PRINCIPAL COMPONENT ANALYSIS OF THE SQUAT FOR THE EVALUATION OF UNICOMPARTIMENTAL AND TOTAL KNEE ARTHROPLASTY

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ABSTRACT

In this work bodyweight squat is studied for revealing different performances of the knee after unicompartimental and total arthroplasty. This movement is chosen because able to reveal the ability in performing a task that can be recognized in most of daily living activities.

The purpose of the present work is to characterize the bilateral lower-extremity kinematics and kinetics associated with bodyweight squatting exercise after unicompartimental and total arthroplasty.

Principal component analysis is applied to compare involved and non-involved limb and to examine differences between arthoplasties.

Principal component analysis allows to find out different critic phases of pathological squat. Hidden information about symmetry/asymmetry and compensatory mechanism is also revealed.

Keywords: Principal component analysis, Symmetry, Squat.

INTRODUCTION

Unicompartmental Knee Arthroplasty (UKA) for unicondylar arthritis has been recently adopted to obtain, in properly selected patients, a more physiological knee function. In the literature UKA is considered more conservative with respect to the total arthroplasty (TKA) [1]. The efficacy of UKA is questioned because of the high rate of failure in the first implants [1]. Outcome evaluation is frequently clinically performed, based on subjective factors such as patient satisfaction or pain occurrence. Only recently UKA have been evaluated by means of imaging techniques such as fluoroscopy and MRI [2] or Movement Analysis base appraisal usually adopted for TKA [3]. These studies are frequently focused on the knee joint disregarding other joints.

In the present work bodyweight squatting of UKA and TKA is analysed. This kind of exercise is selected as a movement able to reveal the ability to stress joints and to control the balance. Moreover it can more closely approximate functional activities, such as stair climbing, rising from a chair, sit to stand or walking.

Principal component analysis (PCA) [4] [5], as a multivariate classification and curve detection methods, is applied to compare involved and non-involved limb and to examine differences between unicompartimental and total knee arthroplasty.

The purpose of the present work is to characterize bodyweight squatting exercise after UKA and TKA.

MATERIALS AND METHODS

Population with knee arthroplasty is composed by 8 TKA and 8 UKA subjects. The mean age is 67 (± 7.2) and the mean body mass is 75 kg (± 8.2). Patients are evaluated 12 months after surgery. Possible injuries affecting the controlateral leg are considered conditions for test exclusion.
Subjects of the control group are free of pathologies altering their locomotor ability and they match to the test sample for age and weight.

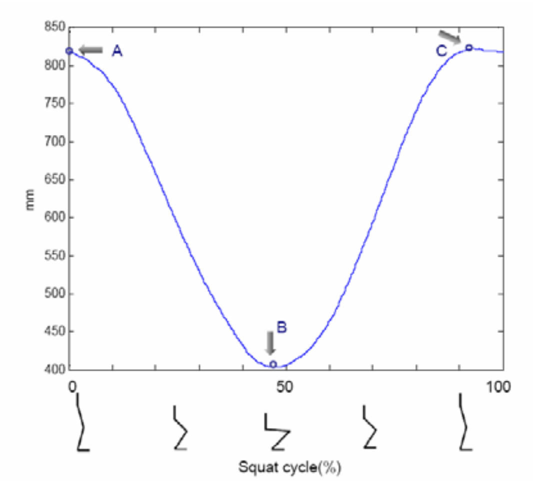

Figure 1. Vertical trajectory of the marker on the hip cluster. A–B: descendent phase; B-C ascending phase

Test modalities are accurately described to the subject before the trials and each one signs a human consent form to give his/her approval to study participation. Procedures needed to guarantee privacy of the data have been accomplished.

Each subject is required to place its feet “in a position of comfort” as recommended by Anderson [6] since the assumption of a comfortable foot placement provides the greatest stability and safety for execution of squat exercise. He/she is asked to stand in upright posture with its knees in extension and with both feet on the platform. Then he/she is instructed to perform squat by bending the knees up to the level he/she feels comfortable [7] [8] and to come back to the start position. Any other indication such as to lift the heel, to bend down up the thighs and shanks touch (deep squat) are voluntary omitted, leaving the subject free to perform the movement. Data are collected after some training trials during which subject becomes familiar with the movement. Three squat cycles are collected.

