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# Effects of physiotherapy treatment on knee osteoarthritis gait data using principal component analysis

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ABSTRACT

*Background:* Interpreting gait data is challenging due to intersubject variability observed in the gait pattern of both normal and pathological populations. The objective of this study was to investigate the impact of using principal component analysis for grouping knee osteoarthritis (OA) patients' gait data in more homogeneous groups when studying the effect of a physiotherapy treatment.
*Methods:* Three-dimensional (3D) knee kinematic and kinetic data were recorded during the gait of 29 participants diagnosed with knee OA before and after they received 12 weeks of physiotherapy treatment. Principal component analysis was applied to extract groups of knee flexion/extension, adduction/abduction and internal/external rotation angle and moment data. The treatment's effect on parameters of interest was assessed using paired t-tests performed before and after grouping the knee kinematic data.
*Findings:* Increased quadriceps and hamstring strength was observed following treatment ($P<0.05$). Except for the knee flexion/extension angle, two different groups ($G_1$ and $G_2$) were extracted from the angle and moment data. When pre- and post-treatment analyses were performed considering the groups, participants exhibiting a $G_2$ knee moment pattern demonstrated a greater first peak flexion moment, lower adduction moment impulse and smaller rotation angle range post-treatment ($P<0.05$). When pre- and post-treatment comparisons were performed without grouping, the data showed no treatment effect.
*Interpretation:* The results of the present study suggest that the effect of physiotherapy on gait mechanics of knee osteoarthritis patients may be masked or underestimated if kinematic data are not separated into more homogeneous groups when performing pre- and post-treatment comparisons.


## 1. Introduction

According to recent clinical guideline recommendations, regular physical activity and lower limb strengthening exercises are key components of knee osteoarthritis (OA) management (Zhang et al., 2007). Exercise has shown to have beneficial effects on decreasing symptoms of pain and improving physical function in knee OA patients. However, its effects on knee biomechanics are still unclear. Although changes in knee biomechanics during gait have been recently reported following a physiotherapy treatment (Turcot et al., 2009), other studies were not conclusive (Lim et al., 2008; Thorstensson et al., 2007). Possible reasons for this discordance may be related to gait outcomes as well as to intersubject variability observed in both gait patterns and responses to the treatment of patients evaluated.

In most gait studies, dynamic joint angles and moment data as a function of the gait cycle are presented in the form of curves (Astephen et al., 2008; Baliunas et al., 2002; Winter, 1988). Specific kinematic or kinetic gait parameters, such as the mean of peak values, are extracted at particular periods of the gait cycle and used for group comparison. However, limitations can be encountered using this technique. Although human gait is a cyclic and repeatable activity, every person has a fairly unique gait pattern, leading to intersubject variability in curve profiles (Winter, 1988). For example, temporal appearance of the parameter of interest can be different among persons being compared. Also, averaging can collapse information to the point of removing important intersubject variability within a given group, whether before or after physiotherapy. To recover the relevant intersubject variability in the gait data before and after physiotherapy

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interventions, principal component analysis (PCA) can be used as a precursor for separating gait data into groups (Carriero et al., 2009). By doing so, homogeneous groups of curve profiles can be extracted from the entire gait data sample and gait features characterizing each group can be identified.

PCA is a modeling technique that can be employed to reduce the dimensionality and evaluate the variability of a high-dimensional data set. Dimensionality reduction is accomplished by projecting the original data into a new lower dimension data set of uncorrelated variables called the principal component scores. The clinical relevance of using PCA for gait data interpretation of knee OA patients has been reported in Deluzio and Astephen (2007). These authors found agreement between the components of the gait signal pattern and the clinical status of knee OA patients. In another study, Carriero et al. (2009) demonstrated that PCA can be used as a preliminary step for clustering cerebral palsy children gait parameters into homogeneous groups. The purpose of this study is to perform dimensionality reduction of complete gait cycle data of knee OA patients using PCA for classifying curve profiles into homogeneous groups and examine the effect of a physiotherapy treatment on three-dimensional (3D) knee OA kinematics. From a technical standpoint, grouping gait data will result in a set of meaningful exemplar curves that accurately represent a group of patient gait data. Gait parameters of interest will be extracted from these exemplar curves and used for pre- and post-treatment comparisons. It is hypothesized that conducting pre- and post-physiotherapy treatment comparisons using the mean of a given parameter extracted from an homogeneous group will be more meaningful than using the mean of a parameter estimated from all the data combined.

