Journal of Biomechanics 47 (2014) 2571–2577

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Multi-segment foot kinematics and ground reaction forces during gait of individuals with plantar fasciitis

Ryan Chang [a,*], Pedro A. Rodrigues [a,c], Richard E.A. Van Emmerik [b], Joseph Hamill [a]

[a] Biomechanics Laboratory, Department of Kinesiology, University of Massachusetts Amherst, Amherst, MA 01003, USA
[b] Motor Control Laboratory, Department of Kinesiology, University of Massachusetts Amherst, Amherst, MA 01003, USA
[c] New Balance Sports Research Laboratory, Lawrence, MA 01843, USA

ARTICLE INFO

Article history:
Accepted 4 June 2014

Keywords:
Medial longitudinal arch
Overuse injuries
Kinetics
Rearfoot
Forefoot

ABSTRACT

Background: Clinically, plantar fasciitis (PF) is believed to be a result and/or prolonged by overpronation and excessive loading, but there is little biomechanical data to support this assertion. The purpose of this study was to determine the differences between healthy individuals and those with PF in (1) rearfoot motion, (2) medial forefoot motion, (3) first metatarsal phalangeal joint (FMPJ) motion, and (4) ground reaction forces (GRF).
Methods: We recruited healthy ($n=22$) and chronic PF individuals ($n=22$, symptomatic over three months) of similar age, height, weight, and foot shape ($p>0.05$). Retro-reflective skin markers were fixed according to a multi-segment foot and shank model. Ground reaction forces and three dimensional kinematics of the shank, rearfoot, medial forefoot, and hallux segment were captured as individuals walked at 1.35 ms^{-1}.
Results: Despite similarities in foot anthropometrics, when compared to healthy individuals, individuals with PF exhibited significantly ($p<0.05$) (1) greater total rearfoot eversion, (2) greater forefoot plantar flexion at initial contact, (3) greater total sagittal plane forefoot motion, (4) greater maximum FMPJ dorsiflexion, and (5) decreased vertical GRF during propulsion.
Conclusion: These data suggest that compared to healthy individuals, individuals with PF exhibit significant differences in foot kinematics and kinetics. Consistent with the theoretical injury mechanisms of PF, we found these individuals to have greater total rearfoot eversion and peak FMPJ dorsiflexion, which may put undue loads on the plantar fascia. Meanwhile, increased medial forefoot plantar flexion at initial contact and decreased propulsive GRF are suggestive of compensatory responses, perhaps to manage pain.

1. Introduction

Plantar fasciitis (PF) is the most common cause of heel pain, yet its aetiology is not well understood (Young et al., 2001). Typically the prognosis of a conservative treatment plan is good, but approximately 10% of cases are recalcitrant (Davis et al., 1994). Numerous factors are thought to contribute to the development of PF; however, biomechanical factors are considered to be the principal contributors (Wearing et al., 2006). Clinicians believe that excessive strain and loading of the plantar fascia (also known as the plantar aponeurosis) occurs concurrently with abnormal subtalar joint overpronation, and flattening of the medial longitudinal arch (often clinically referred to as pes planus, or flat foot) (Kwong et al., 1988; Subotnick, 1981; Taunton et al., 1982). In addition, high ground reaction forces (GRF) during locomotion could also place greater loads on the plantar fascia. Despite that the term "excessive" is commonly used by clinicians to describe certain magnitudes of pronation and loading, it remains difficult to define quantitatively. Nevertheless, clinicians theoretically believe that excessive kinematics and kinetics play a key role in the development and prolongation of recalcitrant PF.

