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REORGANIZATION OF EQUILIBRIUM AND MOVEMENT CONTROL STRATEGIES IN PATIENTS WITH KNEE ARTHRITIS

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ABSTRACT. The purpose of this study was to identify changes in equilibrium and movement control strategies in patients with arthritis of the knee. These strategies were expected to be different from those of healthy subjects because of the impairments caused by knee arthritis. The different phases of a side step were studied in patients with severe knee arthritis using a movement analysis system and force-plates. The duration of the postural phase and the intensity of the horizontal ground reaction forces during the postural phase were increased when the pathological limb was the supporting one. The monopodal phase was shortened on the pathological leg. These results show that knee arthritis patients develop new posturomotor strategies mainly aimed at shortening the monopodal phase when the affected leg is the supporting one. This movement analysis method enables quantification of differences that cannot be observed on clinical examination between knee arthritis patients and control subjects, and provides additional information to the usual clinical evaluation scales.

Key words: evaluation; knee arthritis; movement analysis.

INTRODUCTION

Arthritis of the knee is a common pathology responsible for impairments such as pain, stiffness, decrease in muscular strength (8) and alteration of proprioception (2), which, in turn, can lead to disabilities especially in walking or ascending and descending stairs.

Investigations using movement analysis devices in knee arthritis patients have already been reported (1, 3, 6, 9, 15, 20). In the study by Berman et al. (3), patients with unilateral knee arthritis were studied during gait. They were found to have a longer stance and a longer single support time, as well as a reduced step length, with similar results for the involved and uninvolved limbs. Györy et al. (9) have shown that the sagittal motion of degenerative knee joints was markedly reduced during gait without any correlation with the passive knee range of motion. Messier (15) analyzed the ground reaction forces in knee arthritis patients during gait. They found a decrease in the second peak of the vertical force on the affected side as compared to the sound leg. By contrast, no difference was found in horizontal forces. In the study by Stauffer et al. (20), the vertical ground reaction forces were lower in knee arthritis patients than in control subjects.

These studies have shown that gait patterns of knee arthritis patients differed significantly from those of able-bodied subjects. These studies, however, did not investigate the coordination between posture and movement in patients with degenerative knee joints, such as those which occur during initiation of gait. Because of the impairments related to knee arthritis (i.e. pain, altered proprioception), we expected to observe changes in equilibrium and movement control strategies in knee arthritis patients when performing motor tasks connected with the lower limbs.

The analysis of kinetic, kinematic and EMG recording data during single leg flexion (19) and gait initiation (4, 5, 13) has provided information about the coordination between posture and movement. Gait initiation is shown to be a complex biomechanical task which not only involves a forward acceleration of the center of mass in the sagittal plane but also includes events which take place in the frontal plane (i.e. first shift of the center of pressure towards the stepping leg prior to heel-off, then second shift of the center of pressure towards the supporting leg) (4, 11, 13, 14). Owing to this coordination between the ground reaction forces in the sagittal and frontal plane, gait initiation is a rather complicated process. In the present study we investigated the side-step, which does not include the forward propulsion component of locomotion and requires a lateral weight transfer as in gait initiation. The results of this work should enable a better understanding of the gait initiation. Furthermore, studies in the frontal plane have already been carried out. Mesure et al. (16) analyzed side step in poliomyelitis patients with asymmetrical lower-limb impairment (i.e. motor deficit predominantly affecting the quadriceps). This study has shown that a new strategy was built in order to maintain equilibrium during a side-step. The findings of the study by Mouchnino et al. (17, 18) in below-knee amputees were indicative of a central adaptation of the postural organization to the peripheral impairments using new sequences of muscular activation.

The aim of this work was to identify modifications in equilibrium and movement control strategies in knee arthritis patients during a side-step, using a kinetic and kinematic analysis, in order to improve both the evaluation of knee arthritis patients and the understanding of how the central nervous system deals with impairments secondary to knee arthritis.

MATERIAL AND METHODS

Population

The patients' group included 10 patients with knee arthritis (5 males and 5 females; mean age 66 years, range 46–77) who were scheduled for total knee arthroplasty.

The Hospital for Special Surgery (HSS) score ranged from 16 to 76 (mean 56) with a maximum of 100 (10).