## 2. Methods

### 2.1. Participants

To participate, patients had to be over 50 years of age and they had to be diagnosed with tibiofemoral knee OA according to the clinical criteria proposed by the American College of Rheumatology (Altman et al., 1986). For this project, the clinical and radiological criteria were pain for at least 3 months and a pain level higher than 3 on a verbal numerical scale of 0 (no pain) to 10 (unbearable) during gait, crepitus on joint mobilization and morning stiffness lasting 30 min or less. For the radiographic criteria, the conventional radiographic grading system developed for knee OA by Kellgren and Lawrence (KL) was used to classify patients according to knee OA severity (grades I, II, III or IV). Patients were required to have grades I to IV knee OA primarily affecting the medial compartment. Patients were excluded if the lateral compartment was primarily affected with knee OA, if they presented vestibular, neurological or any other musculoskeletal disorders other than knee OA, if they had a lower extremity injury, any conditions affecting their ability to walk on a treadmill or if they had participated in a physiotherapy program. Twenty-nine patients (22 women and 7 men) were included in the study. In terms of radiographic knee OA severity, the distribution of the patient sample was as follows: grade I = 10 patients, grade II = 5 patients, grade III = 5 patients and grade IV = 9 patients. Medial tibiofemoral OA changes were present in 29 patients, whereas in three patients, appearance of OA degeneration was also observed in the lateral compartment but to a lesser extent. Mean and standard deviation of age, weight, height and body mass index (BMI) were 63.3 (8.4) years, 80.5 (18.3) kg, 1.60 (0.1) m and 31 (5) kg/m$^2$ respectively. Institutional ethics approvals were obtained and all patients signed the informed consent.

### 2.2. Physiotherapy treatment

The physiotherapy treatment was standardized in terms of treatment modalities, which meant that the program was mainly oriented towards muscle strengthening and stretching exercises, proprioceptive exercises and aerobic training. Pain and anti-inflammatory modalities were used as adjuvant therapy if needed. The choice of proposing a program focusing on exercises was based on the recommendations of O'Grady et al. (2000). The strengthening and stretching exercises are synthesized in Table 1, the proprioceptive and balance exercises are summarized in Table 2 and the aerobic training is described briefly in Table 3. A global description of the treatment's progression is outlined in Table 4. An attempt was made to standardize the treatment progression but due to ethical reasons, the progression was adjusted based on the clinical status of each patient, reflecting what happens in a real clinical context: patients were not asked to advance to a more difficult exercise if they could not do so or if they did not respond well to pain management modalities. The treatment was administered twice a week for a period of 12 weeks and each session lasted approximately 1 h.

All patients had two 3D gait and clinical evaluations. The first evaluation was performed prior to enrolment into the physiotherapy treatment. The second evaluation took place a maximum of two weeks after the end of the treatment.

**Table 1**
Synthesis of manual therapy interventions and strengthening exercises.

| Exercises | Goal | Description |
|---|---|---|
| *Manual therapy* | | |
| 1. Knee massage | Relax medial and lateral ligaments of the patella. Relax knee muscular compartment and ligament structures. | While the patient is sitting, the physiotherapist performs translation movements around patella with her fingers and petrissage (kneading) of soft tissues surrounding the knee. |
| 2. Patella mobilization | Promote mobility of the patella in relation to the femur. | While the patient is sitting, the physiotherapist performs lateral and medial movements of the patella with her fingers. |
| 3. Passive stretching of the iliotibial band and of the posterior muscle chain of the leg | Reduce or prevent biceps femoris, iliotibial band and gastrocnemius contractures. Improve elasticity of peri-articular tissues. | While the patient lies on the unaffected side, the physiotherapist gently stretches the ankle into dorsiflexion (affected side), keeping the knee in extension and controlling hip adduction. |
| 4. Passive stretching of the muscular posterior chain of the leg | Reduce or prevent biceps femoris and gastrocnemius contractures. Improve elasticity of peri-articular tissues. | While the patient lies in a supine position with the pelvis in anteversion, the physiotherapist maintains the legs at roughly 60° of hip flexion from the mat. The knees are kept in extension. The physiotherapist also applies gentle force to stretch the ankle in dorsiflexion. |
| *Strengthening exercises* | | |
| 1. Isometric quadriceps contraction | Strengthen quadriceps | In a sitting position, the patient performs 10 quadriceps contractions while keeping the knee in extension and knuckles away from the mat. |
| 2. Half squat with a ball against a wall | Strengthen quadriceps | Standing with a ball pressed between the patient's back and the wall, the patient performs half squats. |

**Table 2**
Synthesis of proprioceptive and balance exercises.

| Exercise | Goal | Description |
|---|---|---|
| *Proprioceptive and balance exercises* | | |
| 1. Stabilization on a ball | Improve proprioception and sensorimotor function of the knees and ankles. | Try to maintain proper balance while sitting on an exercise ball, while moving one knee at a time in extension. |
| 2. Balance with feet one in front of the other | Improve articular stability (medial–lateral) at the knees and ankles and improve proprioception and sensorimotor function. | Stand on a piece of foam (about 2 in. thick) with feet one in front of the other, trying to maintain a proper balance while making small postural adjustments. |
| 3. Balance on a proprioceptive board with 3 points of support on the ground | Improve sensorimotor function involving the muscles of the legs. | Try to maintain balance while standing on a pivoting board in anterior and posterior plane with feet 1) one in front of the other 2) with feet spread apart. |
| 4. Balance on a proprioceptive board with only 1 point of support on the ground | Improve articular stability, enhancing proprioception and sensorimotor function of the legs. | While standing with feet spread apart, try to maintain balance on a multiaxial pivoting board while making small postural adjustments. |
| 5. Climbing and walking down 1 step | Strengthen quadriceps with concentric and eccentric contractions and emphasize knee stabilization. | Climb and walk down a 3-inch step. A concentric action of the knee extensors is used to climb followed by a slow and controlled eccentric action of the knee extensors to walk down. |

