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Classification of Gait Kinematics of Anterior Cruciate Ligament Reconstructed Subjects Using Principal Component Analysis and Regressions Modelling*

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Abstract*— The aim of this study was to compare the knee kinematics of anterior cruciate ligament reconstructed (ACL-R) and healthy subjects (CG) during gait and classify the status of normality. Ten healthy and six ACL-R subjects had their gait analyzed at 60 fps. 3D knee angles were calculated and inserted into three separate matrices used to perform the principal component (PC) analysis. The scores of PCs retained in each analysis were used to calculate the standard distances (SD) of each participant in relation to the center of the CG. The PC scores of the three planes were used in a logistic regression to define normality. In the sagittal plane there was no difference between groups. In the frontal and transverse planes ACL-R subjects showed higher SD values than CG. PCs identified that ACL-R subjects showed increased adduction, internal and external rotation. All these subjects had their gait classified as abnormal by logistic regression. Therefore, in the studied ACL-R subjects the gait pattern did not return to normal levels after surgery. This may lead to degenerative injuries, as osteoarthritis, in the future.

I. INTRODUCTION

Gait analysis is widely used to detect changes in the lower limbs biomechanics, aiming at diagnose injuries, establish physical therapy treatments or surgery, monitor progress in the presence or absence of intervention and predict outcomes [1]. In sport settings gait analysis is commonly used to assess the beginning of rehabilitation programs, being a possible indicative of future alterations during higher demands tasks, as running and jump tasks.

Studies on anterior cruciate ligament injured patients have identified altered knee biomechanics in the frontal and transverse planes during gait, which could increase the risk to the development of osteoarthritis (OA) and re-injury of the ligament [2]. On recent years, gait analysis has helped in the development of treatment strategies that, indeed, decreased the overloads related to the risk of knee OA [3]. However, most studies used discrete variables, like peak and means, for comparing the gait pattern between reconstructed anterior cruciate ligament (ACL) and healthy subjects. The selection of this kind of variables is mostly subjective and has lead to contrasting results, as seen in gait studies of ACL injured subjects.

While some studies reported that the gait pattern returns to a normal level in an average of six months after ligament reconstruction, others showed disturbances even one year later [2]. Chau [4] reported that the extraction of discrete parameters ignore the pattern of movement regarding the temporal information of the signal, leading to misinterpretation of the results. Besides, the selection of discrete variables in the most of the gait studies seems to be subjective, with low scientific evidence of its importance.

To overcome such limitations, principal component analysis (PCA) has been used in previous studies [5]. PCA is a multivariate technique that reduces the data dimensionality, analysing the whole signal waveforms series [6]. However, no study comparing the knee kinematics between ACL-R and healthy subjects during gait with such technique was found. Also, the new set of PCA variables can be used as inputs in linear and nonlinear models to classify the status of normality [7]. Thus, the purpose of this study was to compare knee kinematics of ACL-R and healthy subjects during gait, using PCA, and classify the injured subjects in relation to the status of normality, using logistical regression.

II. MATERIALS AND METHODS

A. Subjects

Ten healthy male subjects (CG) and six males that underwent single-bundle ACL reconstruction using hamstring tendons autografts (ACL-R) participated in this study. To be included in the CG, subjects should have no history of ligament injuries, nor lower limbs pain at the time of the tests. When tested, the ACL-R subjects had a mean of 12 ± 2 months (mean $\pm$ standard deviation) from surgery (range from 9 to 15 months). ACL-R subjects had incurred a complete ACL tear as evidenced by magnetic resonance imaging or the pivot-shift test assessed by the surgeon and confirmed at arthroscopy. All ACL-R subjects had a unilateral tear of their ligament, with no previous ligament injury of either knee, and no history of knee surgery. All surgeries were done by the same surgeon and all ACL-R subjects had a high level of compliance to a similar rehabilitation programs. Anthropometric data of the subjects from both groups are presented in Table I. All participants signed an informed consent form allowing participation in the study. This study was approved by the State University of Rio de Janeiro Research Ethics Council.