The criteria for inclusion were unilateral symptomatic knee arthritis. Patients excluded were those with signs of contralateral knee arthritis, as were patients with locomotor, nervous, vascular or other pathologies which could influence stance and gait.

The control subjects were 6 males and 6 females (mean age 71 years, range 66–78).

MATERIAL

The kinematic study was carried out using an optoelectronic system (ELITE®, Bioengineering Technology and Systems, Via Capecelatro 66, 20148 Milano, Italy). Sixteen light-reflecting markers (Fig. 1) were placed on anatomical landmarks: bilaterally, on the lateral edge of eye orbits, acromions, anterior-superior iliac crests, greater trochanters, external femoral condyles, external malleoli, anterior tibial tuberosities, 5th metatarsal heads. The movements of the markers were recorded by four infra-red cameras, positioned in front of the subjects at a frequency of 100 Hz.

The kinetic parameters (ground reaction forces) were recorded from two AMTI® (Advanced Mechanical Technology Inc., 151 California Street, Newton, Massachusetts, 02158, U.S.A.) force-plates (Fig. 1).

Data were analyzed using an ELITE® software.

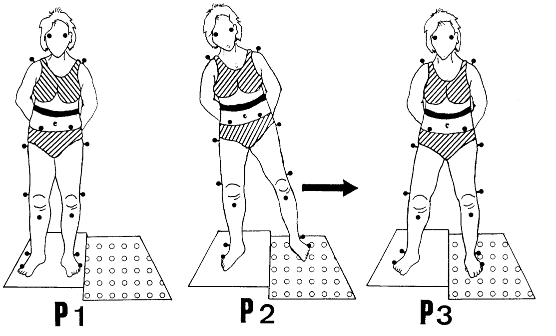

Fig. 1. Subject performing a side-step to the left. Sixteen light-reflecting markers are placed on anatomical landmarks: bilaterally, on the lateral edge of the eye orbits, acromions, anterior-superior iliac crests, greater trochanters, external femoral condyles, external malleoli, anterior tibial tuberosities, 5th metatarsals heads. P1 – postural phase; the subject is standing on his two feet on the the first force-plate. P2 – monopodal phase. P3 – landing phase; each foot is on a different force-plate.

Experimental procedure

All patients were examined by the same specialist in physical medicine and rehabilitation in order to ensure that the criteria for inclusion and exclusion were followed. For each patient, all recordings were done during the same session. The subject had to stand bare-foot on one of the two force-plates, facing the four cameras. The instruction was given to perform a single step sideways, the amplitude of which being about 30 cm, so that the moving limb would land on the second force-plate (Fig. 1). A series of 10 trials were run with the subject moving the right leg and another series of 10 trials with the subject moving the left leg. To perform a side-step to the right, the subject initially had to stand on the left force-plate. The right leg was called the leading leg. In the monopodal phase the left leg was called the supporting limb. The same phraseology was used for the side-step to the left.

Parameters and data analysis

The parameters recorded were:

– The movement of the marker placed on the 5th metatarsal head of the moving limb and of the marker placed on the anterior iliac crest on the side of the movement,

– The displacement of the center of pressure (CPx) in the frontal plane. The CP is the point of application of the resultant of the vertical ground reaction forces. Its position was assessed from the force-plates recordings.

– The horizontal ground reaction forces from two force-plates in the frontal plane. The horizontal ground reaction force in the frontal plane (Fx) recorded from the first force-plate was quantified because it is an accurate index of the acceleration of the center of gravity (CG) in the frontal plane (4).

Three phases were defined on the basis of kinematic and kinetic parameters (Fig. 2).

