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Comparison of Gait Pattern in Athletes with ACL Deficiency and Healthy Individual using an Accelerometer

Heydar Sadeghi[1]*, Hesam Fazlali[2], Saba Sadeghi[3], Seyedmojtaba Ojaghi[4]

[1]*Department of Biomechanics and Sport Injuries, Faculty of Physical Education and Sport Sciences, Kharazmi University, Tehran, Iran*
[2]*Kinesiology Research Center, Kharazmi University, Kusha St., Haghani Highway, Tehran, Iran*
[3]*Faculty of Arts & Sciences, University of Toronto, Toronto, Canada*
[4]*Department of Rehabilitation, Sports Medicine Federation, Tehran, Iran*

Corresponding Author: Heydar Sadeghi, E-mail: Sadeghih@yahoo.com

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ABSTRACT

Background: In athletes with anterior cruciate ligament (ACL) deficiencies could assess functional capabilities with different instruments such as use of a camera in vivo situation. However, these methods have suffered from a large number of limitations such as inability to be repeatable and complexity in technique. **Objective:** The main purpose of this study was to compare gait pattern of the athletes with ACL injury and able-bodied subjects using an accelerometer. **Method:** A three-dimensional accelerometer was placed over the tibia tuberosity of 20 healthy and 20 individuals with ACL-deficiencies (ACLD). After walking on the treadmill, the principal components of the acceleration data were calculated using MATLAB software. **Results:** In this study, Principle Component analysis was used for statistical analysis. The results indicated that subjects with ACL deficiency have different gait pattern compared to the control group. The major differences between stride trajectories of the two groups were at the end of mid-swing and the beginning of terminal swing phases in vertical axis. ACL deficient subjects exhibited different gait patterns during mid and terminal stance phases in anterior- posterior axis compared with normal controls. **Conclusions:** The difference in gait between subjects with ACL deficiency and healthy subjects are depends on variation in the amount of knee flexion and tibia rotation that could be altered to motor recruitment.

Key words: Anterior Cruciate Ligament, Tibia Acceleration, Accelerometry, Gait Analysis, Athletic Injuries

INTRODUCTION

The anterior cruciate ligament (ACL) is one of the most common injured structures of the knee joint. Disruptions in the ACL can lead to alterations in the ability to walk (Georgoulis et al., 2003). Many studies have been done regarding the knee biomechanics after ACL injury (Knoll et al., 2004, Kothari et al., 2012, D. Georgoulis et al., 2003). The human stride has been considered as unibehavior of the lower extremity that is unique for each individual (Fish & Nielsen, 1993).Therefore, recognizing stride alterations could be utilized to assess any deficiencies in the lower extremity upon injury (Ebersbach et al., 1999). Although different methods such as questionnaire, camera and, force-platform have been created for quantitative assessment of stride, there is also several limitations that exist. Questionnaires have low precisions (Clarke et al., 2009), optical systems and, force plates to quantitively assess gait are merely useful in clinical and research settings (Begg and Palaniswami, 2006).

Utilization of camera systems for stride assessment is associated with a high level of complexity and cost in a clinical environment. In the last few decades, there has been an increase in the use of alternative systems such as an accelerometer to assess biomechanics of the knee and its deficiencies (Brayne et al., 2018; Clermont and Barden, 2016; Godfrey et al., 2008; Rodriguez-Silva et al., 2008; Schutte et al., 2018). Numerous studies have demonstrated the sensitivity of the accelerometer in recognition of fast motions (e.g. pathological vibrations). These studies have demonstrated the accelerometer has enough accuracy and validity in quantitative biomechanical analysis of dysfunctions and instabilities of the knee joint among subjects with osteoarthritis and ACL deficiencies (Sakurai et al., 2010, Kavangah et al., 2006, Maeyama et al., 2011).