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TABLE I. ANTHROPOMETRIC DATA OF THE SAMPLE

	CG	ACL-R
Age (years)	27.2 ± 2.9*	31.0 ± 9.8
Height (cm)	178.7 ± 3.6	184 ± 1.6
Body Mass (kg)	81.6 ± 11.0	84.0 ± 6.8

CG: Control group; ACL-R: Anterior Cruciate Ligament Reconstructed group. * mean ± standard deviation

B. Data Collection

Subjects walked along an eight meters long walkway with 17 reflexive markers positioned on the skin, according to the Helen-Hayes marker set, including both greater trochanters (Fig. 1). The markers were captured by a four cameras motion analysis system (MaxPro version 1.4.2.1, INNOVISION Systems, USA), with 60 Hz sample rate. All subjects walked four times along the walkway and the first two steps captured by the motion analysis system were used for analysis.

Figure 1. Marker set used in the data collection.

C. Data Processing

The raw three dimensional (3D) coordinates of each marker were filtered by a low pass 2th order Butterworth filter, applied in the forward and reverse directions, to avoid phase distortions, with a cut-off frequency of 7 Hz. After, the knee kinematics was calculated by a tailor-made routine at MATLAB version 7.8.0 (The Mathworks, USA), according to Vaughan et al. [8]. A standing trial was collected for each subject to mathematically define the anatomical zero degree of the knee. To determine the beginning and final of each cycle, the Foot Velocity Algorithm [9] was used and the data of the three planes of each cycle were interpolated to 51 values, representing 0% to 100%.

For PCA, the 3D knee kinematics of two gait cycles of each subject (20 cycles for the control group and 12 cycles for the ACL-R group) were inserted into three different matrices E [32 x 51], where each row corresponded to subjects and each column corresponded to the interpolated signals. The two cycles were included to represent the variability of the individual gait. This strategy was adopted instead of using the average of some gait cycles, since the use of the latter can alter the temporal structure of the data. PCA was applied to each matrix E, separately [10]. For such approach, initially the mean was subtracted from each matrix E, thus, the covariance matrix S [51 x 51] was calculated and, finally, the eigenvectors and eigenvalues were estimated from S based on a singular value decomposition algorithm, as described below [11]:

$$E = ULX^T \quad (1)$$

where E is the matrix with the original dataset, the columns of U are called the left singular vectors, the rows of X^T are the right singular vectors and the L is a diagonal vectors whose nonzero entries are the singular values. X, L and U contain, respectively, the eigenvectors, the square root of the eigenvalues of E^TE and the principal components (PC) scores of the covariance matrix S.

The number of PC retained in the analysis from each knee kinematic data were those that the cumulative sum accounted approximately 80% of the original data variance. The standard distance (SD) [12] from each kinematic variable was calculated using the selected PC scores. The SD is the square root of the Mahalanobis distance that represents the distance between each ACL-R subject in relation to the centroid of PCs scores of CG, normalized by the respective variance.

D. Statistical Analysis

To compare the SD from both groups a Mann Whitney test was used for each plane of movement. The significance was set at $\alpha = 0.05$.

For classifying the status of normality of the gait pattern, a logistical regression (LR) was performed, using the scores of the retained PCs, as linear modeling technique estimating the probability of a binary outcome (abnormal or normal gait) [13]. The classification threshold was set to 0.5. The stepwise approach was used to find the best LR model among all PC scores possibilities by the Akaike information criterion (AIC). The best model performance was assessed by leave-one-out cross-validation technique. The most important PC scores for classifying all subjects were identified by the regression analysis and the correspondent eigenvectors were analysed in temporal correspondence to the original signals of both groups to identify the location where the variance between them could be explained [6]. The locations where eigenvectors deviate from zero indicate increased differences between groups.

III. RESULTS

Three PCs were retained in each analysis, explaining 78.6%, 91.8% and 82.4% of the total variance in the sagittal, frontal and transverse planes, respectively. The SD of ACL-R in the sagittal plane was not significantly different from CG (ACL-R = 1.72 ± 0.41; CG = 1.53 ± 0.80; $p = 0.1554$). However, significant differences were found in the frontal (ACL-R = 2.04 ± 0.41; CG = 1.60 ± 0.40; $p = 0.0054$) and transverse planes (ACL-R = 2.25 ± 0.67; CG = 1.26 ± 0.61; $p = 0.0004$).