### 2.3. Clinical evaluation

The clinical evaluation included measures of disability, lower limb muscle strength and locomotor function. Disability included measures of knee pain, stiffness and function and was assessed by asking patients to complete the 3.1 French version of the Western Ontario McMaster Universities Osteoarthritis Index (WOMAC) (Bellamy et al., 1988). The 100 mm version of the visual analogue scale was used to measure scores in three domains. An experienced physiotherapist evaluated the patients' maximum isometric quadriceps and hamstring strength using a manual dynamometer (Lafayette Electronic Manual Muscle Tester, Lafayette Instrument, Lafayette, USA), according to the belt-resisted method (Desrosiers et al., 1998). Three consecutive trials were performed for each muscle group (quadriceps and hamstrings). The mean of the three trials was calculated and then normalized to the patient's body weight. The mean value was considered for further analysis. Locomotor function was measured with timed walking, transferring to and from a chair and ascending/descending stairs. The procedures described in McCarthy and Oldham (2004) were followed for the walking and the transferring tests, whereas for the ascending/descending stairs test, the method proposed by Lin et al. (2001) was adopted. Locomotor test procedures are presented briefly here. The aforementioned works can be consulted for more details. For each of the following locomotor tests, a stop watch was used to record the time and patients were instructed to perform all tests at their own comfortable speed. Walking was assessed by recording the time taken by the patient to complete a distance of 8 m. The time to transfer to and from a chair was measured as follows: the patient first walked for 2 m; they were then asked to sit on a chair and immediately stand up and walk back to the starting point. Finally, the time taken to walk up four stairs, turn around without resting and walk down those stairs was measured. Three repetitions were undertaken for each of the locomotor tests and the mean of the times was used for analysis.

**Table 3**
Synthesis of aerobic exercises.

| Exercise | Goal | Description |
|---|---|---|
| *Aerobic exercises* | | |
| 1. Walking on a treadmill | Improve muscular endurance, improve gait, elevate body temperature and promote blood circulation. | Patient walks for 10 min at a comfortable gait velocity on a treadmill. |
| 2. Riding a stationary bike | Strengthen quadriceps, elevate body temperature and promote blood circulation. | Patient pedals a stationary bike for 5 min at a comfortable velocity with no or very low resistance. |

### 2.4. Gait evaluation

Three-dimensional knee kinematics and kinetics were recorded while the patient walked on an instrumented treadmill (ADAL, Med. Development, France) at their comfortable velocity. All participants had a familiarization session on the treadmill for at least 15 min, two to four days before they had their pre-treatment gait evaluation. This allowed for determination of the comfortable gait velocity. The speed of the treadmill was increased progressively, until the patient's comfortable velocity was reached. The same velocity was set for pre- and post-treatment gait evaluations. Moreover, before recording the data, each patient was allowed to have an eight-minute warm-up walking session free of equipment. Following the warm-up session, an exoskeleton (Ganjikia et al., 2000) was installed on the affected side. The exoskeleton was composed of a femoral part, clamped on the femoral condyles, and a tibial part, fixed on the medial side of the tibia. Four reflective markers were installed on both the femoral and tibial parts (rigid bodies). This equipment was designed to reduce skin motion artifacts and validated for gait application studies (Hagemeister et al., 2005; Sudhoff et al., 2007). Four markers were also attached on the sacrum via a sacral belt, and lastly, four markers were secured onto the foot. Once installation of

**Table 4**
Typical treatment progression adjusted according to each patient's progression.

| Modalities | Weeks | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| *Manual therapy and strengthening exercises* | | | | | | | | | | | | |
| Massage | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ |
| Patella mobilization | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ |
| Stretching ITB and leg muscles | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ |
| Stretching leg muscles | | | | √ | √ | √ | √ | √ | √ | √ | √ | √ |
| Isometric quadriceps contraction | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ |
| Half squat with a ball | | | | | √ | √ | √ | √ | √ | √ | √ | √ |
| *Proprioceptive and balance exercises* | | | | | | | | | | | | |
| Stabilization on a ball | √ | √ | √ | √ | | | | | | | | |
| Balance with feet in a tandem position | √ | √ | √ | √ | | | | | | | | |
| Balance on a 3-point proprioceptive board | | | | √ | √ | √ | √ | √ | √ | √ | √ | √ |
| Balance on a 1-point proprioceptive board | | | | √ | √ | √ | √ | √ | √ | √ | √ | √ |
| *Aerobic exercises* | | | | | | | | | | | | |
| Walking on a treadmill | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ |
| Stationary bike | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ |
| Climbing and walking down one step | | | | | | | | √ | √ | √ | √ | √ |
| *Other modalities* | | | | | | | | | | | | |
| Ice | * | * | * | * | * | * | * | * | * | * | * | * |
| Ultrasound | * | * | * | * | * | * | * | * | * | * | * | * |

* = if needed.

the equipment was completed, the patients were instructed to walk for 2 min, allowing them to get accustomed to the experimental set-up. Afterwards, two 25-second trials were recorded and saved for data analysis. In the case of bilateral knee OA, the more symptomatic knee was evaluated.

