FUNCTIONAL DATA ANALYSIS OF THE KINEMATICS OF GAIT IN SUBJECTS WITH A HISTORY OF ACHILLES TENDON INJURY

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Clinical biomechanics research aims to understand the mechanisms of injury to improve prediction, prevention and rehabilitation. Dynamical systems theory suggests that coordination and variability may be key issues in the development of injuries. Traditional analysis has relied on a multivariate approach using discrete measures during stance. This essentially discards kinematic data obtained throughout the entire stance phase. Functional data analysis is an established statistical technique that is now emerging in biomechanics. It views the data as a function, thus using the entire time series data and determines which factors contribute to the variation. The purpose of this study was to examine the predictions of dynamical systems theory on angular kinematic data in subjects with Achilles tendon injury using a functional data analysis approach.

KEY WORDS: dynamical systems, variability, orthoses

INTRODUCTION: An understanding of the risk factors and mechanisms of lower limb injury is important to improve diagnosis and treatment. Current research has identified some risk factors but it has not uncovered the mechanisms behind many injuries. Dynamical systems theory (DST) is based on the premise that the development of movement patterns is influenced by physical and biological systems of the body along with task and environmental demands (Glazier et al., 1999). The neuromuscular system is characterised by many degrees of freedom, which coordinate to provide numerous solutions to achieve a goal-directed action (Hamill et al., 1999). Variability has received particular attention in the literature. Increased variability has been traditionally associated with decreased stability in performance of a movement task. The perceived role of variability is changing as dynamical systems theorists view it as adaptations to local and global perturbations and changes in task constraints (Glazier *et al.*, 2003). Hamill et al. (1999) measured variability using continuous relative phase plots and suggested that reduced variability indicated repetitive movement patterns, which may lead to overuse injury. They suggested that this may be a distinguishing feature between injured and uninjured individuals. Reduced variability has been observed in rotations of the pelvis and thorax in those with Parkinson's disease (Van Emmerik *et al.*, 1999) and low back pain (Selles *et al.*, 2001) but this prediction has not been confirmed in all injury populations. There has been debate about the most appropriate methods to use in quantifying coordination and variability during movement patterns.
Many gait analysis studies use a multivariate approach in examining the kinematics using discrete measures such as angles at HS, peak angles and ROM. This approach provides a limited interpretation of the kinematics as the entire sequence of foot and lower leg movements during ground contact is discarded wasting potentially useful information. Functional data analysis (FDA) uses the entire time series and views the data as a function rather than a series of discrete parameters. It extracts functional principal components, which describe the variation in a family of curves. It has been used previously in the analysis of kinematic vertical jump data (Ryan et al., 2006). The aim of this study was to use a FDA approach to examine time series and coordination data of lower limb kinematics in subjects with a history of chronic Achilles tendon injury and uninjured controls. Specifically, the role of variability during stance was examined to evaluate the predictions of DST in this injury group.

METHOD: Ethical approval was obtained from the University of Salford Ethics Committee. Thirteen subjects (12 male, 1 female; mean age: 40 years; mass: 73 kg; height: 1.75 m) who displayed excessive pronation and with a history of chronic Achilles tendon (AT) injury and fifteen controls (13 male, 2 female; mean age: 41.9 years; mass: 79 kg; height: 1.77 m) consented to participate in the study. All subjects had good fitness levels and no injuries at the time of testing. Retroreflective markers were placed on the posterior and lateral aspects of both lower extremities as follows: two bisecting the posterior heel, two bisecting the posterior shank, one on the 5^{th} metatarsal, lateral malleolus, fibular head and greater trochanter. These markers were used to define the angles described in Table 1. Eight Qualisys ProReflex MCU240 cameras, operating at 200 Hz, obtained three-dimensional coordinates of the markers during treadmill running at self-selected, comfortable speeds. AT subjects ran in two conditions: with customised orthoses (O) and with no orthoses (NO). Control subjects did not wear orthoses. This provided three groups of data: AT(O), AT(NO) and controls. Coordinate data were exported to Peak Motus™ (Peak Performance Technologies, Englewood, CO, USA) for kinematic analysis. Angle-time series data for five footfalls for each subject and condition were calculated relative to subtalar neutral position. Ten frames were added to the beginning and end of the data series to prevent end point distortion. This padding was removed at a later stage during the analysis.