Studies that have been conducted in-vivo situations have had some limitations. Bryant et al. (2009) used the electromyography (EMG) in-vivo, this technique is limited because the data through the EMG is collected within a limited area. Using an accelerometer, Lopomo et al. (2001) also conducted a study under in-vitro situation, and used the acceleration parameters to compare injured with control subjects during pivot-shift test. Tibial rotation during walking has been measured with a high

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speed camera in subjects with ACL-deficiencies (Georgoulis et al., 2003; Stergiou et al., 2007). However, this device is not only costly but also has place limitation. These studies have compared ACL-deficient subjects with healthy subjects in terms of tibia rotation, amount of knee flexion/extension, EMG activities of quadriceps, and, hamstring muscles, and, numerical characteristics of the gait (e.g. step length and, peak values of the stride). It has been assumed that the gait pattern during walking is comprised of all the mentioned differences, and, by obtaining the total gait pattern for both groups a more comprehensive interpretation can be provided. The most significant advantages of using an accelerometer could be related to repeatability, simplicity and, cost-effectiveness.

It was assumed that using the accelerometer to capture the stride of the gait in subjects with ACL injury and, comparing that with the gait pattern in the healthy subjects, could help obtaining more information about the knee joint kinematics in clinical setting. The main purpose of this study was to compare gait pattern of the athletes with ACL injury and able-bodied subjects using an accelerometer.

METHODS

Participants and Design

In this observational study, 20 healthy individuals (26.2±3.0 years, weight 75.9±5.5 kg, and height 175±6 cm) and twenty subjects with a ruptured anterior cruciate ligament who did not undergo surgical reconstruction (25.6±5 years, weight 72.4±6.2kg, and height 179±8cm) participated in this study and no significant difference was shown between groups for demographic data. A sports medicine physician examined all the participants. The injured group did not have meniscus or other ligament injuries in the knee; but, they were either diagnosed with second or third-degree anterior cruciate ligament tears. Subjects with a minimal knee inflammation with flexion approaching normal range at least one month after the injury were accepted in the study. A healthy individual had to have a negative result with the pivot shift and Lachman test, no history of knee or lower extremities injury within a month prior to the testing procedures (Lopomo et al., 2001). All participants had to have no history of any ankle or thigh injuries that could modify their gait performance. Participants completed and signed the informed consent form which was approved by the ethical committee of the medical federation. The tibial tuberosity was selected as the anatomical landmark for the placement of the accelerometer because there are less translations and rotations than other sites on the tibia. The accelerometer was attached by a strap (Stefanczyk et al. 2013) which was adjusted on the leg to avoid soft-tissue artifacts as much as possible and positioned in such a way that the X-axis aligned with the longitudinal axis of the tibia (Figure 1).

Procedure

The participants wore their own sport shoes and were asked to walk on a treadmill for three minutes to get acquainted with the walking procedure. Upon familiarizing with the treadmill, tibial data accelerations were collected for 90 s at a speed set at 1.1 m/s. This value represents the average walking speed of the familiarization trials. Only the middle 30 seconds of treadmill walking starting at heel-strike time was used as the sample signal to ensure a constant walking performance over several steps (Vanhelst et al., 2010).

The instantaneous accelerations were collected at a sampling frequency of 100 Hz with 13 bit resolution in ±16g interval using Matlab software. The X axis was oriented along the longitudinal axis of the tibia, the Z axis was in the anterior-posterior direction. The principal components, which were acquired from the accelerometer signals, and data processing was then performed through this software. The power spectrum method revealed that over 95% of the energy of the signals were placed in the spectrum frequency lower than 10 Hz. Therefore, the grade 4 of the butter-worth low pass filter was performed to remove the shot and Johnson noises.

In order to put all GCs of same class participants under each other and make a group, each GC should be compressed/expanded (time normalizing) in the time axis such that all GCs have the same length. To reach the minimum changings in the length of each participant GC, the average of all GC lengths used as reference for time normalizing method introduced by Rong et al. (2007) and interpolation. However, even after GCs are aligned, temporal differences between events (e.g., peaks and valleys) within the GC still exist (Figure 2).