Positions of all markers were recorded using a six camera optoelectronic system (VICON 460, Oxford Metrics, Oxford, UK) at a sampling frequency of 120 Hz. Marker trajectories were filtered with a singular spectrum analysis filter using a window length of 10. The center of the knee joint and the coordinate systems of the femur and lower leg segments were defined with reference to the functional and postural approach proposed by Hagemeister et al. (2005), which is briefly described here. To define the hip joint center, the patient was instructed to circumduct the leg, and the center of the femoral head in relation to the pelvis was calculated using an optimization method. The lateral and medial femoral condyles were then digitized using a probe. The mid-point was calculated and projected on a functional knee joint axis obtained during an active knee flexion/extension movement. The knee joint center was then expressed in relation to the rigid body of the femur. The ankle joint center was defined by the mid-point of the inter-malleoli distance, which was calculated after the lateral and medial malleoli were digitized. The ankle joint center was expressed in relation to the tibial rigid body.

The system was composed of three axes defined as follows: 1) a proximo-distal axis (internal/external rotation movement) was defined when the projection in the sagittal plane of a vector joining the hip joint center and the knee joint center (femur) was parallel to the projection of a vector joining the knee joint center and the ankle joint center (tibia); 2) a antero-posterior axis (abduction/adduction movement) perpendicular to the proximo-distal axis and perpendicular to the normal of the sagittal plane; and 3) medio-lateral axis (flexion/extension movement) an axis defined by the vectorial product of the other two axes. To meet the objectives of this study, only knee joint data were considered.

Kistler forceplates embedded in the treadmill allowed for the recording of the ground reaction forces in the vertical, antero-posterior and medio-lateral axis at a sampling frequency of 120 Hz. The data were filtered with a fourth-order Butterworth zero-lag filter with a cut-off frequency of 30 Hz. The net moments at the ankle, knee, and hip joints were calculated using a 3D generic inverse dynamic method using wrench notation and quaternion algebra (Dumas et al., 2004). Again, only knee data were considered.

The foot contact and toe-off events of the gait cycle were identified from the vertical ground reaction forces using a threshold of 2% of the patient's body weight. The gait cycles were normalized to 100% and a mean pattern was computed from the most repeatable 15 cycles.

### 2.5. Statistical analysis

Descriptive statistics were used to characterize the patient sample. For clinical data, parameters of interest were quadriceps and hamstring strength, WOMAC scores and locomotor function tests. Pre- and post-treatment comparisons for time distance parameters were performed with paired t-tests.

For kinematic and kinetic gait data, the database consisted of a data matrix of n observations (n = 29 patients) and $P$ variables ($P$ = 100, with the normalized gait cycle consisting of 100 points). Data analysis was performed in 3 steps: 1) pre-treatment data reduction with PCA; 2) pre- and post-treatment data grouping into homogeneous groups of exemplar curves; and 3) extraction of parameters of interest from these exemplar curves to perform pre- and post-treatment comparisons. Firstly, PCA was used to reduce dimensionality by projecting the gait cycle points (consisting of 100 dimensions) on a one-dimensional space. Dimensionality reduction was performed separately on sagittal, frontal and transverse plane gait data. Although the dimensionality reduction was drastic (from 100 to 1), the first principal component accounted for 85% of the variance in the data sets and was considered sufficient for data representation. Secondly, the principal component scores ($PC_{scores}$) signs allowed for the patients' gait data to be grouped into homogeneous exemplar curves. The $PC_{score}$ grouping is consistent with the assumption of a Gaussian distribution of the data which served the derivation of the PCA, namely to determine an orthonormal basis for the $PC_{scores}$ distribution. Since the $PC_{scores}$ are centered to have zero mean, the groups were extracted according to $PC_{scores}$ signs and were named *group 1* ($G_1$) = $PC_{score}>0$, and *group 2* ($G_2$) = $PC_{score}<0$. This procedure was undertaken for each angle and moment at the knee. Grouping the $PC_{scores}$ signs provides an effective method for determining distinct gait patterns (Mezghani et al., 2010, personal communication). Each patient was then identified as belonging to either $G_1$ or $G_2$. Grouping was first performed on the post-treatment data. Then, the grouped post-treatment data labels (i.e., $G_1$ and $G_2$) were back-projected to obtain the corresponding pre-treatment data labels. Thirdly, the following parameters were extracted from the entire group (n = 29) data as well as from $G_1$ and $G_2$ and considered for pre-treatment vs. post-treatment comparisons: the peak and range values for 3D knee angle data and peak values and adduction moment impulse for 3D knee external moment data. For a given movement plane, the angle range was the total movement excursion of the knee during a complete gait cycle. The adduction moment impulse was obtained via the moment-time integral. The normality of the distribution of the gait parameters was tested using a Kolmogorov–Smirnov procedure and the Levene's test was used to test the homogeneity of the variance. Based on these results, the treatment's effect on all parameters was assessed by performing pre-treatment vs. post-treatment comparisons using paired t-tests on 1) the mean of all the data combined (n = 29), and 2) the mean of each of the extracted groups. The level of significance was set at $P<0.05$.

