A New Clustering Method for Knee Movement Impairments using Partitioning Around Medoids Model

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Abstract

Background: The movement system impairment (MSI) model is a clinical model that can be used for the classification, diagnosis, and treatment of knee impairments. By using the partitioning around medoids (PAM) clustering method, patients can be easily clustered in homogeneous groups through the determination of the most discriminative variables. The present study aimed to reduce the number of clinical examination variables, determine the important variables, and simplify the MSI model using the PAM clustering method.

Methods: The present cross-sectional study was performed in Shiraz, Iran, during February-December 2018. A total of 209 patients with knee pain were recruited. Patients’ knee, femoral and tibial movement impairments, and the perceived pain level were examined in quiet standing, sitting, walking, partial squatting, single-leg stance (both sides), sit-to-stand transfer, and stair ambulation. The tests were repeated after correction for impairments. Both the pain pattern and the types of impairment were subsequently used in the PAM clustering analysis.

Results: PAM clustering analysis categorized the patients in two main clusters (valgus and non-valgus) based on the presence or absence of valgus impairment. Secondary analysis of the valgus cluster identified two sub-clusters based on the presence of hypomobility. Analysis of the non-valgus cluster showed four sub-clusters with different characteristics. PAM clustering organized important variables in each analysis and showed that only 23 out of the 41 variables were essential in the sub-clustering of patients with knee pain.

Conclusion: A new direct knee examination method is introduced for the organization of important discriminative tests, which requires fewer clinical examination variables.

Keywords ● Movement system impairment model ● Knee ● Cluster analysis ● Classification ● Syndrome

Introduction

Extra-articular soft tissue injuries are the most common injuries of the knee joint, which may eventually lead to knee osteoarthritis with an estimated prevalence of 24% in adults.¹, ² Knee pain is a common musculoskeletal problem in patients referred to outpatient physical therapy centers. The prevalence of knee...
pain in the United States has increased by 65% over 20 years.\textsuperscript{3} Conservative treatment of non-traumatic knee pain is usually the first line of management versus surgical treatments.\textsuperscript{4} Over the years, various non-surgical treatments with an emphasis on correcting the impaired movement have been developed for knee pain.\textsuperscript{5} Despite the availability of various treatments, it has been suggested that classifying patients into homogeneous groups may simplify the complexities of diagnosis and facilitate treatment options.\textsuperscript{5-7}

Clinical methods classify patients based on their distinct signs, symptoms, treatments, or psychosocial characteristics.\textsuperscript{8, 9} Among the most important clinical classification methods are the pathoanatomic and kinesiopathologic models.\textsuperscript{10-12} The pathoanatomic model focuses on the effect of stresses on tissues and utilizes diagnostic labeling of the causative factors of the patient’s pain (e.g., meniscal tear). However, sometimes patients are referred to a physical therapist with no definite diagnosis. Physical therapists typically treat patients based on their movement impairments rather than on the pathoanatomical source of the pain. As a result, they use the kinesiopathologic model, a movement system diagnostic classification method, as an alternative to the pathoanatomic model.\textsuperscript{11}

Among kinesiopathologic models, the movement system impairment (MSI) model is considered the most suitable classification approach and has been reviewed clinically and kinematically during the current decade.\textsuperscript{5, 13, 14} The MSI model of the knee has been shown to have acceptable intratester reliability.\textsuperscript{14} This model classifies patients with knee pain into seven subgroups based on examining the knee movement, correction of faulty posture, and re-evaluation of the symptoms. The subgroups are tibiofemoral rotation syndrome, tibiofemoral hypomobility syndrome, tibiofemoral accessory hypermobility syndrome, knee extension syndrome; knee hyperextension syndrome, patellar lateral glide syndrome, and knee impairment. Previous studies have reported certain limitations in the MSI model, namely overlapping signs and symptoms,\textsuperscript{13} time-consuming examination process,\textsuperscript{8} challenges in determining the tibiofemoral rotation angle,\textsuperscript{4} and the absence of differences in perceived pain levels between the usual and corrected movement conditions.\textsuperscript{13}

Attempts have been made to validate the classification of syndromes using statistical models such as Ward’s clustering method for hip disorders\textsuperscript{15} and hierarchical clustering method for non-specific patellofemoral pain for the lower extremity examination.\textsuperscript{16} Statistical analysis can be used to describe the characteristics of a population in an idealized model with algorithms based on similarity and differences in signs and symptoms.\textsuperscript{17, 18} Statistical clustering is an unsupervised learning process in which the data are grouped in different clusters free from preconceptions. Unlike other clustering methods, the partitioning around medoids (PAM) model is a unique and flexible clustering method that allows the entry of various forms of variables (nominal, ordinal, or scalar) besides numeric variables.\textsuperscript{17, 18} In the PAM model, one case is selected as a medoid, and the data with the least dissimilarities to the medoid are clustered around it. The medoids are then replaced to gain the smallest dissimilarity. This process continues until no change takes place in medoids and the determined number of clusters itself. This unique process leads to separated data groups with the least within-group dissimilarity and maximum between-group dissimilarity.\textsuperscript{19} This highly accurate method classifies patients into clusters based on their true dissimilarities and distinguishes the important variables for clustering. Thus, classifications based on this model would be simple, most time-efficient, and require less clinical examination variables.