Dynamic time warping (DTW) was used to temporally align all GCs point to point. In this context, the mean of all GCs was selected as the reference. (Figure 3).

Ultimately, as the stride pattern of the subjects with ACL deficiency (Figure 4) and, normal controls were arranged, the data were analyzed by principal component analysis method after the calculation of the mean, standard deviation (SD) and, coefficient of variance (CV).

Statistical Analysis

Using principal component analysis the factor loadings of data were extracted as features of two groups using MATLAB

Figure 1. The tibial tuberosity was selected as the anatomical landmark for the accelerometer. It was positioned in such a way that the vertical axis (X) was oriented along the longitudinal axis of the tibia

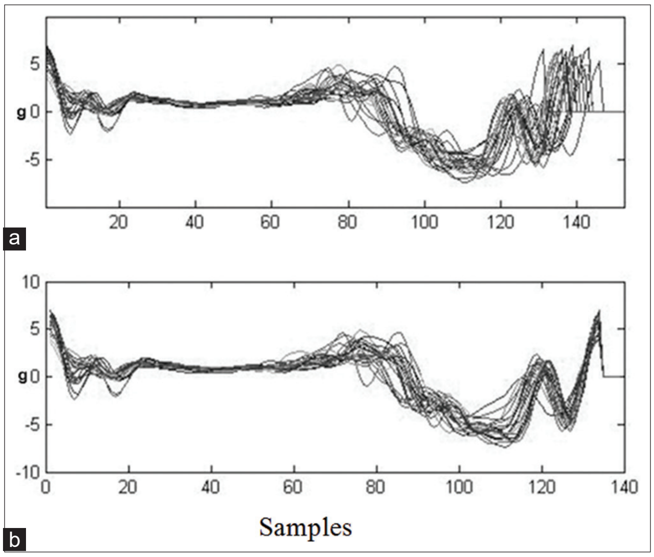

Figure 2. One subject's strides at vertical axis a. before and, b. after time normalization introduced by Liu Rong et al. g in vertical axis is for earth gravity

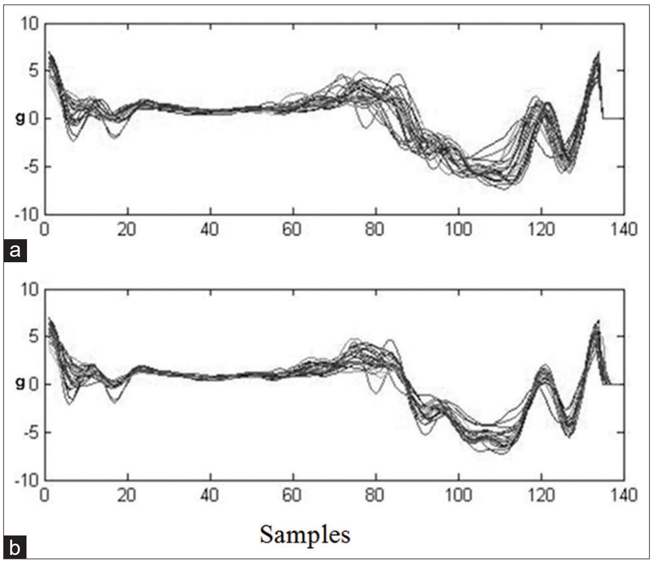

Figure 3. One subject's strides at vertical axis after a. time normalization introduced by Liu Rong et al. and, b. DTW algorithm. Each line illustrates one of the subject's stride

software. We followed the methods described in detail elsewhere (Reid et al. 2010, Muniz et al. 2009, Hair et al. 1998, Ho, 2006) to apply PCA to the averaged gait waveforms of the control data to develop principal component (PC) models for each gait measure (Sanford et al. 2012). To do so, first of all eigen values and eigen vectors extracted from covariance matrix. The principal components obtained correspond to larger eigen values, because they indicate more variance of the data. The factor loadings calculated as correlation coefficients between the variables and the principal components (PCs). Variables with large loading factors are representative of the component, while small loading factors suggest that they are not (Hair et al. 1998). According to previous study the factor loadings greater than 0.4 are considered to meet the bare minimal level of practical significance (Ho, 2006).