The stepwise selection of LR identified the best model when including the first and third PC scores from frontal plane ($p > 0.005$ and AIC = 6). The performance of this model was 93.75% accuracy, 100% sensitivity and 90% specificity. The LR classified all ACL-R subjects as true positive, meaning that all presented abnormal gait. The correspondent eigenvectors (Fig. 2) indicated that the differences in the frontal plane were explained by increased adduction of the ACL-R group from the pre-swing to the mid swing phase (50% to 90%).

Although not identified by the regression model, the regions of increased absolute amplitude of eigenvectors of the transverse plane (arrows in Fig. 2) indicated a small increase in the internal rotation in the loading response (first 10% of the cycle), increased external rotation in the end of terminal stance, pre-swing (from 40% to 60%) and a new increase of internal rotation in the end of swing (80% to 90%) of ACL-R in relation to CG.

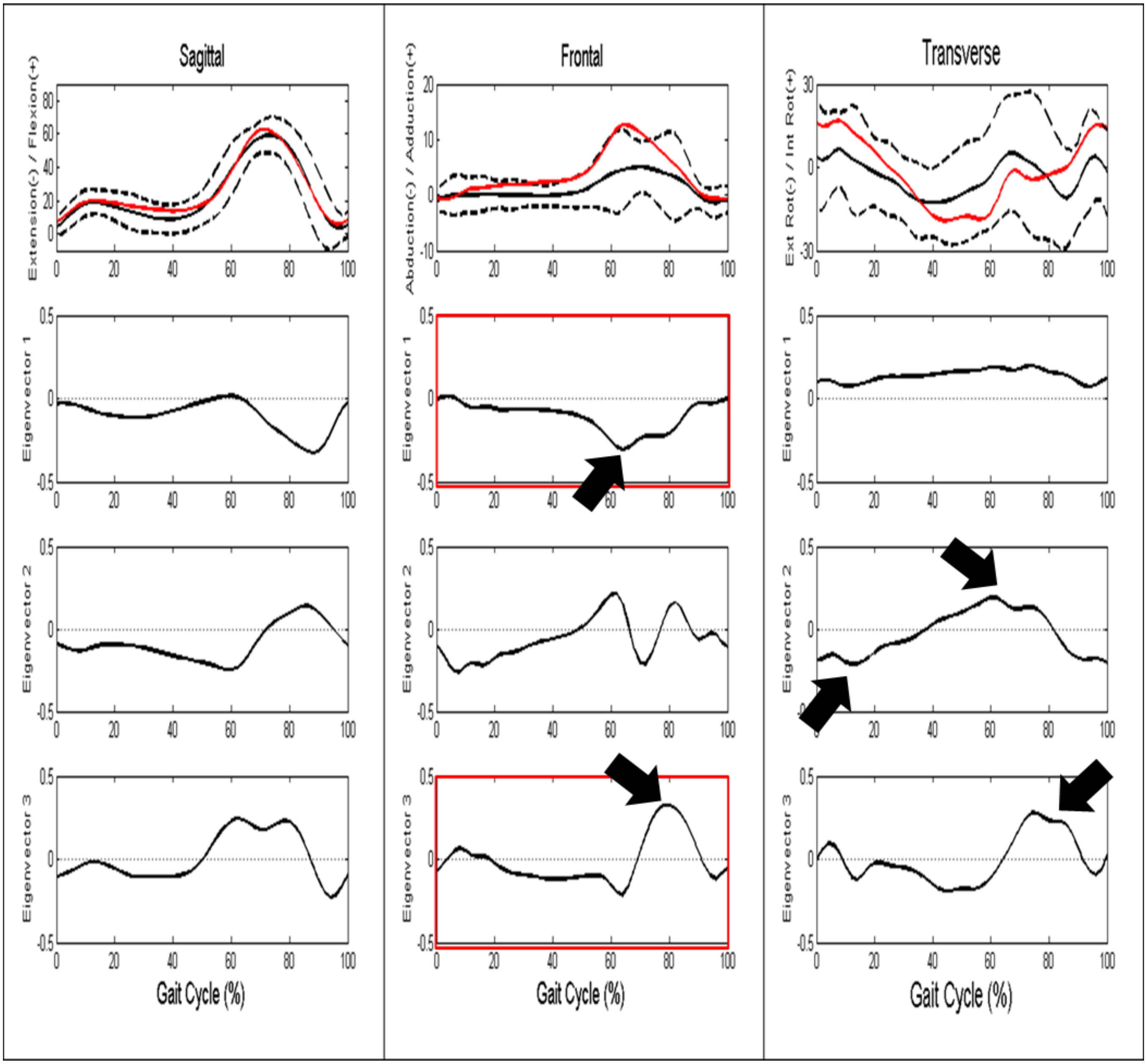

Figure 2. Knee kinematics and the eigenvectors of each plane of movement. Superior graphs: Black solid lines: control group (CG); Black dashed lines: 95%CI of CG; red lines: anterior cruciate ligament reconstructed subjects. Red boxes are related to the PCs selected by logistic regression. Black arrows indicate regions of increased absolut magnitud of eigenvectors, related to increased data variance.

IV. Discussion

Gait analysis is an exam of great value to be performed during rehabilitation programs. The results can help establishing treatment strategies, by identifying the main disturbances in the lower limbs biomechanics [1]. Possibly, if gait pattern is altered, activities with higher demands may also be jeopardized, minimizing the performance and increasing the risk of new injuries [1]. In this study, it was observed that knee kinematics still remains changed during gait even 9 to 15 months after surgery. Indeed, the frontal plane movement alterations identified by the regression analysis may be related to the higher risk of injuries commonly described [14], such as knee osteoarthritis. The abnormal knee kinematic pattern during gait classified by the LR, can explain the high incidence of early degeneration of knee joint after ACL injuries.