Studies evaluating the reliability of the MSI model have reported difficulties in classifying patients based on the signs and symptoms.\textsuperscript{7, 14} We believe that this could be due to difficulties in the judging part of the MSI model. Another study also reported that knee examination based on the MSI model is too time-consuming (about 45 minutes).\textsuperscript{14} To address these issues, the main objective of the present study was to use the PAM clustering method for the classification of patients based on their signs and symptoms derived from the MSI model. In addition, we aimed to identify those key tests directly related to knee examination for the sole purpose of reducing examination time.

**Patients and Methods**

In the present cross-sectional study, patients with knee pain were recruited from several orthopedic and rehabilitation clinics affiliated to Shiraz University of Medical Sciences (Shiraz, Iran) during February-December 2018. The participants were selected using the convenient sampling method, and the sample size was estimated in accordance with previous studies.\textsuperscript{5, 14} and by using the statistical rules of thumb.\textsuperscript{20} A total of 209 patients with knee pain referred for physical therapy by an orthopedic surgeon were recruited in the study. The study was approved
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by the local Medical Ethics Committee (number: IR.SUMS.REC.1396.S993), and written informed consent was obtained from the participants.

The inclusion criteria were aged 18-60 years and experiencing non-traumatic pain around the knee (scoring between 3 and 7 in a standing position on a numerical rating scale) for the last two months.5, 14 The exclusion criteria were any history of surgery (bone ostotomy, bone fracture repair or surgical correction of structural deformities in the trunk or lower extremity), major general metabolic or systemic diseases, neurological diseases (radiculopathy), obvious leg length discrepancy leading to limping, pregnancy; and the use of walking aids, analgesic, and anti-inflammatory drugs up to or at the day of examination.5, 14 The examiner was a physical therapist with 12 years of experience in treating patients using the MSI model. All procedures were conducted according to the Declaration of Helsinki.

The examination procedure began with a documentation of the patient’s history (height, weight, age, sex, pain location, and intensity) followed by a physical examination. The activity level was measured using the Persian version of the Tegner questionnaire, which was previously validated with an acceptable level of reliability.21 The questionnaire is a self-administered activity rating system (based on a scale of 0 to 10) for patients with various knee disorders. The physical postural examination included assessment of correct alignment (anterior, posterior, and side views) in standing and sitting positions as described in the MSI model.10 The knee, femoral, and tibial movements were evaluated during different activities such as walking, half-squatting, single-leg stance (comparing both sides), and stair ambulation. A walkway and an adjustable chair were used to perform the walking and sit-to-stand transfer, respectively. Climbing was performed on stairs of 20 cm height.

The initial perceived level of pain was recorded during each movement. In case of faulty movement patterns, the therapist trained the participants on the correct pattern, requesting repetition of the movement, and report of the perceived pain level. The difference in the pain level between faulty and corrected movements was coded for each activity and rated from 0 to 7: 0: no change, 1: valgus correction, 2: varus correction, 3: hyperextension correction, 4: patellar movement correction, 5: no immediate correction available, 6: no alignment deficit, and 7: increased pain). This process was repeated in all positions. The examiner palpated each segment during movements, and if an activity was performed incorrectly (with valgus or excessive tibial external rotation), the participant was informed about the correct movement pattern. The movement was then repeated in the corrected form (if possible) and re-evaluated by the examiner. If an obvious difference was found between the previous and corrected movements, the faulty movement was recorded as the impairment. Impairments that could not be corrected immediately (hypomobility) were recorded without repetition of the movement. The deployed coding system was based on the MSI model and previous studies.5, 14 A total of 41 scalars (pain) and nominal (alignment deficits) variables were counted during different activities. A muscle stiffness-flexibility test was performed in the supine position to determine the muscle-joint relative flexibility. It consisted of a two-joint hip flexors length test, and the result was reported positive if the tibia was abduced or rotated laterally while lowering the hip in extension. The joint integrity was measured by assessing the accessory motions of the patellofemoral and tibiofemoral joints. The McConnell patellar test 10 and patellar grind test were also performed. The foot arch was measured by determining the Feiss line and classified as high, low, or normal arch. The variables collected during examination based on the PAM clustering analysis are presented in table 1. Manual muscle testing was also performed for the muscles of the lower extremity. However, the results were not used in the PAM analysis, since muscle power is not a discriminating factor for clustering.