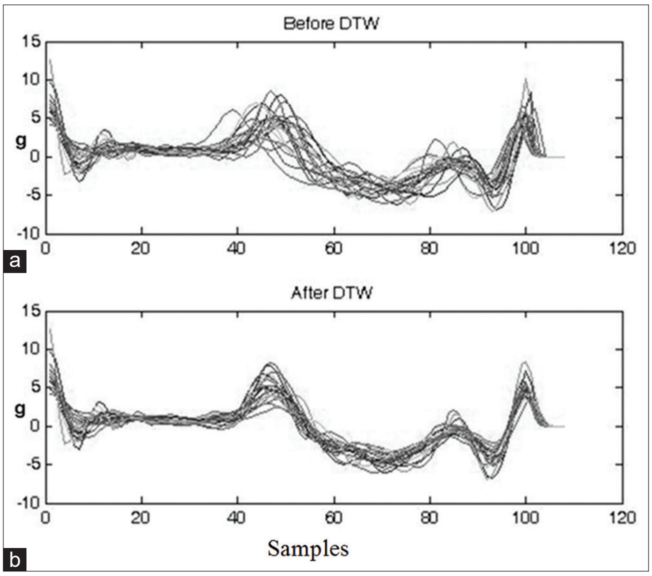

Figure 4. The stride trajectories of the subjects with ACL-deficiency a. before and, b. after DTW algorithm. Each line illustrates each subject's stride pattern

Table 1. The characteristics of participants

Groups	Age (years)	Weight (kg)	Height (cm)
Able-bodied	26.2±3.0	75.9±5.5	175±6
ACLR	25.6±5	72.4±6.2	179±8

In this study we fixed the factor loading threshold at 0.6 (Figures 5, 6). The variables with high factor loadings on the first PCs are those that account for the majority of the variability between in the dataset. Therefore, the differences between the indexes of factor loadings (where one PC passes 0.6) were compared. The coefficient of variations (CV) is defined as the ratio of the standard deviation of the filtered signal by each method over its mean.

RESULTS

Table 1 illustrates the characteristics of participants in both groups of individuals. According to the Table 1, there is no significant difference in age, weight, and height between two groups.

Figure 7 portrays the CV of the healthy and ACL-deficiencies individuals in vertical and anterior-posterior axes. It shows that the data have appropriate CV to be applied in principal component analysis.

Figure 5 and 6 illustrate that the major differences between the stride trajectories of two groups were found at the end of mid-swing and initial of terminal swing phases. During these phases first the tibia bone decelerated and then through the change of direction accelerated. Also there were the subtle differences in the initial swing phase. Differences have occurred as the limb has been off from the ground and, knee joint has been in flexion position and, has accelerated in upward direction.

In normal controls at second PC, dissimilarity was found during onset of the terminal swing phase, exclusively. Dis-