## 3. Results

### 3.1. Clinical evaluation

#### 3.1.1. Pre-treatment vs. post-treatment comparison, clinical evaluation

Table 5 outlines the pre- and post-treatment results related to clinical evaluations. The overall clinical status of the patients improved following the physiotherapy treatment. The WOMAC scores demonstrated that the patients had less knee pain, less stiffness and felt less disabled. Isometric quadriceps and hamstring strength was also improved. Moreover, all patients could perform the three locomotor function tests at a faster pace.

### 3.2. Gait evaluation

#### 3.2.1. Pre-treatment vs. post-treatment comparison, spatio-temporal gait parameters

Following the physiotherapy treatment, patients walked at a lower cadence (104.5 steps/min (8.8) vs. 101.3 steps/min (9); $P<0.05$) and had a longer step length (0.47 m (0.10) vs. 0.49 m (8.1); $P<0.05$).

**Table 5**
Pre-treatment vs. post-treatment results of the clinical evaluation measures (n = 29).

| Clinical tests | Pre-treatment Mean (SD) | Post-treatment Mean (SD) |
|---|---|---|
| WOMAC scores | | |
| Pain | 198 (91.7) | 63.7 (66.4)* |
| Stiffness | 102.4 (59.8) | 39.33 (35.3)* |
| Function | 623.5 (352.66) | 252.5 (241.8)* |
| Isometric muscle strength | | |
| Quadriceps (N/kg) | 3.1 (1) | 3.9 (1.2)* |
| Hamstrings (N/kg) | 2.3 (0.5) | 2.6 (0.5)* |
| Locomotor function tests | | |
| Walking (s) | 6.33 (1.17) | 5.72 (0.74)* |
| Transferring to and from chair (s) | 7.16 (1.28) | 6.08 (0.97)* |
| Ascending/descending stairs (s) | 4.75 (1.35) | 3.82 (0.75)* |

* Significant $P$ value < 0.01.

*3.2.2. Pre-treatment vs. post-treatment comparison, angles and moments, all the data combined (n = 29)*

Mean values and standard deviations of the parameters of interest are presented in Table 6. The results show that the physiotherapy treatment had no significant effect on gait kinematic and kinetic parameters when all patients were included in the group for the pre-treatment vs. post-treatment comparison.

*3.2.3. Pre-treatment vs. post-treatment comparison, angles and moments, groups of data*

Except for the knee flexion/extension angle curve profiles, two different groups ($G_1$ and $G_2$) were extracted from the angle and moment data. Therefore, for each movement plane (sagittal, frontal and transverse), patients were identified as exhibiting either a $G_1$ or a $G_2$ exemplar curve pattern. The knee moment (sagittal and frontal planes) and angle (transverse plane) curve profiles for all the data combined (n = 29) and for the groups are depicted in Fig. 1. Mean values and standard deviations of the chosen parameters for $G_1$ and $G_2$ are presented in Table 6. When pre- and post-treatment analyses were performed on the groups, a greater first peak flexion moment, a lower adduction moment impulse and a smaller rotation angle range were found following the physiotherapy treatment ($P<0.05$) for patients exhibiting $G_2$ patterns. For the above-mentioned parameters, the number of patients belonging to each group and the knee OA severity of the patients are specified in Fig. 1. For clarity and to facilitate interpretation of the results, patients with grades I and II OA severity were considered as having mild/moderate knee OA and those with grades III and IV were considered as having severe knee OA. No treatment effect was observed for patients exhibiting $G_1$ patterns for angle or moment curve profiles in the sagittal, frontal and transverse planes.

## 4. Discussion

In this study, the gait of knee OA patients was assessed before and after they completed a 12-week physiotherapy treatment program. The objective was to investigate the impact of using PCA to classify the data into more homogeneous groups when studying the effect of a physiotherapy treatment on knee OA patient gait data. Following the physiotherapy treatment, the results obtained from the clinical evaluation showed that the clinical status of the patients improved significantly. The patients felt less pain and stiffness, had better function and could perform locomotor tasks faster. These findings coincide with many other studies reporting the beneficial effects of physiotherapy modalities on pain and function (Deyle et al., 2000, 2005; Jan et al., 2009; Weng et al., 2009). As reported by Deyle et al. (2000), the self-perception of pain relief and reduced knee stiffness may be attributed to the stimulation of muscular and peri-articular connective tissues induced by the multi-modal physiotherapy treatment administered. Knowing that a gain in muscle strength is closely related to improvement in knee function (O'Reilly et al., 1999), the increase in the patients' quadriceps and hamstring strength observed following the treatment may explain why their performance in locomotor tasks was better following treatment.