Data from both legs are acquired. Foot, shank, tight, pelvis and upper body are studied (ELITE, B|T|S, F_{acq}=100Hz) [9]. Main angular joint rotations are computed and maximum flexions are extracted [10], [11]. Trajectories of forces exchanged with the ground (GRF) (platform BERTEC, F_{acq}=500Hz) are recorded.

The time (T) needed to each subject to complete the exercise (descent and rising) is considered and the 10% is calculated. To compare data among subjects, the exercise is processed considering as start, the time instant in which he/she begins to descend and as end, the time T put 10% up. The squat is subdivided in two phases: descendent (0-50%) and ascending (61-90%) phase. Vertical trajectory of a marker positioned on the hip is considered for identify the previous mentioned phases. The first begins at the instant in which subject starts to descend and finishes when the trajectory reaches the minimum. The second phase starts in the time instant in which subject begins to rise and finishes when marker trajectory come back at the start value (Fig. 1)

Movement modality (for example lifting/no lifting of the heels, flexion forward of the trunk) and stability during execution are considered important factors for extracting performance predictors. Center of Pressure trajectory normalised with respect dimension of the foot (CoP), squat width in percentage, normalised with respect to the shoulder width (SQW%) [7] [8], descending and ascending velocity and foot orientation are analysed. This last parameter is defined by the angle (α) between the straight line passing through the heel and the middle of the first and the fifth metatarsal heads.

PCA is used to identify the main structure of kinetic trajectories of examined arthoplasties. This technique is applied, separately, to the kinetic curves of pathological and control subjects.

Four steps are involved in the application of the PCA [4], [5], [12-16]. Initially different matrices are created for each kinetic trajectories (three GRF and two CoP). Three different matrix are created for each group of the sampled population: UKA, TKA and control group. Data matrix is

$$\boldsymbol{X}=[x_{i,j}], \qquad i=1\ldots M, j=1\ldots N \qquad (1)$$

where $x_{i,j}$ is the jth sample of the ith patient, M=8, N=256. After finding the covariance matrix of the data, the first representative curve principal components (PC) are retained as important factors. Varimax rotation is used in the third step to achieve the basic structure in a set of data by rotating the PC axes. The fourth step is to describe the PCs trend with respect to a possible interpretation. To facilitate interpretation of the PCs, it generally suggested that the portion of each extracted PC curve called factor loading with value of 0.7 or higher is described [17]. In this instance, factor loading higher than 0.7 are used for further biomechanical interpretation [18], [19].

Similarity among groups is thought to be present if each three corresponding representative curves (PC) derived from each trajectories, describe the same portion of the squat cycle. Identifying the main characteristics of the continuous kinetic data in pathological and control subjects, it explains the possible existence of task discrepancies in the actions executed.

	TKA	***UKA***	***Control group***
Descending velocity	98.51 *(42.5)*	70.55 *(37.4)*	316.08 *(161.3)*
Ascending velocity	194.6 *(79.7)*	136.84 *(93.5)*	457.54 *(60.25)*

Table.1 Mean velocities and standard deviations during descending and ascending phase of the squat.

PCA is also applied to the kinematic parameters (maximum flexions) to determine symmetry or asymmetry [20], [21]. In fact PCA is applied once to identify the actions of each joint separately and a second time to determine symmetry between the lower limbs by simultaneously analysing all the joints of each limb.

For this last application (symmetry/asymmetry) we applied the same procedure described above. Particular attention is done for creating the matrixes data. For the simultaneous analysis of all the joints of the lower limb (global symmetry), two matrix are formed: one related to treated leg and the other to the controlateral. For each matrix the first rows contain the ankle data, while the remaining rows contain the knee and hip data of the same limb. To identify the action of each joint separately (local symmetry) a matrix for every joint is created. Lower limb local/global symmetry is recognised when the operated limb representative curve is compared to its corresponding principal component at the controlateral limb.

RESULTS AND DISCUSSION

Squat is performed by each subject examined. Any patient has not performed full squat, remaining always with his/her heel on the ground. All subjects examined adopt a narrow stance. The UKA subjects adopted an average stance width in percentage ($SQW\%_n$) larger (86.2%) than the TKA (67.9%) and the control group (59.6%).