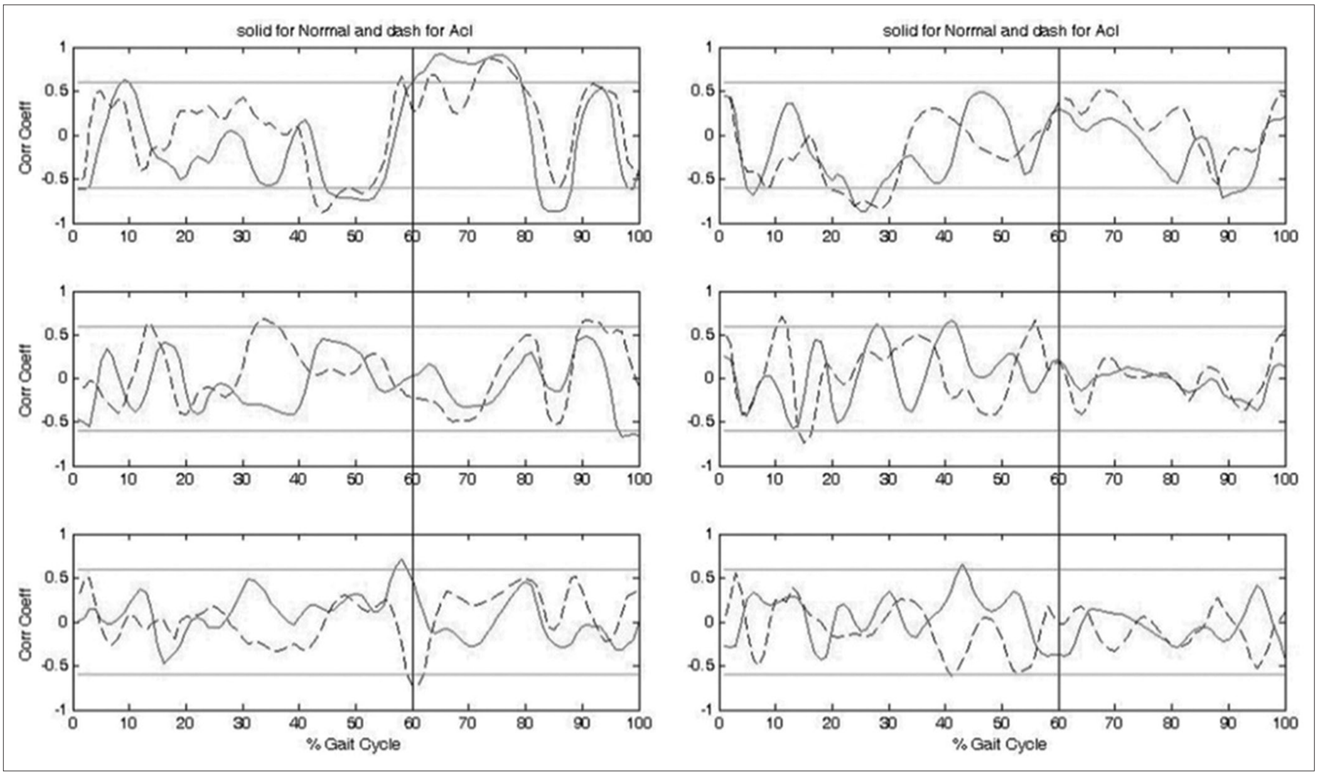

Figure 5. The loading factor trajectories of two groups at x axis; left-up as PC1 to right-down as PC6