Although the benefit of quadriceps strengthening exercises on knee function is now well recognized, their effect on gait biomechanics and joint structure is not well established. Our findings demonstrate that when the patients' data were not separated into groups, no difference was observed in pre-treatment vs. post-treatment comparisons. There have been only a few studies that have investigated whether or not strengthening exercises can modify gait biomechanics (Lim et al., 2008; Thorstensson et al., 2007; Turcot et al., 2009). Lim et al. (2008) and Thorstensson et al. (2007) used peak knee external adductor moments as the biomechanical outcome to measure the effect of strengthening exercises. These authors concluded that knee adductor moments remained unchanged following completion of a quadriceps strengthening exercise program. Although the external knee adductor moment is widely accepted as a biomechanical determinant of knee OA progression, this does not necessarily imply that strengthening exercises are ineffective; the gain in strength may act on other gait parameters as demonstrated in the study conducted by Turcot et al. (2009). These authors used an accelerometric-based method to detect changes in gait biomechanics following a physiotherapy treatment that included quadriceps and hamstring strengthening exercises. They reported that anterior posterior (AP) knee acceleration was reduced post-treatment, meaning that AP knee instability can possibly be improved following treatment. Moreover, given that every person has a specific clinical status and gait pattern, every person may respond differently to a treatment approach. If intersubject variability is not taken into account, the effect of the strengthening exercises can be masked.

**Table 6**
Pre-treatment vs. post-treatment results for knee kinematic and kinetic parameters.

| Knee kinematic and kinetic parameters | All data combined | | Group 1 ($G_1$) | | Group 2 ($G_2$) | |
|---|---|---|---|---|---|---|
| | Pre tx | Post tx | Pre tx | Post tx | Pre tx | Post tx |
| | Mean (SD) | Mean (SD) | Mean (SD) | Mean (SD) | Mean (SD) | Mean (SD) |
| Sagittal plane | | | | | | |
| Peak flexion angle early stance (°) | 18.1 (6.8) | 18.6 (7.3) | 18.0 (6.8) | 18.6 (5.8) | – | – |
| Peak flexion angle swing (°) | 65.1 (4.5) | 66.0 (4.7) | 65.2 (4.5) | 66 (4.6) | – | – |
| Angle range (°) | 58.0 (8.5) | 59.5 (8.3) | 58.9 (8.5) | 59.5 (8.3) | – | – |
| Peak flexion moment (M1) (% BWH) | −1.96 (1.27) | −2.2 (1.34) | −1.77 (1.54) | −1.82 (1.69) | −2.05 (1.16) | 2.54 (1.10)* |
| Peak extension moment (% BWH) | 0.66 (1.5) | 0.49 (1.35) | 0.48 (1.63) | 0.54 (1.53) | 0.85 (1.38) | 0.43 (1.16) |
| Peak flexion moment (M2) (% BWH) | −1.1 (0.6) | −1.2 (0.6) | −0.91 (0.50) | −0.95 (0.61) | −1.30 (0.57) | −1.47 (0.48) |
| Frontal plane | | | | | | |
| Peak adduction angle (°) | 6.5 (5) | 6 (5) | 7 (5.3) | 6.6 (6) | 6.1 (4.9) | 5.5 (4.3) |
| Peak abduction angle (°) | −2.3 (5.6) | −3.1 (6.6) | −4 (4.2) | −5.8 (4.5) | −1.1 (3.4) | 0.9 (3.3) |
| Angle range (°) | 8.8 (3.6) | 9.0 (3.4) | 11 (3.2) | 12.4 (1.9) | 7.2 (3.2) | 6.4 (1.9) |
| Peak adduction moment 1 (M1) (% BWH) | −2.35 (1.19) | −2.45 (1.03) | −2.34 (1.41) | −2.46 (1.19) | −2.57 (0.41) | −2.65 (0.36) |
| Peak adduction moment 2 (M2, $G_2$ only) (% BWH) | – | – | – | – | −2.13 (1.38) | −2.25 (1.16) |
| Adduction moment impulse (time integral) | 94.1 (11.3) | 88.2 (11.7) | 93.2 (6.4) | 87.4 (9.1) | 99.6 (8.2) | 89.8 (8.9)* |
| Transverse plane | | | | | | |
| Peak internal rotation angle (°) | −3.2 (2.9) | −3.7 (2.7) | −3.1 (2.5) | −3.9 (2.6) | −5 (3.3) | −4.4 (3) |
| Peak external rotation angle (°) | 5.2 (4.1) | 4.9 (3.9) | 6.7 (3.1) | 7.1 (3.5) | 4.8 (1.3) | 3.4 (1.3) |
| Angle range (°) | 8.3 (2.8) | 8.5 (3.3) | 9.9 (2.9) | 11 (2.3) | 9.8 (2.4) | 7.9 (2.5)* |
| Peak internal rotation moment (% BWH) | 0.66 (0.28) | 0.61 (0.3) | 0.69 (0.32) | 0.76 (0.23) | 0.46 (0.37) | 0.53 (0.30) |
| Peak external rotation moment (% BWH) | −0.27 (0.28) | −0.25 (0.32) | −0.31 (0.12) | −0.2 (0.16) | −0.15 (0.17) | −0.13 (0.15) |

* Significant $P$ value < 0.05.