The findings of biomechanical studies, however, are contrary to the clinical assertion that foot overpronation and PF are associated. Research studies in rearfoot motion (Messier and Pittala, 1988; Warren and Jones, 1987), arch kinematics (Wearing et al., 2004), and arch height (Rome et al., 2001; Warren, 1984) have not found a relationship between these characteristics and PF. There are two limitations with these studies. First, there are errors associated with evaluating overpronation, a movement that is three dimensional (3D) in nature, with a two dimensional (2D) measurement. Second, the modeling of the foot as a single rigid segment is problematic. The plantar fascia attaches to the rearfoot, forefoot and toes, and therefore, the plantar fascia can become elongated

* Corresponding author. Tel.: +1 781 686 4817.
E-mail address: ryan.chang.umass@gmail.com (R. Chang).

http://dx.doi.org/10.1016/j.jbiomech.2014.06.003
0021-9290/

with intrinsic foot motion. It has long been shown that the movements of the medial arch and the hallux are strongly related to the dynamics of the plantar fascia (Hicks, 1954). Therefore, modeling of the foot as a single rigid segment provides no insight regarding the deformation and loading of the plantar fascia, and limits our understanding of how the plantar fascia may become injured. These two limitations can be overcome using 3D multi-segment foot models (Pohl and Buckley, 2008; Rao et al., 2007) and can potentially shed some light on the foot kinematics pertinent to PF (Chang et al., 2008).

Moreover, there is disagreement in the literature concerning the extent to which vertical GRF are affected in individuals with PF in comparison to healthy controls. Some researchers have shown that vertical GRF are unchanged in individuals with PF during gait (Liddle et al., 2000; Wearing et al., 2003), while others have shown reductions in the peak magnitudes (Katoh et al., 1983). These previous studies were conducted at subject-selected walking speeds, however, peak GRFs are directly related to walking speed (Andriacchi et al., 1977). Plantar fasciitis individuals may have selected a slower walking speed to compensate for pain. Controlling walking speed may provide additional insights as to whether GRFs are altered in individuals with PF.

Therefore, the purpose of this study was to determine whether healthy and PF feet are different with respect to multi-segment foot kinematics and GRF. Compared to healthy controls, we hypothesized that individuals with PF would exhibit greater rearfoot, forefoot, and hallux motion (i.e. greater maxima, total excursions, and maximum angular velocities). Additionally, we hypothesized that the peak vertical GRF at loading and at propulsion would differ between PF and healthy controls.

2. Methods

2.1. Participants

Twenty-two healthy controls and 22 chronic PF individuals gave their informed consent to participate. Individuals qualified if they were 30–60 years of age. Participants were limited to 60 years to minimize the potential confounding influence of age-related changes to plantar soft tissue (Kwan et al., 2010). All potential participants underwent a clinical examination by a Canadian Certified Pedorthist with previous clinical experience with PF, and various other foot pathologies. The examination consisted of a clinical history, functional tests, palpations, and range of motion tests of the major joints of the foot and shank. Participants in the control group qualified if they had no history of injury or foot pain, and had no pain elicited during the exam. Individuals with PF were included if they had heel pain upon palpation of the plantar fascia's insertion point, persistent symptoms for at least three months leading up to the study, experienced a minimum of five episodes of first-step pain within the last month (a hallmark of PF), and were otherwise healthy. Potential PF participants were screened with awareness that there are other forms of heel pain with presentations similar to PF (e.g. Achilles tendonitis, heel fat pad syndrome, calcaneal stress fracture). Exclusion criteria included a history of a local steroid injection within the last 2 months, arthritis (self-report), local traumatic injury, and a body mass index greater than 35. Foot posture was quantified via the standing arch ratio (Williams and McClay, 2000) and the foot posture index (Redmond et al., 2006) Due to their purported mechanical differences, we excluded individuals with a high arch foot type (Schuster, 1977) (a standing arch ratio one standard deviation above our laboratory's mean).

2.2. Protocol

Spherical markers (8 mm diameter) were fixed to the skin according to a multi-segment foot model (Leardini et al., 2007). The foot model included a rearfoot, a medial forefoot, and a hallux (Fig. 1). All foot markers remained on the skin for both the standing calibration trials and the dynamic trials.