The extracted data from all patients were analyzed using ClusterR and VarSelLCM packages of R software (R core team, version 3.5.3, New Zealand). PAM analysis allows the management of different types of variables (nominal, ordinal, or scalar) and is robust against outlier observations.11, 17 Moreover, it reduces the number of variables, prioritizes, and categorizes data into homogeneous clusters. The weight of each variable was defined through the discriminatory power (DP), i.e., the contribution of each variable in cluster analysis.11, 17 After the initial PAM clustering, the analysis was repeated for each cluster to identify sub-clusters that included all variables. All other statistical analyses were performed using SPSS software, version 25.0 (IBM Inc. Chicago, IL, USA). The quality of the clusters and sub-clusters was analyzed using the silhouette coefficient internal index, ranging from 1 to -1. Values close to 1 indicated more dense clusters with more distances from other clusters (i.e., best possible categorization) and those close to -1 indicated too many or too few clusters.22
Results

A total of 209 patients (67 men, 152 women) participated in the study of which 108 (51%) had pain of the right knee and 101 (48%) had pain of the left knee. The mean age of the patients was 43±12 years, the mean weight of 73±13 kg, and the mean height of 166±8 centimeters. Based on a visual analog scale, the pain level at the time of examination in standing position was 17±19. The mean total score of the Tegner questionnaire was 4±1. Based on all signs and symptoms, the PAM clustering analysis resulted in two main clusters and six sub-clusters.

Main Clusters

The optimum number of clusters was two with a silhouette coefficient value of 0.41. The results of the PAM clustering analysis showed that 23 out of the 41 variables were necessary for an initial clustering of patients into two main clusters (table 2). The clusters were labeled according to the most discriminative features of the diagnosed condition. The main discriminative characteristic was knee valgus, thus the corresponding clusters were labeled “Valgus” and “Non-valgus” The non-valgus cluster included characteristics of varus or no deformity. The valgus and non-valgus clusters contained 120 (57.4%) and 89 (42.6%) patients, respectively. Among all variables, the frontal plane knee deficits (valgus and varus) had the highest DP, especially in activities such as sit-to-stand transfer (DP=90.76), stair ambulation (DP=84.82), and partial squat (DP=77.10). The PAM analysis was repeated for each cluster to determine sub-clusters.

Table 1: The list of variables recorded during examination

| Position                          | Symptoms                                      | Signs                                                      |
|-----------------------------------|-----------------------------------------------|------------------------------------------------------------|
| Walking                           | Symptom alleviation with the correction of walking | Knee valgus and varus                                      |
|                                   |                                               | Femoral abduction and adduction                            |
|                                   |                                               | Tibial abduction and adduction                              |
|                                   |                                               | Tibial medial and lateral rotation                         |
|                                   |                                               | Knee hyperextension and lack of extension                  |
| Partial squat                     | Symptom alleviation with the correction of partial squatting | Knee valgus and varus                                      |
|                                   |                                               | Femoral abduction and adduction                            |
|                                   |                                               | Tibial abduction and adduction                              |
|                                   |                                               | Tibial medial and lateral rotation                         |
| Sit-to-stand                      | Symptom alleviation with the correction of sit-to-standing | Knee valgus and varus                                      |
|                                   |                                               | Femoral abduction and adduction                            |
|                                   |                                               | Tibial abduction and adduction                              |
|                                   |                                               | Tibial medial and lateral rotation                         |
| Single-leg stance on involved limb| Symptom alleviation with the correction of single-leg stance | Knee valgus and varus                                      |
|                                   |                                               | Femoral abduction and adduction                            |
|                                   |                                               | Tibial abduction and adduction                              |
|                                   |                                               | Tibial medial and lateral rotation                         |
| Knee flexion in single-leg stance on uninvolved limb | Symptom alleviation with the correction of knee flexion while standing on uninvolved limb | Knee valgus and varus                                      |
|                                   |                                               | Femoral abduction and adduction                            |
|                                   |                                               | Tibial abduction and adduction                              |
|                                   |                                               | Tibial medial and lateral rotation                         |
| Stair ambulation                  | Symptom alleviation with the correction of stair ambulation | Knee valgus and varus                                      |
|                                   |                                               | Femoral abduction and adduction                            |
|                                   |                                               | Tibial abduction and adduction                              |
|                                   |                                               | Tibial medial and lateral rotation                         |
|                                   |                                               | Knee hyperextension and lack of extension                  |
|                                   |                                               | Tibial roll on foot in stair climb                         |
| Prone                             | Symptom alleviation with the correction of prone knee flexion | Tibial abduction and adduction                            |
|                                   |                                               | Tibial medial and lateral rotation                         |
| Supine                            | Symptom alleviation with the correction during two-joint hip flexor length test | Relative flexibility with two-joint hip flexor length test |
|                                   |                                               | Joint integrity                                            |
|                                   | McConnel and patellar grind test              | Pain location                                              |
| Standing                          | -                                             | Foot pronation                                             |