– Postural phase (P1): the motor task begins at the time t1 corresponding to the first shift in the center of pressure (CPx) in

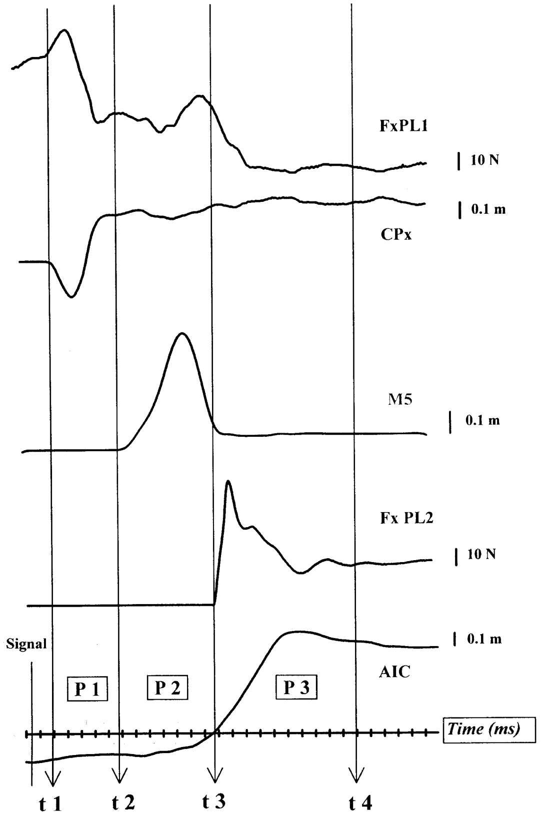

Fig. 2. Determination of the different phases of the movement: t1: first shift of the center of pressure in the frontal plane (CPx). t2: first displacement of the marker placed on the top of the 5th metatarsal head (M5). t3: reception of the leading foot on the second force-plate (horizontal ground reaction force in the frontal plane:Fx). t4: end of the displacement in the frontal plane of the marker placed on the anterior iliac crest (AIC) of the side of the moving limb. P1: postural phase. P2: monopodal phase. P3: landing phase. The first curve on top shows the changes in the horizontal ground reaction forces (Fx) in the horizontal plane recorded on the first force-plate.

the frontal plane. The end of the postural phase took place at time t2 with the onset of the movement of the marker placed on the 5th metatarsal head.

– Monopodal phase (P2): this phase started at time t2 and ended at time t3 corresponding to the landing of the foot on the second force-plate.

– Landing and stabilization phase (P3): this started at time t3 and finished at time t4 with the end of the displacement of the marker placed on the anterior superior iliac spine.

Statistical methods

A paired Student t test was used to compare side steps to the right and side steps to the left in control subjects, and side steps to the affected side and to the sound leg in knee arthritis patients. A Student's *t* test was used to compare control subjects and patients. The level of significance was taken to be at least $p < 0.05$ level.

RESULTS

Movement duration

Mean value and standard-deviation of the different phases and total movement duration are expressed in Table I for all control subjects performing side-steps towards the left (LS) and side-steps towards the right (RS). Table II presents the mean value and the standard deviation of each phase duration and of total movement duration in knee arthritis patients performing a side-step with the sound limb supporting (SLS) and with the affected limb supporting (ALS).

Comparison of steps towards the right (RS) and steps towards the left (LS) in control subjects. No statistically significant difference was found between RS and LS for each phase and for total movement duration. Hence, the mean of RS and LS value was used for comparison with knee arthritis patients.

Comparison of steps with the SLS and steps with the ALS (Fig. 3). P1, which corresponds to the postural phase is longer for the ALS steps than for the SLS steps ($t = 3.9$; $p < 0.0036$).

P2, which is the monopodal phase, is shorter for the ALS steps than for the SLS steps ($t = -2.4$; $p < 0.0404$).

There is no difference between steps with the sound or affected limb supporting in the landing and stabilization phase and total movement duration.

Table I. *Mean value (M) and standard deviation (SD) of P1, P2, P3, and total movement durations (ms) in control subjects, for steps to the right (RS), to the left (LS) and for all steps together.* ($n = 11$)

	Postural phase P1			Monopodal phase P2			Landing and stabilization Phase P3			Total duration		
	RS	LS	All	RS	LS	All	RS	LS	All	RS	LS	All
M	273.1	302.7	288	592.1	614.3	603	823	795	809	1688.2	1712	1700
SD	89.2	79	83.6	96.4	87.7	90.6	108.4	106.6	106	141.5	143.3	139.5

Table II. *Mean value (M) and standard deviation (SD) of P1, P2, P3, and total movement durations (ms) in patients for steps with the affected limb supporting (ALS) and with the sound limb supporting (SLS).* (*n* = 10)

	Postural Phase P1		Monopodal Phase P2		Landing and Stabilization Phase P3		Total duration	
	ALS	SLS	ALS	SLS	ALS	SLS	ALS	SLS
M	430	303.3	519.3	581.5	1054.2	1056.8	2003.6	1941.5
SD	128	75.5	51.4	89.8	144.2	162.9	199.3	249.1

Comparison of side steps in control subjects and steps with the ALS in knee arthritis patients (Fig. 3). The P1 phase is longer for ALS steps than for control subjects ($t = 3.8$; $p < 0.007$).