The shank was defined and tracked using an existing shank model and marker set (Manal et al., 2000). The shank segment was defined by four segment

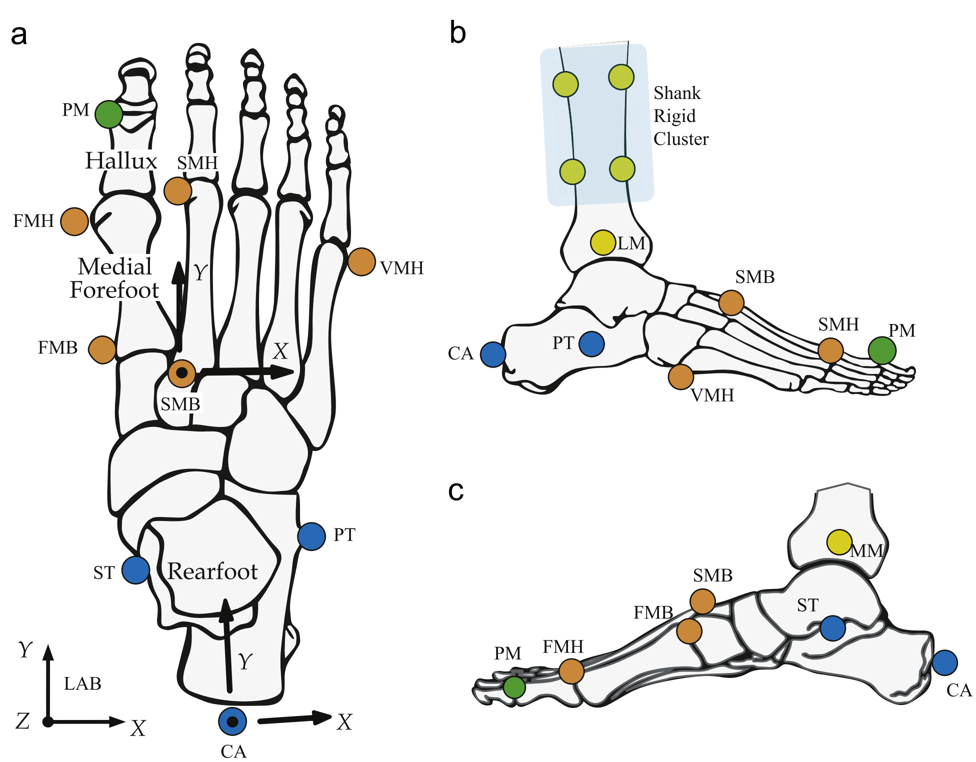

Fig. 1. (a) Multi-segment foot model consisting of three dimensional medial forefoot and rearfoot segments, and a two dimensional hallux line segment. A laboratory coordinate system and segment coordinate systems are provided for medial forefoot and rearfoot segments constructed from anatomically placed skin markers (Leardini et al., 2007) (first metatarsal (FM), second metatarsal (SM), head (H), base (B), peroneal tubercle (PT) sustentaculum tali (ST), calcaneus (CA). The rearfoot's origin was located at CA. The rearfoot's Y-axis was aligned to a midpoint between the ST and the PT. The rearfoot's *X*-axis was aligned to a transverse plane defined by rearfoot *Y*-axis and the ST. The rearfoot's *Z*-axis was orthogonal to the rearfoot's *XY* plane. The medial forefoot's origin was located at the SMB. The medial forefoot's *Y*-axis was a projection of the line joining SMB and SMH on the transverse plane passing through the origin and FMH and VMH. The medial forefoot *X*-axis was orthogonal to forefoot *Y*-axis and resided in this transverse plane. The medial forefoot *Z* axis was orthogonal to the medial forefoot *XY* plane. Hallux line segment was defined by the marker on the proximal phalanx of the hallux (PM) and the FMH.[29] Lower image provides a sagittal view of the foot model with sagittal medial forefoot angle inscribed. (B) Lateral view of the foot and shank. A rigid set of four markers on a plate was fixed to the lateral shank (lateral malleolus (LM)). (C) A medial view of the foot and shank with medial malleolus marker (MM) shown.