Table 1 Angles defined to describe frontal and sagittal plane motion

Angle	Definition
Medial lower leg (MLL)	Angle between the lower leg and ground on medial side from posterior
Rearfoot (Rft)	Angle between the rearfoot and ground on medial side from posterior
Achilles Tendon (AT)	In/eversion position of rearfoot relative to the lower leg
Ankle DF angle (ADF)	Anatomical joint angle between fibular head, ankle and 5^{th} metatarsal
Knee flexion (KF)	Anatomical joint angle between greater trochanter, fibular head and ankle

Functional data analysis involved several steps as outlined in Ryan et al. (2006).
(i) The raw data for each stance phase were smoothed to remove any observational noise. The data were then represented as functions in the form, $g(x)$

$$g(x) = \sum_{j=1}^{J} c_j \beta_j (x) \quad \text{where } c_j \text{ are suitably chosen coefficients and } j = 1....J$$

(ii) Smooth functions were achieved using B-splines and a least squares (goodness of fit) approach and by adding a roughness penalty to the fitting procedure. The roughness penalty was controlled by an arbitrary smoothing parameter λ, to ensure that both the least squares fit and the roughness were involved in finding the most appropriate fit for the curves. A smoothing coefficient of $1x10^{-8}$ was used to fit the curves for AT and ADF angles.
(iii) Functional Principal Component (FPC) analysis was used to transform the original data into a smaller set of linear combinations that accounted for most of the original variance. The values of these linear combinations are called FPC scores. These FPCs were defined in the same domain as the original functional observations of the study. A multiple of each FPC was added and subtracted to the overall mean to display how these components influenced the mean curve. Similar methods were used to obtain bivariate FPCs to describe coordination between ADF and AT angles.
(iv) The total number of FPCs that can be extracted equals the number of points used to describe the data however, a relatively small number of FPCs usually describe the essential features of gait (Daffertshofer *et al.*, 2004). The number of FPCs that accounted for approximately 95% of the variation are usually analysed as any FPCs beyond this are typically of very small influence. The FPC scores corresponding to each extracted FPC were determined. Boxplots of the FPC scores were examined to reveal if there were any differences between AT and control groups and between O and NO conditions.
(v) Discriminant analysis with FPC score as the independent variable and group as the dependent variable was used to assess the ability of the FPC to distinguish between groups.

RESULTS: As space constraints limit the data that can be presented here and FDA output is mostly graphical, selected FDA results for AT and ADF angles will be discussed here. The first three FPCs for AT angle accounted for 94% of the total variation in the curves for all groups. FPC1 accounted for 57.1%, 55.5% and 69.3% of the total variation for controls, AT(NO) and AT(O) respectively. The first FPC extracted accounts for the largest amount of variation in the data and in this case represents variation around the overall mean. Interpreting the FPCs can be quite difficult and a useful technique is to examine plots of the overall mean function and the functions obtained by adding and subtracting a suitable multiple of the FPC in question. The choice of this multiple is arbitrary (a value of 2 is chosen here) and is usually selected to give more easily interpretable results. The addition of a FPC to the mean curve indicates the direction that the mean curve would be shifted for an individual who scored highly on this FPC (denoted by the plus signs). The minus signs illustrate the direction the curve would be shifted for a low scorer on this FPC. Figures 1 and 2 show clear differences in FPC1 for AT angle between the AT and control groups. The control group is characterised by variation around the mean throughout stance while the AT group showed most variation in the initial 10% and last 40% stance. In contrast, this FPC accounts for very little variation from the mean curve between 10 and 60% of stance. Boxplots of the FPC scores provided further evidence of functional differences between AT(O) and control groups. FPC2 described the AT ROM. This feature distinguished between injured and uninjured subjects as the control group displayed less eversion ROM compared to the AT group. Orthoses had a tendency to increase this ROM further. FPC analysis for ADF angle revealed that orthoses reduced ADF ROM compared to the NO condition and provided curves that more closely resembled those of controls. Results also revealed differences in coordination patterns between control and AT groups.