The P2 phase is shorter for ALS steps than for control subjects ($t = -2.72$; $p < 0.0108$).

The P3 phase and total movement duration are longer for ALS steps than for control subjects ($p < 0.0001$ in both cases).

Comparison of side-steps in control subjects and steps with the SLS in knee arthritis patients (Fig. 3). There is no difference between P1 and P2 phases.

P3 phase and total movement duration are longer for SLS steps than in healthy subjects ($t = 5.2$; $p < 0.0001$, and $t = 3.5$; $p < 0.0014$, respectively).

Initial displacement of the center of pressure in the frontal plane during the postural phase (CPx) (Tables III and IV). The center of pressure was found to shift first towards the supporting limb during the postural phase, and then to move in the opposite direction towards the stepping leg (Fig. 1), in both control subjects and patients. The length of the initial displacement of the CPx was measured.

No difference was found between steps to the right and steps to the left in control subjects. Thus, the mean of RS and LS was used for comparison with knee arthritis patients.

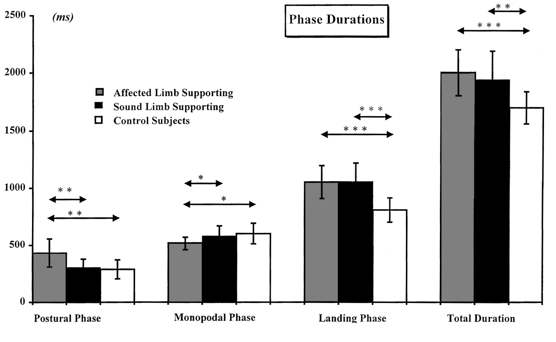

Fig. 3. Comparison of the durations of the postural, the monopodal and the landing phases, and of the total movement duration in patients when the affected limb is the supporting one, in patients when the sound limb is the supporting one, and in control subjects ($p < 0.05$:*, $p < 0.01$:**, $p < 0.001$: ***).

Table III. *Mean value (M) and standard deviation (SD) of the displacement of the center of pressure (CPx) in the frontal plane (mm) in control subjects, for steps to the right (RS), to the left (LS) and for all steps together.* (*n* = 11)

	CPx displacement (mm) Right steps	CPx displacement (mm) Left steps	CPx displacement (mm) All
M	15.63	15.61	15.62
SD	11.1	8.48	9.63

The initial displacement of the CPx was longer in patients for ALS steps than for SLS steps ($t = 3.49$; $p = 0.003$). It was also more important for ALS steps than steps of control subjects ($t = 2.065$; $p = 0.047$).

No statistically significant difference was found between SLS steps and control subjects' steps.

Horizontal ground reaction forces in the frontal plane during the postural phase (Tables V and VI). As can be seen in Fig. 1, the horizontal ground reaction force (Fx) moved in the opposite direction to the CP.

Table IV. *Mean value (M) and standard deviation (SD) of the displacement of the center of pressure (CPx) in the frontal plane (mm) in patients for steps with the affected limb supporting (ALS) and with the sound limb supporting (SLS).* (*n* = 10)

	Cpx displacement (mm) ALS steps	Cpx displacement (mm) SLS steps
M	22.77	12.88
SD	5.83	6.2

Table V. *Mean value (M) and standard deviation (SD) of the horizontal ground reaction force in the frontal plane (Fx) measured at its first peak, in control subjects, for steps to the right (RS), to the left (LS) and for all steps together.* ($n = 11$)

	Fx (N) Right steps	Fx (N) Left steps	Fx (N) All
M	8.6	9.7	9.15
SD	4.5	4.3	4.35

Table VI. *Mean value (M) and standard deviation (SD) of the horizontal ground reaction force in the frontal plane (Fx) measured at its first peak, in patients for steps with the affected limb supporting (ALS) and with the sound limb supporting (SLS).* ($n = 10$)