On the sagittal plane there were no significant differences. This agrees with most of the literature, suggesting that sometime after surgery, knee flexion/ extension pattern is restored [2]. This is an important finding since there is evidence that disturbances in the sagittal plane can be related to decreased quadriceps force, decreasing the rate of return to high level sports [15]. In the frontal and transverse planes, differences were found between groups. ACL-R subjects showed increased knee adduction, internal rotation in the beginning and end of the cycle and external rotation in the middle of the cycle. Such movement increase can be related to cartilage degeneration [16]. However, only the frontal plane kinematics had high importance for classifying the status of normality. The differences were found mainly in the end of the stance phase and beginning of the swing phase. Some studies also described these differences after injury. Although it may seem restored one year after reconstruction, it still remains altered during high demands activities, as jumps [2]. It is important to report that most studies used discrete values for comparing data. These parameters may have covered some differences still present in gait kinematics. The use of PCA also evidenced those differences. Therefore, extra caution is recommended when using discrete variables to compare patterns of movement, as reported by Leporace et al. [6].

The low number of PCs in all analysis suggests that there is a simple underlying structure in the kinematics waveforms during gait. Therefore, PCA can uncover more complex relationships between the groups [4]. Although widely employed, the gait analysis by discrete parameters does not consider the high degree of correlation that exists among various aspects of gait or the information that may lie in the pattern of the waveform [17]. Indeed, in some situations, several statistical differences may be found and with the use of classical parameters it is not possible to identify the importance of each. Using PCA and logistic regression, as in this study, allowed the identification of the differences and pointed out the most important ones. It is proposed for future studies the development of models that would allow the prediction of the variables related to the return of gait to a normal level.

V. Conclusion

This study showed that some changes in gait pattern may still be present more than one year after ACL reconstruction surgery. Some of these differences were not identified by others authors maybe because most of them used discrete parameters to compare the kinematic data, hiding important information contained in the original signal. The disturbances found in this study are related to the risk of developing early osteoarthritis in the future. It is important that in the beginning of the rehabilitation, physical therapists treat ACL-R subjects to avoid that these alterations remain in later stages, near to the return to high level sports.

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