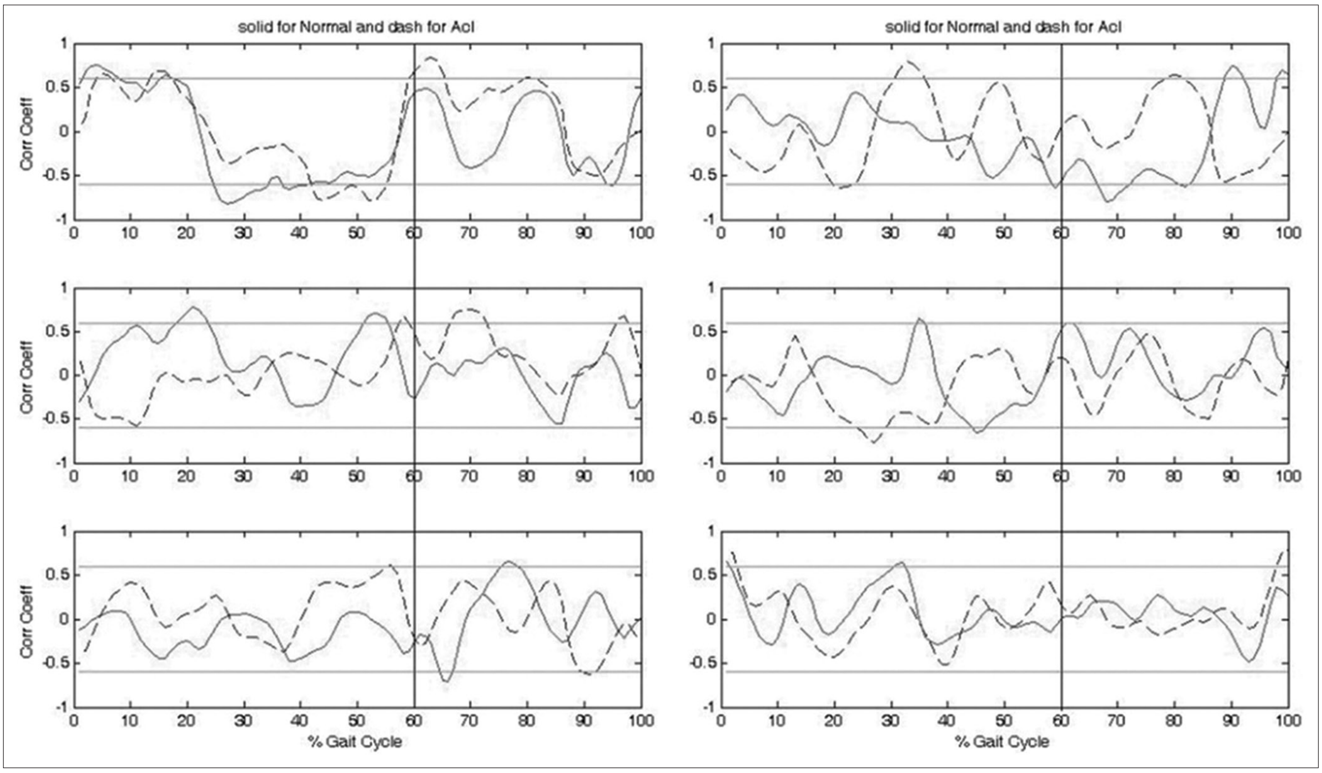

Figure 6. The loading factor trajectories of two groups at z axis; left-up as PC1 to right-down as PC6

similarity reflects that this stage was significant in normal controls. In ACL deficient subjects the third PC was significant however any stages of stride of the gait in normal controls didn't exhibit significant in third PC and/or higher PCs. The results of the current study are in consistent with findings of other studies that have been directed to investigate the pattern of muscle activities (Knoll et al., 2004;.Bryant et al., 2009).

At anterior-posterior axis, significant differences were indicated during stance phase. The normal controls exhibit-