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### Table 2: Discriminative variables and the corresponding discriminative power and percentile of the key characteristics in each main cluster of patients with knee pain

| Variables                                      | Discriminative power | Discriminative power (%) | Main cluster: Valgus | Main cluster: Non-valgus |
|------------------------------------------------|-----------------------|---------------------------|----------------------|-------------------------|
| 1. Knee valgus and varus on sit-to-stand movement | 90.76                 | 9.14                      | 90% increased valgus  | 47% increased varus     |
| 2. Knee valgus and varus on stair ambulation     | 84.82                 | 8.55                      | 95% increased valgus  | 49% increased varus     |
| 3. Knee valgus and varus on partial squat movement| 77.10                 | 7.77                      | 87% increased valgus  | 47% increased varus     |
| 4. Femoral abduction and adduction on sit-to-stand movement | 75.54                 | 7.61                      | 81% increased adduction | 38% increased adduction |
| 5. Femoral abduction and adduction on partial squat movement | 74.42                 | 7.50                      | 77% increased adduction | 59% no change           |
| 6. Femoral abduction and adduction on stair ambulation | 73.96                 | 7.45                      | 85% increased adduction | 52% no change           |
| 7. Tibial abduction and adduction on stair ambulation | 50.54                 | 5.09                      | 65% increased adduction | 5% increased adduction  |
| 8. Femoral abduction and adduction on walking     | 44.14                 | 4.45                      | 64% increased adduction | 2% increased adduction  |
| 9. Symptom alleviation on stair ambulation        | 43.73                 | 4.41                      | 43% Val cor           | 79% no change           |
| 10. Femoral abduction and adduction on single-leg stance | 39.03                 | 3.93                      | 70% increased adduction | 4% increased adduction  |
| 11. Tibial abduction and adduction on partial squat movement | 38.97                 | 3.93                      | 61% increased adduction | 66% no change           |
| 12. Tibial abduction and adduction on sit-to-stand movement | 36.42                 | 3.67                      | 56% increased adduction | 73% no change           |
| 13. Symptom alleviation on partial squat movement  | 36.03                 | 3.63                      | 36% Val cor           | 19% increased adduction  |
| 14. Symptom alleviation on single-leg stance      | 28.72                 | 2.89                      | 50% no change in pain  | 46.1% no change in pain  |
| 15. Tibial abduction and adduction on single-leg stance | 26.88                 | 2.71                      | 66% no change          | 16% with no Imm. Cor.    |
| 16. Symptom alleviation on sit-to-stand movement  | 24.47                 | 2.47                      | 50% no change in pain  | 21% with Var cor        |
| 17. Tibial abduction and adduction on walking     | 23.98                 | 2.42                      | 75% no change          | 16% with Hyperext cor   |
Sub-clusters of Valgus

The optimum number of sub-clusters of valgus was four with a silhouette coefficient of 0.26. The results of the PAM analysis showed that 12 out of the 41 variables were necessary for the sub-clustering of patients (table 3). Two sub-clusters were selected based on the presence or absence of knee hypomobility, being the most discriminative characteristic among all sub-clusters. The characteristics of each sub-cluster are listed in table 3. These sub-clusters were labeled “Valgus with hypomobility” and “Valgus”, since the most discriminative feature was knee hypomobility with the highest DP, especially in a single-leg stance (DP=65.30), walking (DP=57.71), and tibiofemoral joint integrity (DP=48.48).

Valgus with Hypomobility: A total of 16 (7%) patients with a mean age of 52 years exhibited valgus combined with hypomobility. Movement pattern modification, especially in the partial squat and stair ambulation, was the major correction to alleviate the symptoms. The patients also exhibited knee valgus in the sit-to-stand transfer. The major discriminator was the lack of knee extension, especially in a single-leg stance (DP=65.30) and walking (DP=57.71).

Valgus: A total of 104 (49.7%) patients with a mean age of 5 years exhibited valgus in a sit-to-stand transfer, partial squat, and stair ambulation as major discriminators.

Sub-clusters of Non-valgus

The PAM analysis was repeated for the non-valgus cluster to identify its sub-clusters. The optimum number of sub-clusters was two with a silhouette coefficient of 0.26. The results showed that 23 out of the 41 variables were needed for the sub-clustering of patients (table 4). These sub-clusters were labeled “Hyperextension”, “Hypomobility”, “Varus”, and “Minimal pain and dysfunction”. Among all the variables, joint integrity (DP=41.49), hypomobility in single-leg stance (DP=38.24), symptoms in stair ambulation (DP=36.77), and knee hyperextension and hypomobility in single-leg stance (DP=34.04) had the highest DP.