This can be considered as a natural mechanism adopted for preserving knee integrity. In fact Escamilla et al. [7] [8] asserts that a narrow stance for squat is characterized by lower tibio-femoral compressive forces than wide stance.

The modality of squat execution has been examined also calculating the velocity adopted by each subject, during the descending and ascending phases. Mean velocities for each group, are shown in the table 1.

The descending velocity is generally lower than the ascending. The velocity during descendent phase is strictly dependent by the efficiency in the muscular control acting to reduce the effect of the body weight lowering. Both the velocities for the patients groups are lower than for the control group and the velocities for the TKA group are higher than for the UKA.

This result can be explained by a careful control planed by means muscle and ligaments to reduce stress at the joint. The presence of the ligaments and the partial integrity of cartilage for the UKA subjects provide more knee stability and efficiency in performing movement.

	TKA	*UKA*	*Control group*
PC1	46	30	58
PC2	17	20	22

Table.2 The variance extracted (%) by the first two PCs for the Antero-posterior component of GRF of the three different groups.

Kinetic analysis gives useful information to examine pathological squat.

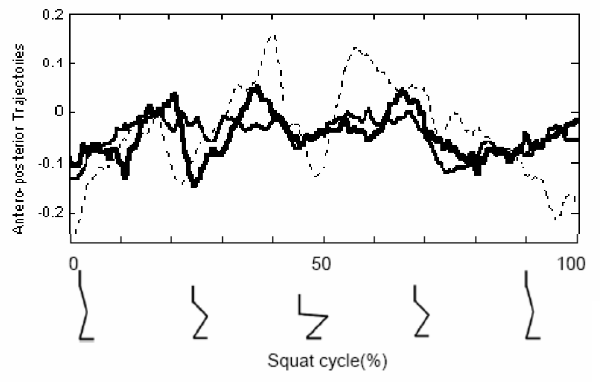

Fig.2 Average antero – posterior raw GRF trajectories related to TKA (thin line), UKA (thick line) and control group (dashed line).

For the UKA subjects, the maximum excursion of CoP in the Antero-Posterior direction, normalised with respect the foot length, is comparable (0.41) with data obtained by the control group (0.43) but larger with respect to the TKA (0.32). This result provides information regarding the degree of the movement control. Reducing the maximum excursion of CoP in the Antero-Posterior direction, increases the risk of instability and requires a greater degree of control. TKA subjects are less willing to shift forward their CoP.

The trajectories of kinetic trajectories (GRFs and Centre of Pressure) do not provide useful indication to reveal a common behaviour among subjects belonging to the same patient group (Fig 2).

Nevertheless results of PCA can be used to detect the main functional structure of these trajectories. Task discrepancies are recognised when comparisons are made among each corresponding representative principal components of each group. In particular GRF in the antero-posterior direction offers information to discriminate UKA and TKA squat.

The eigenvalues related to the variance of the kinetic data extracted by each PC are presented in table 2. The third and highest PCs which accounted for the remaining variations are not taken into consideration since they presents random variations which are difficult to interpret [22]. The first representative curves (PCs) which account on average for over 44% of the information in the original trajectories are presented in figure 3. The first PC accounted for 46% and 30% of the variation in the TKA and UKA groups, while over the 58% in the control group.

The significant factor loading (over 0.7) of TKA principal component is distributed between 70-80% of the squat cycle. For the UKA it is localized between 20-30%. These PCs highlight a different behaviour in performing squat exercise. UKA have different descending phase and TKA in ascending phase with respect to the control population (fig. 3).

Different critical phases are shown by analysing PC related to antero-posterior GRF component. It is essential to apply a multivariate analysis method, such as PCA, to characterise different pathological behaviour. In fact analysis of row trajectories do not allow to detect the structure of the data (fig 2).