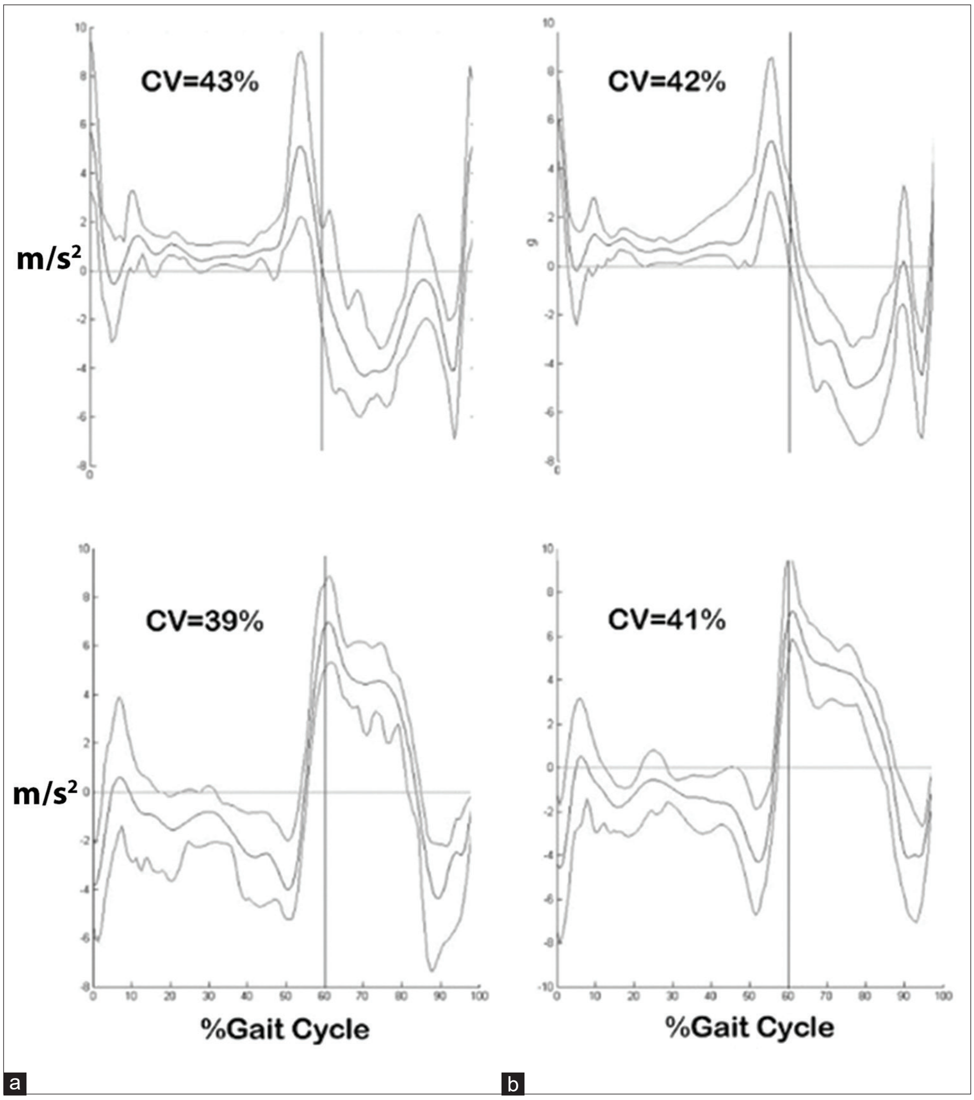

Figure 7. The mean (black line) and, SD (gray line) and, CV of the stride trajectories at x and, z axes in a. ACL-deficient subjects and, b. normal control and, during walking on treadmill

ed the most significant during deceleration phase of the heel contact and, mid-stance at anterior-posterior axis. However, in subjects with ACL deficiency most significant at anterior-posterior axis was exhibited only at mid and, terminal stance phases. In this group the most significant was at pre-swing and, initial swing phase as the tibia bone has been accelerated. However, the normal controls have exhibited second-grade significant during swing phase. In normal controls at initial phase of terminal stance there existed significant. Additionally, normal controls have indicated third-grade significant during mid-stance phase, whereas ACL deficient subjects have exhibited fourth-grade significance in this phase.

DISCUSSION

Using accelerometer, the main objective of the study was to compare the gait pattern of 20 athletes with ACL deficiency and 20 able-bodied individuals. The major differences between the stride trajectories of two groups were found at the end of mid-swing and, initial of terminal swing phases in vertical axis and at stance phase in anterior-posterior axis. As the previous studies have demonstrated that each disorder such as excessive tibia rotation, raising the peak of acceleration at medial-lateral axis during stance phase and/or higher electromyography activities of the muscles could have affected on the stride of the gait (Georgoulis et al., 2003; Kothari et al., 2012; Sakurai et al., 2010; Tashman et al., 2006), therefore the current study hypothesized that the accelerometer through capturing stride of the gait, could help obtain more information about the knee joint biomechanics in subjects with ACL deficiency.

In the current study as two accelerated phases, and, two decelerated phases of the stride in normal controls have exhibited significant therefore stride pattern of the gait at vertical axis were labeled accelerated-decelerated. However, in subjects with ACL deficiency deceleration at the end of mid-stance phase, and, deceleration at swing phase of the gait have exhibited significant therefore stride pattern of gait were labeled decelerated. Also the stride pattern of the gait in anterior-posterior axis was labeled decelerated-accelerated and accelerated, in normal controls and, subjects with ACL deficiency respectively.