Hyperextension: A total of 10 (4%) patients with a mean age of 32 years were clustered as having hyperextension, especially in single-leg stance and walking. Although correction of faulty movement pattern may not immediately reduce the symptoms in these patients, attention to the signs of sagittal-plane knee function impairments can be a discriminator for categorization since all patients had hyperextension in walking (DP=34.01) and standing on the examined leg (DP=34.04).

Hypomobility: A total of 23 (11%) patients with a mean age of 54 years exhibited a lack of full extension, especially in single-leg stance and walking. Movement pattern modification reduced the pain, particularly in stair ambulation and single-leg stance. All patients exhibited a lack of knee extension in stair ambulation (DP=28.96). Most of the patients with hypomobility exhibited varus in movements, especially in sit-to-stand transfer (73%), partial squatting (73%), and stair ambulation (78%).
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Varus: A total of 26 (12.4%) patients with a mean age of 48 years exhibited knee varus as the main sign. The majority of these patients (73.1%) immediately showed reduced symptoms after movement pattern correction, especially in single-leg stance.

Minimal Pain and Dysfunction: The last sub-cluster consisted of 30 (14.3%) patients with a mean age of 35 years who had no preferred alignment fault and movement pattern correction or modified their preferred movement pattern to relieve pain symptoms. Most of them were young athletes (Tegner score of 5) scoring 8 out of 100 on a visual analog scale for average pain. The manual muscle testing of these patients showed a higher muscle strength and lower pain intensity than other patients.

A total of 23 examination variables were essential in sub-clustering knee classifications. 18 items were not considered group discriminators although they could have contributed to patient management. Irrelevant items included factors related to prone position (symptoms, tibial abduction-adduction, tibial medial-lateral rotation), tibial medial-lateral rotation (walking, partial squat, sit-to-stand transfer, single-leg stance, knee flexion while standing on the uninvolved limb, and stair ambulation); the McConnell patellar test, foot pronation, and femoral medial-lateral rotation in single-leg stance position.

### Table 3: Discriminative variables and the corresponding discriminative power and percentile of the key characteristics in valgus sub-clusters

| Variables                                               | Discriminative power (%) | Discriminative power (%) | Sub-cluster: Valgus with hypomobility | Sub-cluster: Valgus with hypermobility |
|---------------------------------------------------------|--------------------------|--------------------------|--------------------------------------|---------------------------------------|
| Knee hyperextension and extension lack on single-leg stance | 65.30                    | 20.39                    | 100% extension lack                  | 91% no change                         |
| Knee hyperextension and extension lack on walking        | 57.71                    | 38.40                    | 100% extension lack                  | 91% no change                         |
| Joint integrity                                         | 48.48                    | 53.54                    | 100% tibiofemoral hypomobility       | 95% no change                         |
| Knee hyperextension and extension lack on stair ambulation | 46.80                    | 68.15                    | 93% extension lack                   | 78% no change                         |
| Symptom alleviation on stair ambulation                  | 29.30                    | 77.29                    | 62% with no Imm. Cor.                | 50% Val cor                           |
| Symptom alleviation on partial squat movement             | 26.88                    | 85.68                    | 68% with no Imm. Cor.                | 42% Val cor                           |
| Symptom alleviation on singleleg stance                   | 11.50                    | 89.28                    | 43% with no Imm. Cor.                | 50% no change                         |
| Relative flexibility                                     | 9.29                     | 92.18                    | 100% relative tibial rotation        | 97% relative tibial rotation           |
| Symptom alleviation on sit-to-stand movement              | 9.29                     | 95.08                    | 62% no change in pain                | 49% no change                         |
| Symptom alleviation on Knee flexion in single-leg stance on uninvolved limb | 7.44                     | 97.40                    | 56% no change in pain                | 78% no change                         |
| Symptom alleviation on walking                            | 5.18                     | 99.01                    | 81% no change in pain                | 75% no change                         |
| Symptom alleviation during two-joint hip flexor length test | 3.16                     | 100.00                   | 100% no change in pain               | 62% no change                         |