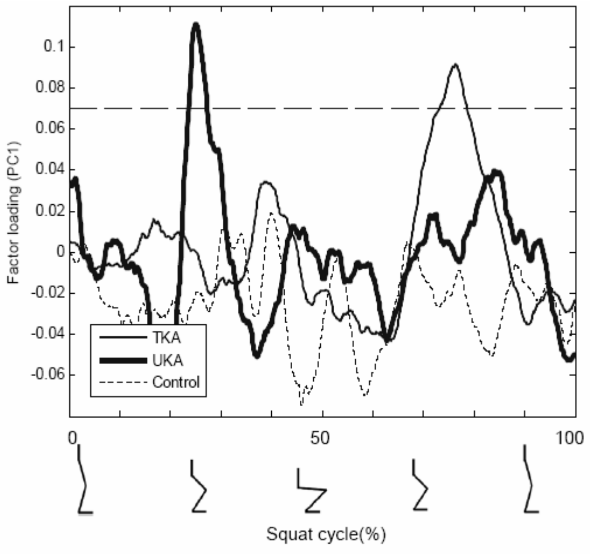

Fig.3 The first Principal Component extracted from GRF antero-posterior trajectories calculated for TKA (thin line), UKA (thick line) and control group (dashed line).

The trajectory of the main joints rotations calculated for ankle, knee, hip and upper body does not provide useful indication to reveal a common behaviour among subjects belonging to the same patient group.

Maximum flexions developed at the right and left ankles, knees and hips during the stance phase are analysed. Only the maximum knee flexion gives useful information. For both groups of patients, values related to operated knee, is smaller (62° TKA, 68° UKA) than for the control group (115°). The range of values obtained for both group, at 12 months after surgery, is on average larger of 60°. Results in literature [7], [8] put into evidence the increase of the shear forces when knee flexion exceeds the above mentioned value. Then the superior maximum knee flexion obtained with UKA can be justified by a more physiological condition of the joint and by a stabilising action of the ligaments during flexion. This action is absent in the case of TKA.

The analysis of all kinematic parameters with PCA allows to characterize global and local squat symmetry.

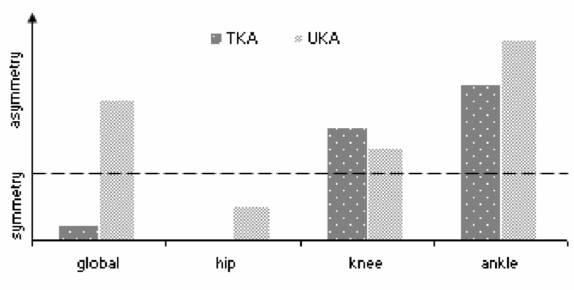

Fig.4 Global and local symmetry analysis. Factors loading differences between treated and controlateral leg are obtained for each joint and for each patients group.

People of the control group is characterized by a local and global symmetry. Instead results reveal a local and global asymmetry in UKA kinematics parameters. In fact different factor loading are obtained analysing each joint both separately and simultaneously. TKA trials have a global symmetrical behaviour, but specific joints (knee and ankle) are characterized by different factors loading, indexes of local asymmetry. It seems that compensatory mechanisms might be the best explanation to describe global squat symmetry while different actions are taken by specific joints.

CONCLUSION

Classic analysis of parameters and trajectories obtained by the movement analysis gives some information to characterize bodyweight squatting exercise after UKA and TKA.

PCA is able to characterise UKA and TKA squat. Using this technique it is possible to reveal both underlying structure of analysed trajectories and their correlations with the different phases of the squat cycle. Two different critic phases are identified for pathological squat. TKA subjects have a different descending phase with respect to the control population. UKA group is characterized by a different ascending phase.

This result can be related to a different physiological condition of the joint after unicompartimental and total arthroplasty. Stabilising action of the ligaments and the partial integrity of the cartilage during knee extension provide more joint stability and efficacy in performing the ascending phase for UKA subjects. Trials related to TKA subjects reveal a reduced ability to extend its knee with respect to the UKA and control group subjects. Different interpretations can be done, but for understanding these results it would be useful to investigate the muscular activity.

Moreover to characterize entire lower limb behaviour and determine if squat is symmetrical or not, it is essential to apply a multivariate analysis method which has the capability of detecting the structure of the data. In fact PCA allows to find out hidden information about symmetry/asymmetry. The synergistic interaction between body segments in a close chain exercise, such as squat, manifests in compensatory mechanism adopted by each subject.

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