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Characterization of gait using plantar force transfer trajectory in individuals with hallux valgus deformity

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ABSTRACT

Background: Hallux Valgus (HV) is the most common fore-foot deformity, which causes foot pain and limited motion that are encountered in podiatric and orthopedic practices. The purpose of this study is to develop a reliable pattern recognition method to identify the presence of HV based on plantar force measurements.
Method: Forces at five discrete metatarsal regions are measured at discrete time intervals under the right foot. Under this method, it is hypothesized that force measurement at a given time interval is related to the forces at a previous time interval by using Markovian transition matrix (**T** matrix). Thirty volunteers' (10 with HV, 10 without HV and 10 with un-diagnosed HV) condition were examined. The use of a Markovian transition matrix for gait characterization is novel. **T** matrices of all the participants were obtained and compared using means and standard deviations of each of the matrix elements. The comparison was undertaken using a new measure called the "Diagnostic Ratio" (DR). Independent Sample T-test was performed on the **T** matrix elements.
Results: A significant difference was observed between the HV and non-HV groups. HV volunteers were recognized from the dispersion of the **T** matrices' elements. For volunteers with un-diagnosed condition exhibiting borderline DR may be interpreted as them being prone to HV.
Conclusion: Comparison of transfer matrices using means and standard deviations of the HV and non-HV groups revealed that a DR of higher than 40% could suggest having an HV condition for five volunteers of the undiagnosed group and two were found to be prone to getting the condition.

1. Introduction

Hallux Valgus (HV) is a progressive subluxation of the first metatarsophalangeal joint [1], represented by hypermobility and lateral deviation of the hallux with respect to the first metatarsal bone by more than 15° [2,3]. HV can cause pain and deterioration of health-related quality of life [3–5] as well as being associated with poor balance, risk of falling [6], and gait impairments [7,8]. Understanding the plantar force pattern under the foot can be used to identify the foot pathologies. Centre of pressures (COP) are used to describe the complex dynamic function of the foot and the foot-ground interface during gait [9]. Moreover, COP trajectory gives information on how the gait patterns in patients with HV differ from those without HV. Regarding which, increased COP has been observed in patients with HV when compared to those with normal feet. In previous studies, the COP progression was modelled linearly and the results of regression analysis reveal that the COP trajectory is a more complicated movement, involving polynomial expressions of the stance time. Understanding the dynamic COP trajectory can provide additional information relating to lower extremity moments and balance control during gait [10].

This suggests examining plantar force distribution, and analyzing force transfer under the metatarsals during locomotion, as this might provide further information about the condition and its course of development. In the previous studies, individuals with HV showed altered pressure distribution in their fore-foot during walking, such that areas with increased load were observed under the medial metatarsal regions [11] and central metatarsal heads [12]. However, the relationship between altered plantar pressure patterns and changes in gait pattern has been suggested as not being straightforward. Several studies have reported altered plantar pressures in individuals with HV, albeit with inconsistent findings for hallux [13,14], and fore-foot loading [15–17].

No investigation has been carried out in relation to measuring force

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transformation among the metatarsals region to identify the existence of HV or to diagnose the deformity in the early stages of its progression. Early detection of a possible developing HV allows a range of clinical interventions to immediately begin, facilitating prevention before the deformity is entrenched. The aim of the present study was to develop a pattern recognition method to identify the presence of HV based on plantar foot force measurements during gait.

2. Methods

2.1. Participants

Volunteers, recruited over a year, with a mild deformity of a hallux angle less than 25° were tested. Thirty volunteers took part in the study with a mean age of 39.25 years old, mean weight of 68.75 kg, mean body mass index of 23.4 and females to males ratio by 17:13. Ten participants with HV were clinically diagnosed by a surgeon by measuring the deformity and classifying it as being present when the angle of the first metatarsal was higher than 15°. This method was also reported by [18], who stated that subluxation of the big toe of a patient of more than 15° was assumed as being a person with HV. Moreover, all volunteers were free of any other deformity involving the lower limbs. Furthermore, none of the participants was suffering any pain due to the HV condition as pain influences the load pattern. The Research Ethics Committee of the School of Engineering, Design and Physical sciences of Brunel University London approved the conduct of the study and all the participants provided consent prior to taking part in the tests.

2.2. Gait analysis

The plantar force distribution pattern was measured using an RSscan device (International NV, Belgium) with the dimensions 578 mm × 418 mm × 12 mm (length × width × height), for participants walking barefoot at the speed of 0.4–0.45 milliseconds which is the range that most of participants walked naturally in between or close to that range. As speed has a direct influence on the load pattern, any speed measured outside this range was rejected. The pressure mat was positioned approximately in the middle of a six-meter-long track on top of the floor in the laboratory. For each participant, an initial familiarization was conducted three times before the actual test to ensure that the participant's right foot made clear contact with the mat. Familiarization was undertaken to encourage as natural a gait as possible by participants. Trials were repeated if the participant stepped incorrectly on to the mat. Volunteers had direct foot contact with the pressure mat to obtain more accurate results. Ten walking trials were recorded from each participant at the defined speed.