No change: No change in movement, Val cor: Symptoms alleviated with valgus correction, Var cor: Symptoms alleviated with varus correction, No Imm. Cor: Movement was not correctable immediately, Hyperext cor: Symptoms alleviated with prevention of knee hyperextension, Patella cor: Symptoms alleviated with correction of patellar alignment, No Spec. Mal.: No pain difference recorded as no correction was performed, Incr Lat Rot: Increased lateral rotation, Incr Med Rot: Increased medial rotation.
| Variables | Discriminative power | Discriminative power (%) | Sub-cluster: Hyperextension | Sub-cluster: Hypomobility | Sub-cluster: Varus | Sub-cluster: Self-management |
|-----------|----------------------|--------------------------|----------------------------|--------------------------|------------------|-----------------------------|
| 1 Joint integrity | 41.49 | 8.04 | 70% no change 30% tibiofemoral hypermobility | 95% tibiofemoral hypomobility 4% no change | 100% no change | 56% tibiofemoral hypermobility 43% no change |
| 2 Symptom alleviation on single-leg stance movement | 38.24 | 15.46 | 50% no change in pain 40% Hyperext cor 10% no Spec. Mal. | 60% with no Imm. Cor. 39% no change in pain | 73.1% with Var cor 19% no change in pain 7% with Patella cor | 73% no change in pain 13% with Patella cor 13% with no Spec. Mal. |
| 3 Symptom alleviation on stair ambulation | 36.77 | 22.59 | 60% with Hyperext cor 40% no change in pain | 60% with no Imm. Cor. 39% no change in pain | 50% with Var cor 46% no change in pain 3% with Patella cor | 40% no change in pain 30% with Patella cor 23% with No Spec. Mal. 6% with Hyperext cor |
| 4 Knee hyperextension and extension lack on single-leg stance | 34.04 | 29.19 | 100% knee hyper-extension 8% no change | 91% extension lack 8% no change | 65% no change 34% knee hyperextension | 66% no change 30% knee hyperextension 3% extension lack |
| 5 Knee hyperextension and extension lack on walking | 34.01 | 35.78 | 100% knee hyper-extension 8% no change | 91% extension lack 8% no change | 65% no change 34% knee hyperextension | 66% no change 30% knee hyperextension 3% extension lack |
| 6 Symptom alleviation on partial squat movement | 29.26 | 41.46 | 80% no change in pain 10% with Hyperext cor 10% with no Spec. Mal. | 65% with no Imm. Cor. 34% no change in pain | 53% with Var cor 42% no change in pain 3% with Patella cor | 46% no change in pain 26% with Patella cor 23% with No Spec. Mal. 3% with hyper-extension prevention |
| 7 Knee hyperextension and extension lack on stair ambulation | 28.96 | 47.07 | 90% knee hyper-extension 10% no change | 100% knee extension lack | 65% no change 30% knee hyper-extension 3% knee extension lack | 63% no change 33% knee hyper-extension 3% knee extension lag |
| 8 Knee valgus and varus on sit-to-stand movement | 28.77 | 52.65 | 100% no change | 73% increased varus 17% no change 8% increased valgus | 88% increased varus 7% no change 3% increased valgus | 86% no change 6% increased varus 6% increased valgus |
| 9 Knee valgus and varus on stair ambulation | 27.28 | 57.94 | 100% no change | 78% increased varus 17% no change 4% increased valgus | 92% increased varus 3% no change 3% increased valgus | 56% no change 30% increased valgus 13% increased varus |
| 10 Knee valgus and varus on partial squat movement | 26.87 | 63.15 | 100% no change | 73% increased varus 13% no change 13% increased valgus | 80% increased varus 15% no change 13% increased valgus | 76% no change 13% increased varus 10% increased valgus |
| 11 Symptom alleviation on sit-to-stand movement | 26.65 | 68.32 | 70% no change in pain 20% with Hyperext cor 10% with No Spec. Mal. | 60% no change in pain 39% with No Imm. Cor. | 53% no change in pain 42% with Var cor 3% with Patella cor | 73% no change in pain 16% with Patella cor 6% with No Spec. Mal. 3% with Hyperext cor |
| 12 Femoral abduction and adduction on stair ambulation | 20.52 | 72.30 | 100% no change | 69% increased abduction 26.1% no change 4% increased adduction | 80% increased abduction 11% no change 7% increased adduction | 63% no change 23% increased adduction 13% increased abduction |
| Variables                                                                 | Discriminative power (%) | Discriminative power | Sub-cluster: Hyperextension | Sub-cluster: Hypomobility | Sub-cluster: Varus | Sub-cluster: Self-management |
|---------------------------------------------------------------------------|---------------------------|----------------------|-----------------------------|--------------------------|-------------------|-----------------------------|
| 13 Femoral abduction and adduction on sit-to-stand movement               | 19.97                     | 76.17                | 100% no change              | 52% increased abduction  | 76% increased abduction | 93% no change               |
|                                                                           |                           |                      |                             | 19% no change            | 19% no change        | 6% increased abduction     |
|                                                                           |                           |                      |                             | 4% increased adduction   | 3% increased adduction|                             |
| 14 Femoral abduction and adduction on partial squat movement              | 17.15                     | 79.49                | 100% no change              | 60% increased abduction  | 73.1% increased abduction | 80% no change               |
|                                                                           |                           |                      |                             | 26% no change            | 26% no change        | 13% increased abduction    |