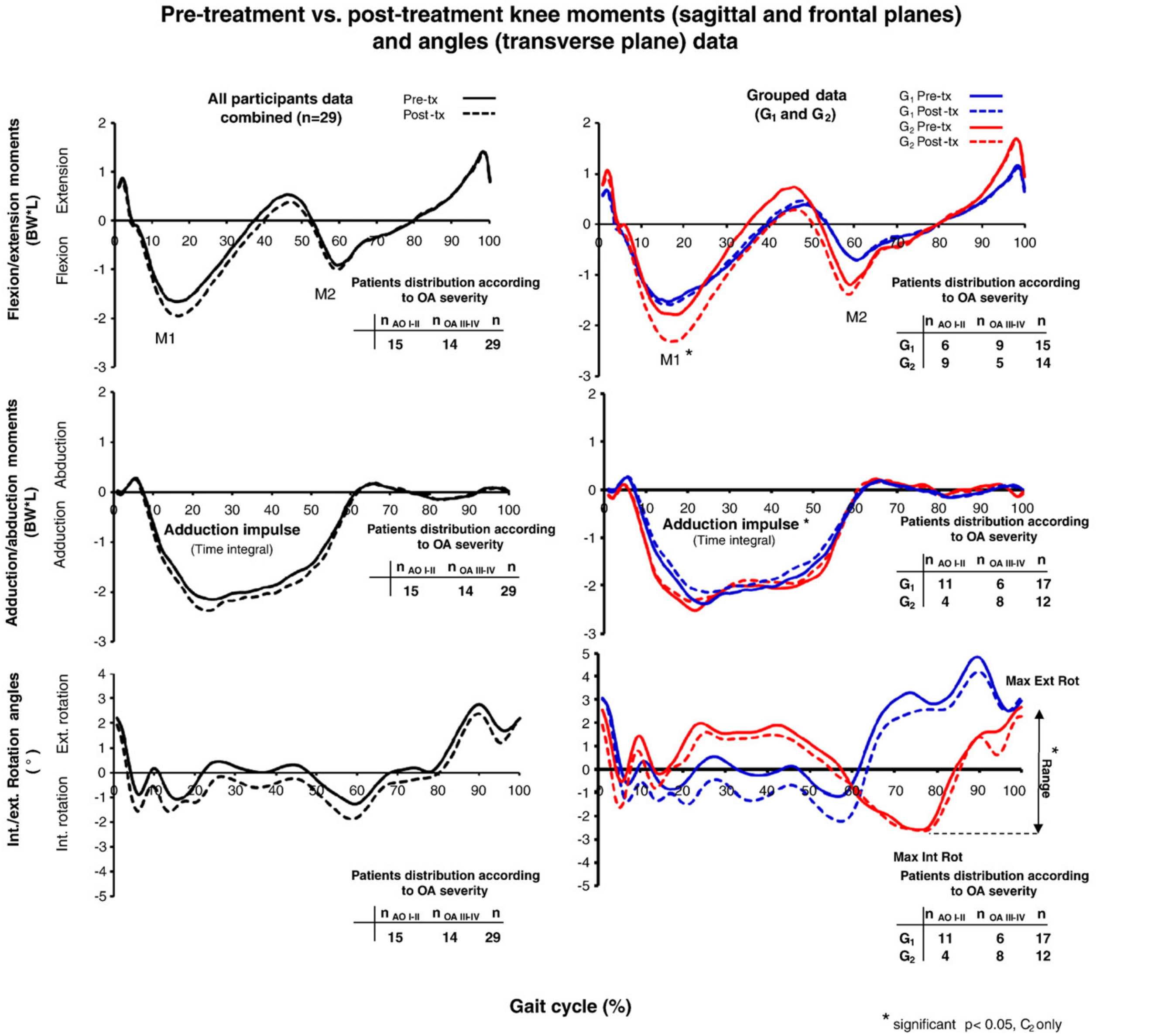


**Fig. 1.** Pre-treatment vs. post-treatment comparisons of 3D kinematic and kinetic parameters showing statistical significance ($P<0.05$). The graphs on the left side of the figure depict the mean curve profiles obtained from all OA patients' data combined. The mean curve profiles of the groups ($G_1$ and $G_2$) are graphically presented on the right side of the figure. The number of patients and the distribution of patients according to knee OA severity are presented on the lower right portion of each graph for the combined data and for the grouped data. M1 refers to the first peak external flexion moment and M2 refers to the second peak external flexion moment. The rotation range is the difference between the maximal external rotation angle minus the maximal internal rotation angle.

