Gait & Posture 57 (2017) 85–90

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Full length article

Altered leverage around the ankle in people with diabetes: A natural strategy to modify the muscular contribution during walking?

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ARTICLE INFO

Keywords:
Gait
Moment arms
Lower limbs
Diabetes
Effective mechanical advantage

ABSTRACT

Diabetes patients display gait alterations compared to controls including a higher metabolic cost of walking. This study aimed to investigate whether differences in external moment arm (ExtMA) and effective mechanical advantage (EMA) at the ankle in diabetes patients could partly explain the increased cost of walking compared to controls. Thirty one non-diabetic controls (Ctrl); 22 diabetes patients without peripheral neuropathy (DM) and 14 patients with moderate/severe diabetic peripheral neuropathy (DPN) underwent gait analysis using a motion analysis system and force plates. The internal Achilles tendon moment arm length was determined using magnetic resonance imaging during weight-bearing and ExtMA was calculated using gait analysis. A greater value ($P < 0.01$) for the EMA at the ankle was found in the DPN (0.488) and DM (0.46) groups compared to Ctrl (0.448). The increased EMA was mainly caused by a smaller ExtMA in the DPN (9.63 cm; $P < 0.01$) and DM (10.31 cm) groups compared to Ctrl (10.42 cm) These findings indicate that the ankle plantarflexor muscles would need to generate lower forces to overcome the external resistance during walking compared to controls. Our findings do not explain the previously observedhigher metabolic cost of walking in the DM and DPN groups, but uncover a new mechanism through which patients with diabetes and particularly those with DPN reduce the joint moment at the ankle during walking: by applying the ground reaction force more proximally on the foot, or at an angle directed more towards the ankle, thereby increasing the EMA and reducing the ankle joint moment.

1. Introduction

Diabetes presents a global health challenge with an international prevalence between 2% and 24% [1,2]. Diabetic peripheral neuropathy (DPN) is a major complication occurring in 30–50% of all patients, causing dysfunction of peripheral nerves [3], with implications for not only sensory but also motor nerves, causing movement dysfunction [4,5]. People with diabetes walk more slowly, take shorter strides and generate lower knee and ankle joint moments during walking [6,7]. We have recently shown a higher metabolic cost of walking (CoW) across a range of matched walking speeds in patients with diabetes and particularly in those with DPN compared to controls [12]. This higher CoW in people with diabetes may underpin their lower physical activity levels, contributing towards a negative spiral where there is a greater perception of difficulty for walking, which causes less engagement in physical activity, leading to poorer metabolic control and worsening of the diabetic condition. To allow interventions to break this negative cycle, it is therefore important to understand the factors that contribute to increasing the CoW in diabetes.

One potential factor contributing to the increased CoW is a lower effective mechanical advantage (EMA), caused by a greater external moment arm (ExtMA) of the resultant ground reaction force (GRF) around the ankle. The EMA around the ankle is given by the ratio of the internal moment arm of the plantarflexors (IntMA) to the ExtMA, with lower values reflecting a relatively greater contribution from the plantarflexor muscles towards the joint moment required to overcome the external resistance [8,9]. Many diabetes patients have some level of foot deformity such as high arch, or toe deformities [11], which may

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http://dx.doi.org/10.1016/j.gaitpost.2017.05.016
Received 16 December 2016; Received in revised form 8 March 2017; Accepted 16 May 2017

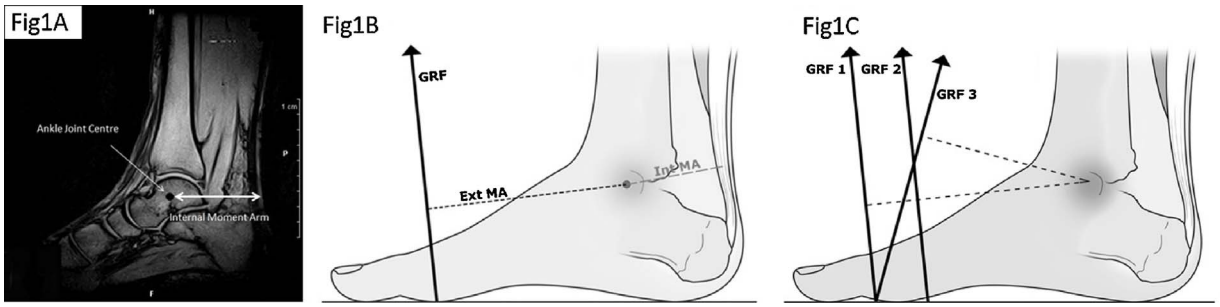

Fig. 1. Definition of internal and external moment arms and illustration of key concepts. A. An example sagittal plane MRI scan of the lower limb showing the measurement of the internal moment arm length (indicated by the white arrow). B. Diagram showing the external moment arm length (Ext MA; black dashed line) as the perpendicular distance between the resultant GRF vector and the joint centre of rotation (●); the internal Achilles tendon moment arm (Int MA; red dashed line) as the perpendicular distance between the tendon's action line and the ankle joint centre (●). The EMA is calculated as: *IntMA/ExtMA*. C. Illustrative example of how the GRF can be applied on the foot in two different ways causing a reduction in the ExtMA (dashed lines), thereby increasing the EMA and reducing the ankle joint moment and the muscular force contribution from the plantarflexors: i) with the point of application closer to the ankle joint centre (GRF 2 compared to GFR 1) and/or ii) by an altered angle of application (GRF 3 compared to GRF 1).