|                                                                           |                           |                      |                             | 13% increased adduction  | 13% increased adduction| 6% increased adduction     |
| 15 Symptom alleviation on walking                                        | 15.68                     | 82.53                | 90% no change in pain       | 65% no change in pain    | 61% no change in pain   | 96% no change in pain       |
|                                                                           |                           |                      | 10% with Hyperext cor       | 34% with no Imm. Cor.    | 34% with Var cor      | 3% with Patella cor         |
| 16 Femoral medial and lateral rotation on stair ambulation               | 13.64                     | 85.18                | 90% No change               | 60% Incr Med Rot         | 73.1% Incr Med Rot    | 46% Incr Med Rot            |
|                                                                           |                           |                      | 10% Incr Lat Rot            | 21% Incr Med Rot         | 23.1% Incr Lat Rot    | 43% no change               |
|                                                                           |                           |                      |                             | 4% Incr Lat Rot          | 3% no change          | 10% Incr Lat Rot           |
| 17 Femoral medial and lateral rotation on partial squat                  | 13.26                     | 87.75                | 100% no change              | 60% Incr Med Rot         | 65% Incr Med Rot      | 60% no change               |
|                                                                           |                           |                      |                             | 34% no change            | 19% Incr Med Rot      | 40% Incr Med Rot            |
|                                                                           |                           |                      |                             | 4% Incr Lat Rot          | 15% no change         |                             |
| 18 Femoral medial and lateral rotation on sit-to-stand                   | 10.64                     | 89.81                | 100% no change              | 52% Incr Med Rot         | 73.1% Incr Med Rot    | 63% no change               |
|                                                                           |                           |                      |                             | 39% no change            | 15% no change         | 36% Incr Med Rot            |
|                                                                           |                           |                      |                             | 8% Incr Lat Rot          | 11% Incr Lat Rot      |                             |
| 19 Tibial abduction and adduction on stair ambulation                    | 7.66                      | 91.30                | 100% no change              | 56% no change            | 53% no change         | 80% no change               |
|                                                                           |                           |                      |                             | 39% increased adduction  | 48% increased adduction| 16% increased abduction   |
|                                                                           |                           |                      |                             | 4% increased adduction   |                             | 3% increased adduction      |
| 20 Tibial roll on foot in stair climb                                    | 7.35                      | 92.72                | 100% did not roll           | 65% did not roll         | 61% did not roll      | 80% rolled                  |
|                                                                           |                           |                      |                             | 34% rolled               | 38% rolled            | 20% did not roll           |
| 21 Tibial abduction and adduction on partial squat                        | 6.34                      | 93.95                | 100% no change              | 56% no change            | 53% no change         | 3% abd, 96% no def          |
|                                                                           |                           |                      |                             | 39% increased adduction  | 38% increased adduction|                             |
|                                                                           |                           |                      |                             | 4% increased adduction   | 7% increased adduction  |                             |
| 22 Femoral medial and lateral rotation on single leg stance              | 5.98                      | 95.11                | 100% no change              | 73% Incr Med Rot         | 76% Incr Med Rot      | 66% Incr Med Rot            |
|                                                                           |                           |                      |                             | 17% no change            | 19% Incr Med Rot      | 30% no change               |
|                                                                           |                           |                      |                             | 3% Incr Lat Rot          | 3% Incr Lat Rot       | 3% Incr Lat Rot             |
| 23 Symptom alleviation during two-joint hip flexor length test            | 5.35                      | 96.15                | 100% no change              | 100% no change           | 76% no change         | 60% no change               |
|                                                                           |                           |                      |                             | 11% Var Cor              | 11% Var Cor           | 40% patellar cor            |