Our findings show that except for knee flexion/extension angles curve profiles, two different groups ($G_1$ and $G_2$) could be extracted from each movement plane of the patients' gait patterns. Grouping gait data is interesting as long as a clinically meaningful interpretation can be drawn from doing so. These groups are different from each other in terms of magnitude of mean angle or moment values and, in some cases, in relation to movement direction for a given period of the gait cycle. Grouping knee flexion/extension angle profiles was irrelevant due to low interpatient variability observed for these data; all patients demonstrated similar knee flexion/extension gait patterns. Following physiotherapy treatment, patients exhibiting $G_2$ gait pattern profiles demonstrated a significantly higher external peak flexion moment, lower external adduction angular impulse and lower internal/external rotation range. A possible explanation for the difference in the treatment effect observed when the data are grouped may be related to the severity of knee OA of the patients included in each group. When one looks at the sagittal plane moment, $G_1$ and $G_2$ moment profiles are different in terms of the amplitude of the peak moment values. Patients exhibiting $G_2$ moment profiles show higher peak external knee flexion moment values. It is worth noting that nine out of fourteen patients exhibiting a $G_2$ knee flexion/extension moment profile had grade I or grade II knee OA severity. The knee joint structures are probably less damaged for these patients compared to grades III and IV patients; therefore, they can probably rely on the well-functioning neuromuscular and proprioceptive mechanisms needed to increase knee extensor torque to prevent collapsing of the knee during weight acceptance. The gain in quadriceps strength observed following the physiotherapy treatment might have been helpful for patients with less severe knee OA. It is also possible that these patients could progress to more difficult strengthening and proprioceptive exercises and that can be reflected in the moment profiles.

As regards $G_1$ and $G_2$ frontal plane knee moment profiles, the two groups differ from each other in terms of the shape of the curve. One peak external adductor moment can be observed in the $G_1$ profiles, whereas two distinct peaks appear in the $G_2$ profiles. This difference in gait pattern is masked when all the data combined (i.e., both groups) is considered. The results of our study show no effect of the physiotherapy treatment for peak external adductor moments and these findings are in accordance with those of Lim et al. (2008) and Thorstensson et al. (2007). Quadriceps and hamstring strengthening may not be specific enough to modify frontal plane knee kinetics; therefore, strengthening of other muscle groups, such as hip abductors and adductors may be required (Bennell et al., 2007; Chang et al., 2005; Thorp et al., 2010). However, patients exhibiting a $G_2$ knee adduction/abduction moment profile demonstrated lower post-treatment adduction moment impulse during the stance phase of gait than they did before treatment. Of the 12 patients exhibiting a $G_2$ adduction/abduction knee moment profile, eight presented severe knee OA (grades III and IV). It is possible that patients with more severe knee OA were less active before enrolling in the physiotherapy program. For those patients, the increase in activity level associated with their participation in the physiotherapy program and performance of the aerobic exercises might have been sufficient enough to increase hip abductor strength. Stronger abductors may reduce knee external adductor moments during stance by stabilizing the pelvis and preventing the body's center of mass from moving towards the swing limb (Chang et al., 2005; Thorp et al., 2010). This interpretation is only speculative since hip muscle strength was not measured and analysis of hip kinematic and kinetic data was not the aim of the present study. Moreover, Sled et al. (2010) did not find an effect of hip abductor strength on the knee adductor moment. It is worth mentioning that adduction moment impulse is an interesting parameter because it takes the temporal aspect of the signal into account (Thorp et al., 2006). Therefore, this parameter could be used as an indicator of the amount of loading on the joint throughout the duration of the stance phase.

The rotation angle pattern was quite unstable for all participants in the early portion of the stance phase. The rotation angle range was reduced in patients exhibiting a $G_2$ angle rotation profile. The $G_2$ rotation angle profile group was mainly composed of patients diagnosed with grade III or grade IV knee OA severity (8 out of 12 patients). The physiotherapy program was composed of both quadriceps and hamstring muscle strengthening exercises. Through its insertion on the femoral condyles, the stronger hamstrings might have helped to decrease the range of rotation occurring at the knee during the gait cycle. But more importantly, proprioceptive exercises are related to improvement in functional performance (Lin et al., 2009). It is possible that muscular coordination and synchronization were enhanced after the treatment and that helped to control rotational movements. This decrease in rotation can help prevent further damage to the knee (Andriacchi et al., 2006; Buckland-Wright et al., 2000).

### 4.1. Study limitation

Although the treatment progression followed established recommendations, the treatment progression could not be exactly the same for every patient since they may have reacted differently according to their respective clinical status. Although this can be seen as a limitation, it is worth mentioning that the advantage of the treatment program administered in this study is that it mimics what happens in real life. The small number of patients represents the main limitation in this study. An increase in the database size could improve the precision of the grouping procedure. Moreover, data related to the hip would have helped in interpreting some findings and should be included simultaneously with the knee data in future studies.

## 5. Conclusion

The results of the present study suggest that effects of physiotherapy on gait biomechanics may be easier to detect when using a data reduction analysis followed by a grouping procedure. It is now recognized that modification in gait biomechanics contributes to improper joint loading and possibly to cartilage degeneration. This study opens up interesting avenues for future research in monitoring knee OA patients. This method could be used to evaluate the effectiveness of different types of rehabilitation therapy on the biomechanics of the knee. By providing more appropriate treatment, we not only improve the quality of life of these patients but also hope to slow down the disease progression.

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