	Fx (N) ALS steps	Fx (N) SLS steps
M	17.87	9.95
SD	12.9	6.77

Fx was measured at the first peak of the curve occurring during the postural phase. Fx was found to be increased for ALS steps as compared to SLS steps ($t = 2.155$; $p = 0.047$) and to steps of control subjects. No statistically significant difference was found between SLS steps and steps performed by control subjects. The increase in the Fx during the postural phase reflects the acceleration of the center of gravity towards the moving side. In order to confirm this result, the maximal velocity of the marker placed on the anterior iliac crest on the supporting side was measured for all trials of one subject and was shown to be significantly increased for ALS steps (mean value 486.83 mm/s; SD 34.1) as compared to SLS steps (mean value 383.67 mm/s; SD 25.74, $t = -9.354$; $p < 2.92\text{E}-6$).

DISCUSSION

The present study was developed in patients suffering from a severe unilateral knee arthritis in order to assess the changes of postural and movement strategies during the performance of a lateral step, using movement analysis and ground reaction force measurement devices. The timing of the sequence of events occurring during this task, as well as the amplitude of the CP displacement and the Fx during the postural phase were selectively modified in an asymetrical way according to the leg used as supporting leg during the task.

Postural phase (P1) and monopodal phase (P2)

The postural phase is longer in knee arthritis patients, for ALS steps as compared to SLS steps and steps performed by control subjects. By contrast, there is no difference between knee arthritis patients when the sound limb is the supporting one, and control subjects. A shortening of the monopodal phase is observed in knee arthritis patients when the affected limb is the supporting one. The duration of this phase is the same in control subjects and in knee arthritis patients when the sound limb is the supporting one. The initial displacement of the center of pressure towards the supporting leg is more important and the horizontal ground reaction forces which are exerted in the opposite direction are greater for ALS steps as compared to SLS steps and steps performed by control subjects. By contrast, there is no difference between knee arthritis patients when the sound limb is the supporting one, and control subjects.

Contrary to what was expected, shear forces in the frontal plane are exerted with an increased intensity and for a longer time for ALS steps during the postural phase. The increase in Fx results in a higher acceleration of the center of gravity and an increase of the maximal velocity of the CG as indicated by the measurement made with the marker placed on the anterior iliac crest. The higher acceleration of the CG is associated with a shortening of the monopodal phase. Hence, it seems that knee arthritis patients build up new posturomotor strategies aimed at shortening the monopodal phase. Since all our patients experienced pain when performing a side-step, this result can be explained by the fact that patients try to avoid mechanical constraints on the pathological knee and try to shorten the time when weight is supported only by the affected limb. However, knee arthritis is also responsible for impairments such as altered proprioception (2), decrease in muscular strength (7, 8, 12), and joint stiffness. It is likely that these impairments make weight-bearing more difficult on the affected limb and cause a shortening of the monopodal phase.

Landing and stabilization phase (P3)

This phase is longer in knee arthritis patients than in normal subjects both when the sound and the affected limbs are the supporting ones. This result can be explained by the fact that knee arthritis patients have difficulty in controlling weight distribution on the sound and the pathological limbs because of the impairments caused by degenerative knee joints.

Total movement duration

Total movement duration is longer in knee arthritis patients than in control subjects regardless of which leg is the supporting one. The reason is that the landing and stabilization phase is much longer in patients than in control subjects.

CONCLUSION

1. Our study presents a methodology which allows us to identify and quantify the duration of the different phases of a side-step in patients with severe knee arthritis. Thus, it was possible to measure the duration of the postural phase and the intensity of the ground reaction forces, which cannot be determined in the course of a clinical examination. The duration of the postural phase and the intensity of the horizontal ground reaction forces during the postural phase were increased when the pathological limb was the supporting one. The monopodal phase was shortened on the pathological leg. These results show that patients with knee arthritis develop new postural and motor strategies mainly aimed at shortening the monopodal phase.

2. Our study provides a new approach to disabilities secondary to knee arthritis. Further studies will investigate the duration of side-step phases in our population of knee arthritis patients after undergoing total knee arthroplasty.