result in applying force to the ground more distal on the foot, thereby decreasing the EMA due to the increased ExtMA around the ankle. One consequence of this leverage alteration is that the plantarflexion muscles would need to produce more active force to generate the ankle moment required for propulsion. The EMA around the ankle in diabetes patients could also be affected by altered use of the lower limb and foot caused by sensory deficits and plantarflexor muscle weakness. A relative increase in the contribution from ankle plantarflexor muscles during walking may contribute to the increased CoW in diabetes patients.

The aim of this study was to establish whether there are differences in the ExtMA and EMA at the ankle in patients with diabetes and DPN compared to controls at a range of matched walking speeds, as a potential mechanism contributing to the increased CoW recently observed in diabetes patients [12]. We hypothesized that the ExtMA will be higher and the EMA will be lower in diabetes patients compared to controls.

2. Methods

2.1. Participants

After receiving ethical approval for the study from all relevant bodies, a total of 67 participants were recruited, who gave written informed consent to participate. Participants were allocated into one of three groups based upon defined criteria: patients with diabetes and moderate-severe peripheral neuropathy (n = 14, 12 men, 2 women), patients with diabetes but no neuropathy (n = 22, 12 men, 10 women) and healthy controls without diabetes or peripheral neuropathy (n = 31, 19 men, 12 women). Major exclusion criteria included: disorders of the vestibular system, musculoskeletal injury, recent surgery affecting gait, foot or lower limb amputation and open foot ulcer.

2.2. Clinical assessment of peripheral neuropathy

A clinical evaluation was undertaken to quantify neuropathy in diabetes patients. Peripheral neuropathy was assessed by using the modified Neuropathy Disability Score (mNDS) and the vibration perception threshold (VPT) [13]. A random blood glucose test was performed in the Ctrl group to confirm the absence of diabetes and the above neuropathy tests conducted to confirm the absence of neuropathy in the Ctrl group resulting from any aetiology.

2.3. Gait analysis

Kinematic data were collected at 100 Hz using a full-body modified Plug-In-Gait marker set [5] with 54 markers and a 10-camera Vicon motion capture system (Vicon, Oxford, UK) positioned around the 10-m walkway. Ground reaction forces were measured at 1000 Hz synchronously with motion capturing using three force platforms (Kistler, Zurich, Switzerland) embedded into the walkway. Where possible markers were placed directly onto the skin; to minimise movement artefacts resulting from loose clothing. All participants wore tight-fitting shorts and t-shirts. Participants were instructed to walk the length of the walkway at different walking speeds performed in a specific order (0.6, 0.8, 1.0, 1.2, 1.4 and 1.6 m/s). Walking speed was controlled by measuring the velocity of a marker attached to the sacrum after each trial from the motion analysis data and providing immediate verbal feedback for participants as to whether they needed to walk more quickly or slower on the next trial to achieve the required speed. Although this approach involved a systematic, rather than randomised order of walking speeds, it was deemed the most optimal approach to achieve the required speeds while retaining a natural gait, compared to alternatives such as a metronome that restricts cadence. Furthermore, given that walking is not an unusual or unaccustomed task, there is little reason to expect any learning or order effects. Walking trials were repeated to obtain three 'clean' foot contacts with the force platforms per limb, per speed condition. All participants wore the same standardised shoes (MedSurg, Darco, Raisting, Germany).

2.4. MRI scanning and analysis

Magnetic resonance imaging (MRI) was used to quantify the IntMA length as the Achilles tendon moment arm length at the ankle, as previously described [14]. IntMA was defined as the perpendicular distance from the centre of rotation on the talus to the Achilles tendon line of action (Fig. 1a) [15,16]. The IntMA lengths were determined with participants standing upright (i.e., full weight-bearing) in a 0.25T MRI scanner (E-Scan, Esaote Biomedica, Genoa, Italy). Weight-bearing scans were acquired across the predominant range of ankle joint angles (10 deg dorsiflexion, neutral position, 10 deg plantarflexion) experienced during walking, to relate these measurements as closely as possible to the conditions of walking. The ankle joint instant centre of rotation was located following the graphical approach described by Reuleaux [17] for ankle angle rotations from −10 to 10 deg. Instant centre of rotation was determined by measuring the rotation of the talus, which was considered to represent the whole rotating foot, relative to the tibia. IntMA was measured on the neutral ankle scan. All images were analysed using a custom-script written in MATLAB software.

2.5. Measurement of the ExtMA at the ankle during walking and foot length

Foot length was measured in the standing position as the distance between the end of the big toe and the heel. ExtMA length around the