The RSscan software divides the area under each foot into ten anatomical regions automatically, including toe one, toes two-five, five metatarsals, mid-foot, medial heel and lateral heel. Force data is collected by the RSscan device at a rate of 500 samples per second. These were normalized to the body weight, and the contact time with the pressure mat was normalized to 100 steps. Based on the walking speed in each individual, with full contact, typically, 250 to 450 samples were collected. The investigation focused on the last 20% of the stance when the fore-foot area was in contact with the pressure mat, when there were force readings under all the metatarsals. Any results appeared to be unusual was discarded and experiment was repeated. Furthermore, gait variability observed was not significant as data was normalized. The data was reliable as the device was calibrated and tested by supplier.

2.2.1. Force pattern characterization theory

The study was based on readings taken from the RSscan force sensors under five metatarsal regions at regular intervals during gait cycle. It was assumed that readings taken at a sampling step were related to the readings taken at the next sampling step. Moreover, the assumption was made that relationship between these subsequent sets could be represented by a Markov Chain transition matrix (**T**). The novelty of the method is in the use of **T** matrix as a means of pattern recognition in identifying the HV condition. A Markov Chain transfer matrix is a probability matrix which associates the state vector at time "e" with that at time "e + 1".

A**T** matrix was used to associate force measurement at metatarsal regions at sequential time intervals. It was hypothesized that five readings from the sensing areas (five metatarsals) at a given "sampling time during the stance phase of a gait cycle are related to the readings at the next sampling point and this relationship can be represented by a Markov Chain transfer matrix. A**T** matrix is used to model force transformation at a selected position under the foot. It was assumed $\boldsymbol{x}_e$ represents a force vector containing five force values $x_e = \{x_1, x_2, x_3, x_4, x_5\}_e$ recorded from each of the five metatarsals at time "*e*". Similarly, the force vector at the next point in time, "e + 1", was given by "x_{e+1}". To obtain the transfer matrix(**T**)from Eq. (1) (also shown in Eq. (2)), five vectors of force readings needed to be selected and assembled, as shown in Eq. (3).

$$\boldsymbol{x}_{e+1} = \mathbf{T}\boldsymbol{x}_e \tag{1}$$

Writing Eq. (1) in full,

$$\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{bmatrix}_{e+1} = \begin{bmatrix} T_{11} & T_{12} & T_{13} & T_{14} & T_{15} \\ T_{21} & T_{22} & T_{23} & T_{24} & T_{25} \\ T_{31} & T_{32} & T_{33} & T_{34} & T_{35} \\ T_{41} & T_{42} & T_{43} & T_{44} & T_{45} \\ T_{51} & T_{52} & T_{53} & T_{54} & T_{55} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{bmatrix}_{e} \tag{2}$$

Assembling Eq. (2) for five time intervals (six time steps), the following equation is obtained:

$$\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{bmatrix}_{e+1} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{bmatrix}_{e+2} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{bmatrix}_{e+3} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{bmatrix}_{e+4} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{bmatrix}_{e+5} = \begin{bmatrix} T_{11} & T_{12} & T_{13} & T_{14} & T_{15} \\ T_{21} & T_{22} & T_{23} & T_{24} & T_{25} \\ T_{31} & T_{32} & T_{33} & T_{34} & T_{35} \\ T_{41} & T_{42} & T_{43} & T_{44} & T_{45} \\ T_{51} & T_{52} & T_{53} & T_{54} & T_{55} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{bmatrix}_{e} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{bmatrix}_{e+1} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{bmatrix}_{e+2} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{bmatrix}_{e+3} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{bmatrix}_{e+4} \tag{3}$$

The force vectors in Eq. (3) can be assembled in matrices **A** and **B** below:

$$\begin{aligned} \boldsymbol{A} &= [\boldsymbol{x}_e \boldsymbol{x}_{e+1} \boldsymbol{x}_{e+2} \boldsymbol{x}_{e+3} \boldsymbol{x}_{e+4}] \\ \mathrm{B} &= [\boldsymbol{x}_{e+1} \boldsymbol{x}_{e+2} \boldsymbol{x}_{e+3} \boldsymbol{x}_{e+4} \boldsymbol{x}_{e+5}] \end{aligned} \tag{4}$$

Matrix **A** contains five force vectors measured at metatarsal regions at five points in time, from "e" to "e + 4". Matrix **B** contains the force values measured at the same regions at five points in times, from "e + 1" to "e + 5". Frames are taken at equal time intervals.

Now Eq. (3) may be written as:

$$\mathbf{B} = \mathrm{T}\mathbf{A} \tag{5}$$

And, **T** matrix can be obtained by post multiplying **B** by $\mathbf{A}^{-1}$, giving Eq. (6).

$$\mathbf{T} = \mathbf{B}\mathbf{A}^{-1} \tag{6}$$

The time shift between the measured forces had to be taken with the great care as it was important to ensure that the force readings were valid. When the toes were in an off the ground position, the sensors recorded zero readings and this led to the matrix becoming singular. To overcome this, only the time steps were chosen that the force was recorded for all the metatarsals with no zeros. Furthermore, the time gap between data steps was considered as one normalized time step and during the investigations multiple time steps were included. This procedure was the same for all participants.