REFERENCES

1. Andriacchi, T. P., Andersson, G. B. J., Fermier, R. W., Stern, D. & Galante, J. O.: A study of lower limb mechanics during stair climbing. J Bone Joint Surg *62A:* 749, 1980.
2. Barett, D. S., Cobb, A. G. & Bentley, J.: Joint proprioception in normal, osteoarthritic and replaced knees. J Bone Joint Surg *73B:* 53, 1991.
3. Berman, A. T., Zarro, V. J., Bosacco, S. J. & Israelite, C.: Quantitative gait analysis after unilateral or bilateral total knee replacement. J Bone Joint Surg *69A:* 1340, 1987.
4. Brenière, Y., Do, M. C. & Sanchez, J.: A biomechanical study of the gait initiation process. J Biophys et Med Nucl *5:* 197, 1981.
5. Brenière, Y. & Do, M. C.: Control of gait initiation. J Motor Behavior *23:* 235, 1991.
6. Callaghan, M. J. & Baltzopoulos, V.: Gait analysis in patients with anterior knee pain. Clin Biomech *9:* 79, 1994.
7. Campbell, M. J., McComas, A. J. & Petito, F.: Physiological changes in ageing muscles. J Neurol Neurosurg Psychiatry *36:* 174, 1973.
8. Fisher, N. M., Pendergast, D. R., Gresham, G. E. & Calkins, E.: Muscle rehabilitation: its effects on muscular and functional performance of patients with knee osteoarthritis. Arch Phys Med Rehabil *72:* 367, 1991.
9. Györy, A. N., Chao, E. Y. S. & Stauffer, R. N.: Functional evaluation of normal and pathologic knees during gait. Arch Phys Med Rehabil *57:* 571, 1976.
10. Insall, J. N., Ranawat, C. S., Aglietti, P. & Shine, J.: A comparison of four models of total knee-replacement prostheses. J Bone Joint Surg *58A:* 754, 1976.
11. Jian, Y., Winter, D. A., Ishac, M. G. & Gilchrist, L.: Trajectory of the body COG and COP during initiation and termination of gait. Gait and Posture *1:* 9, 1993.
12. Lankhorst, G. J., Van de Stadt, R. J. & Van der Korst, J. K.: The relationships of functional capacity, pain, and isometric and isokinetic torque in osteoarthrosis of the knee. Scand J Rehab Med *17:* 167, 1985.
13. Mann, R. A., Hagy, J. L., White, V. & Liddell, D.: The initiation of gait. J Bone Joint Surg *61A:* 232, 1979.
14. Massion, J.: Movement, posture and equilibrium: interaction and coordination. Progress in Neurobiology *38:* 35, 1992.
15. Messier, S. P.: Osteoarthritis of the knee and associated factors of age and obesity: effects on gait. Med Sci Sports Exer *26:* 12, 1446, 1994.
16. Mesure, S., Cincera, M., Trives, M., Pedotti, A., Bardot, A., Delarque, A. & Massion, J.: Organisation posturale lors du transfert latéral d'appui chez le patient poliomyélitique. Ann Méd Phys Réadapt. In press.
17. Mouchnino, L., Aurenty, R., Massion, J. & Pedotti, A.: Coordinated control of posture and equilibrium during leg movement. *In* Disorders of Posture and Gait (eds. T. Brandt, W. Paulus, W. Bles, M. Dieterich, S. Krafczyk & A. Straube), pp. 68–71. Georg Thieme, Stuttgart, 1990.
18. Mouchnino, L., Mille, M.-L., Cincera, M., Bardot, A. & Delarque, A.: Weight-shifting strategy in below knee amputees during lateral raising of the leg. *In* Studies in Perception and Action III, (eds. B. G. Bardy, R. J. Bootsma & Y. Guiard), p. 1297, 1995.
19. Rogers, M. W. & Paï, Y. C.: Dynamic transition in stance support accompanying leg flexion movements in man. Exp Brain Res *81:* 398, 1990.
20. Stauffer, R. N., Chao, E. Y. S. & Györy, A. N.: Biomechanical gait analysis of the diseased knee joint. Clin Orthop *126:* 246, 1977.

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