No change: No change in movement, Val cor: Symptoms alleviated with valgus correction, Var cor: Symptoms alleviated with varus correction, No Imm. Cor.: Movement was not correctable immediately, Hyperext cor: Symptoms alleviated with prevention of knee hyperextension, Patella cor: Symptoms alleviated with correction of patellar alignment, No Spec. Mal.: No pain difference recorded as no correction was performed, Incr Lat Rot: Increased lateral rotation, Incr Med Rot: Increased medial rotation
Discussion

In the present study, we found that 23 out of the 41 clinical examination variables were adequate to categorize the patients in appropriate clusters and sub-clusters. We identified two main clusters (valgus and non-valgus) and six sub-clusters (valgus, valgus with hypomobility, hyperextension, hypomobility, varus, and minimal pain and dysfunction). The results showed that patients with knee impairment can be classified efficiently with a fewer number of examination variables than the MSI model. These variables were prioritized according to importance and DP in each step. The PAM analysis was also used as a novel method for knee examination to allocate patients to different sub-clusters.

A comparison of PAM sub-clusters with the MSI model showed that both models used similar impairments (valgus, varus, hypomobility, and hyperextension) as classification criteria. Patients with knee extension syndrome, as classified in the MSI model, were not entered into the study due to the reported low presence.\(^5\) 14 In line with the MSI model, patients in the sub-cluster “minimal pain and dysfunction” mostly exhibited the characteristics of patients with patellofemoral pain and knee joint hypermobility. These patients did not express pain during routine tests, making it necessary to perform more specific high loading or neuromuscular tests to determine the characteristics of this cluster. Patients with no specific alignment deficits have been labeled as neuromuscular or muscular deficits, one of the subcategories of patellofemoral pain.\(^23\) Patellofemoral dysfunctions were not classified as a separate cluster for two reasons. First, tests such as stair climbing were not effective in discriminating the pain source of the patellofemoral or tibiofemoral joint.\(^24\) Nonetheless, they were among the most important discriminative variables in our study. Second, pain variables were not that essential in diagnostic tests for the patellofemoral joint impairment.\(^24\) Keays and colleagues categorized patients with patellofemoral pain into four main categories. Among all, the patellar osteoarthritis group was only distinguished by the use of X-ray imaging.\(^25\) In the current study, patellar deficiency associated with knee impairments was assigned to the main sub-clusters.

The majority of our patients had dynamic knee valgus as the dominant movement pattern (valgus cluster). This was in line with previous studies reporting a high frequency of valgus movement in patients with knee pain.\(^14, 25\) The main clusters identified in the current study were somehow similar to previous studies.\(^5, 14, 25\)

Signs can be a key factor in classifying patients when symptoms are not conclusive. We found that signs were more important in primary clustering and valgus sub-clustering of patients since, they were more obvious and with higher DP than symptoms. However, symptoms had a higher diagnostic value in patients with a dominant movement pattern other than valgus. Kajbafvala and colleagues also reported similar findings.\(^5\) They used factor analysis to validate four syndromes of the knee classification system in which only one factor included symptoms and the other three included signs only. Salsich and colleagues found that despite the correction of tibiofemoral alignment, the patient’s pain did not decrease significantly.\(^13\) Another study on the validation of the knee MSI model reported that the category “patellar lateral glide syndrome” was the only factor in which pain was important.\(^5\) This syndrome was not identified in the PAM sub-clustering, since the examination variables related to the patella (pain location, McConnell patellar and symptom alleviation with patellar correction) did not have a DP higher than other variables. On the other hand, deficient patella rarely occurs in isolation and is usually a secondary diagnosis based on a primary diagnosis of tibiofemoral rotation or knee hyperextension.\(^11, 13\) Additional tests such as X-ray or trunk evaluation could be useful to attain a more uniform group.\(^25, 26\)

In the present study, we also identified a pattern for knee examination based on the most important variables. Physical therapists should pay attention to the presence of valgus in activities, since it is the most observed faulty movement pattern among patients. It is very common to diagnose this pattern in patients during sit-to-rise transfer, stair ambulation, or partial squat. After the diagnosis of knee valgus in conjunction with hypomobility, the patient may be treated differently from those without such impairment. Hypomobility can be easily detected when a patient stands on the impaired leg or walks. Back again to the first step, if the patient shows a varus pattern in movement or has no frontal plane deficits, therapists should pay attention to the presence of deformities in the sagittal plane such as hypomobility or hyperextension. In this step, therapists should primarily examine the joint, pay attention to the pain pattern, and observe the faulty movements especially in walking and standing on the impaired leg. If therapists need a complete and accurate assessment, all the 23 variables should be examined. The identification of the applicable patient’s cluster is determined by the skills of the physical therapist on examination, palpation,
and interpretation of the findings.

The present study had some limitations. First, patients with severe symptoms (numerical rating scale above 7 in standing position or failure to perform the test because of severe pain) were not included due to the inability to perform all the tests, especially those with high loading activities. Second, clustering analysis could not classify those patients showing high tolerance to tests, since they could not fully reveal deficits in the signs and symptoms of a test. Usually, activities with high physical demand (single-leg hop test and single-leg squat test) are performed for accurate classification. Another limitation of the study was that we applied tests that can generally be used for all patients with knee pain. Hence, specific tests such as single-leg squat, jump, and hop tests were not performed on patients with a low level of impairments.

Conclusion

A new direct knee examination method is introduced that organizes important discriminative tests and requires fewer clinical examination variables. By examining the essential variables determined in each step, one can easily classify patients with knee impairments using the proposed knee examination approach. Future studies should focus on comparing the result of the current study with the syndromes described in the MSI model. To the best of our knowledge, no studies have been performed on the efficiency of the MSI model on patients with knee pain. Hence, specific tests such as single-leg squat, jump, and hop tests were not performed on patients with a low level of impairments.

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