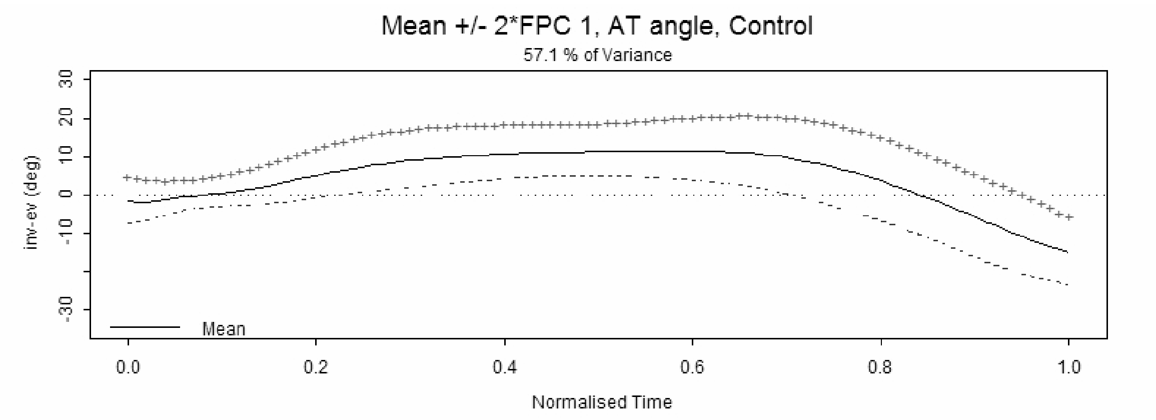

Figure 1 Mean AT angle time series curve for control group with 2*FPC1 added and subtracted from the mean curve.

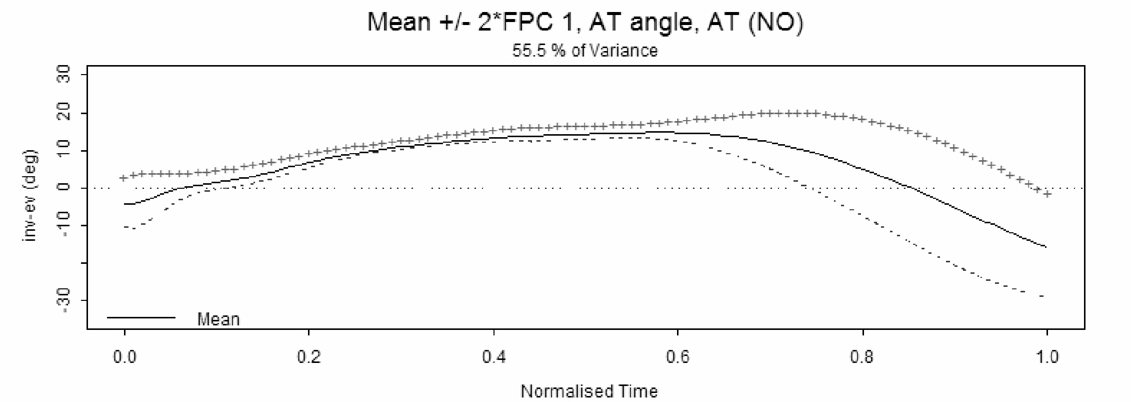

Figure 2 Mean AT angle time series curve for AT(NO) group with 2*FPC1 added and subtracted from the mean curve.

DISCUSSION: The data provided clear evidence of functional differences between subjects with a history of Achilles tendon injury and controls. AT subjects were recruited for this study based on presentation of the same movement pattern involving high levels of pronation during running. This explains why the subjects displayed high eversion ROM and suggests that this may be related to injury as EV ROM levels were much lower in randomly selected controls. The reduced variability displayed by the AT subjects between 10 and 60% of stance suggested that all subjects underwent similar loading patterns during this time regardless of HS position. Controls showed variation from the mean curve throughout stance indicating between subject differences that would be expected in a randomly selected population. This indicates that the loading period is critical in understanding the mechanisms of AT injury. This result confirmed that these subjects showed the same movement pattern and supports the predictions of dynamical systems theorists that reduced variability can be a distinguishing feature of injury (Hamill et al., 1999). The data supported the use of orthoses in decreasing ADF ROM in this specific injury group. FDA was also used to identify the relative importance of AT and ADF angles in the coordination relationship. FDA provides a versatile approach to analysing curve data and can be applied to angle time series, coordination and continuous relative phase data. Existing methods of analysing continuous relative phase use data from the entire curve, but ultimately reduce the data to average values of coupling angle and variability during specific phases of stance. FDA can be used to examine this data throughout the entire stance period. While FDA is an established procedure in mathematics, it has had limited use in biomechanics research to date. The results of this study show that it is a useful method of analysis and that it can reveal functional changes that are not obvious from traditional multivariate approaches.

CONCLUSION: FDA revealed clear functional differences in AT and ADF angle time series and ADF-AT coordination between O and NO conditions and between subjects with a history of Achilles tendon injury and uninjured controls. Variation in AT angle was lower in injured subjects compared to controls, which provides statistical support for the predictions of dynamical systems theory in this specific injury population (Hamill et al., 1999). FDA revealed that this difference was evident during the loading period of stance making this period critical when examining the mechanisms of AT injury. These results highlight the potential of FDA in examining kinematics and variability during gait particularly in injured populations.

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