A previous study has revealed that ACL deficient subjects compared to normal controls exhibit different tibia rotation during pre-swing phase of the gait (Georgoulis et al., 2003). The current study revealed different acceleration pattern during pre-swing phase between two groups. The findings of the current study were in sync with the previous study which has revealed that ACL deficient subjects exhibit excessive tibia internal rotation (Georgoulis et al., 2003). It was assumed that different acceleration pattern of the tibia bone at anterior-posterior axis in ACL deficient subjects could be due to excessive tibia internal rotation.

Knoll et al (2004) has disclosed that the patients with ACL deficiency less than one month ago (acute) exhibit different amount of the knee flexion compare with healthy subjects during initial swing phase of the gait. However this study did not find any differences in the amount of the knee flexion between healthy controls, and, subjects with ACL deficiency more than one year ago (chronic). In this study, the time of injury for ACL-deficient subjects is varied between acute and chronic. For the majority of ACL-deficient individuals, mismatching and various knee flexion ranges can be considered. This decreased knee flexion has caused the difference in forward-backward and, vertical acceleration pattern at corresponding moment.

Furthermore, several studies have verified that the quadriceps and, hamstring muscles have a role on the knee function and, they regulate excessive displacement and, rotation of the tibia. These studies have reported that the quadriceps and, hamstring muscles are more activated at initiation and at the end of swing phase, respectively (Georgoulis et al., 2003; Knoll et al., 2004; Bryant et al., 2009; Tashman et al., 2006). One of these studies has showed the onset of hamstring muscle activity in subjects with ACL deficiency before heel contact has occurred earlier than quadriceps muscle to prevent tibia displacement (Georgoulis et al., 2003). The current study indicated that there are obvious differences during initial swing phase relative to significance of the acceleration at vertical and anterior-posterior axes. Also, while the normal controls exhibited the most significant during heel contact and, mid-stance at anterior-posterior axis but the subjects with ACL deficiency exhibited most significant at mid and terminal stance phases. Therefore, it was assumed that existing differences between the two groups during swing and stance phases of stride of the gait could be due to altered motor recruitment of the knee muscles in ACL deficient subjects.

The current study has indicated that through capturing the acceleration of the tibia could assess the differences of stride of the gait between subjects with ACL deficiency and, healthy subjects. This issue could be utilized during rehabilitation of the injured athletes. It sounds that existent differences such as dissimilarities of the tibia rotation and, altered motor control of the knee muscles affect the acceleration pattern of the tibia bone during stride of the gait in ACL deficient subjects compare with normal controls. Additionally, during the current study tubercle of the tibia bone was used at first time as the landmark to compare stride of the subjects with ACL deficiency. Therefore to extract the stride of the gait from raw data should be applied the novel methods which those need more research.

ACLR is one of the problems causing differentiation in gait patterns with its symptoms among several injuries and disease. Therefor assessing the different walking patterns would be useful in those studies. Treadmill walking allowed for a regular and stable gait cycles when steps variations could be expected in ground walking causes different effects on cutoff frequencies. It sounds to acquire the more precise results, it is better to extract the specificity of data through the wavelet transformation and/or other non-linear methods. It could be assumed that by using two accelerometers on the knee and ankle joints simultaneously and/or utilization of the accelerometer with a gyroscope, more information around the altered biomechanics in subjects with ACL deficiency could be obtained. Probably, through the bilateral comparison of stride of the gait with an accelerometer could identify the impact of ACL deficiency on the contra-lateral side. Furthermore, utilization of the accelerometer as a cost effective tool assessing the other musculoskeletal deficits in-vivo situations could be the way of the future studies.

CONCLUSION

The current study indicated that the subjects with ACL deficiency have different gait pattern compared to normal controls. The current differences could be related to variations in the amount of knee flexion and, tibia rotation due to altered motor recruitment among the subjects with ACL deficiency and, normal controls.

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