-off, as the more everted initial contact leads to a less stable foot.[17] This event can possibly cause lower limb torque modification during gait, inducing alterations in the load attenuation within the kinetic chain.

This detailed characterization of the rocker mechanism is clinically relevant because these findings can be used to develop clinical interventions such as insoles, taping and therapeutic exercises useful for the rehabilitation of this dysfunction.

Furthermore, this study evaluated a population that was predominantly female who participated in this study and exhibited similar levels of physical activity compared with the control group, which decreased the possibility that gender and variable levels of physical activity interfered with our results.

CONCLUSION

Individuals with PFPS exhibit a foot rollover pattern that is medially directed at the rearfoot during initial heel contact and laterally directed at the forefoot during propulsion. These alterations during the foot rollover process can be used to develop clinical interventions that use insoles, taping and therapeutic exercise to rehabilitate this dysfunction.

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