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Multiple linear regression approach for the analysis of the relationships between joints mobility and regional pressure-based parameters in the normal-arched foot

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ABSTRACT

Plantar load can be considered as a measure of the foot ability to transmit forces at the foot/ground, or foot/footwear interface during ambulatory activities via the lower limb kinematic chain. While morphological and functional measures have been shown to be correlated with plantar load, no exhaustive data are currently available on the possible relationships between range of motion of foot joints and plantar load regional parameters.

Joints' kinematics from a validated multi-segmental foot model were recorded together with plantar pressure parameters in 21 normal-arched healthy subjects during three barefoot walking trials. Plantar pressure maps were divided into six anatomically-based regions of interest associated to corresponding foot segments. A stepwise multiple regression analysis was performed to determine the relationships between pressure-based parameters, joints range of motion and normalized walking speed (speed/subject height).

Sagittal- and frontal-plane joint motion were those most correlated to plantar load. Foot joints' range of motion and normalized walking speed explained between 6% and 43% of the model variance (adjusted R^2) for pressure-based parameters. In general, those joints' presenting lower mobility during stance were associated to lower vertical force at forefoot and to larger mean and peak pressure at hindfoot and forefoot. Normalized walking speed was always positively correlated to mean and peak pressure at hindfoot and forefoot.

While a large variance in plantar pressure data is still not accounted for by the present models, this study provides statistical corroboration of the close relationship between joint mobility and plantar pressure during stance in the normal healthy foot.

1. Introduction

The foot represents the most distal segment of the lower limb kinematic chain providing body support, adaptation to different terrains and propulsion during walking and running. While as many as 33 joints connect the 28 foot bones, the most traditional biomechanical model of the foot is comprised of just one rigid segment connected to the leg via a hinge-joint. Over the last decade several multi-segmental foot models have thus been proposed (Rankine et al., 2008), however only few have been validated and are normally used in clinical and research settings (Carson et al., 2001; Leardini et al., 2007).

Ultimately, mobility of foot joints allows for a smooth roll-over and force exchange with the ground. This is expressed in terms of plantar load, which may be deemed as the foot ability to transmit forces at the foot/ground or at the foot/footwear interface. In the morphologically normal and healthy foot, plantar load during barefoot walking moves from hindfoot to forefoot with peak pressures being normally located at the center of the heel, under the second and third metatarsal heads, and under the hallux. Local peak pressures may expose critical areas at higher risk of callus, pain and, in the worst scenario, ulcers. Achieving a uniform plantar load distribution is particularly important in at risk feet (Bus, 2012), in order to prevent foot overuse injuries during high-impact repetitive tasks (Kaufman et al., 1999), and to optimize the energy-cost of walking (McNeill Alexander, 2002).

Walking speed is possibly the single spatio-temporal parameter most affecting plantar pressure magnitude and distribution (Kaufman, 2000; Pataky et al., 2008; Rosenbaum et al., 1994).

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It has extensively been shown how speed strongly alter body dynamics during walking, with the vertical displacement of the body center of gravity increasing with increasing horizontal velocity (Cavagna and Margaria, 1966; Orendurff et al., 2004). This results in larger vertical acceleration of the center of mass which is reflected by larger foot-to-ground reaction force, thus larger plantar load (Keller et al., 1996; Nilsson and Thorstensson, 1989). Moreover, the increased activity of the intrinsic foot muscles affects foot compliance (Kelly et al., 2014) by stiffening the longitudinal arch, resulting in increased hindfoot and forefoot pressure during fast-walking gaits (Caravaggi et al., 2010). Additionally, in the normal foot, morphological and functional factors have been shown to be correlated to plantar pressure (Cavanagh et al., 1997; Mootanah et al., 2013; Morag and Cavanagh, 1999). Hindfoot to forefoot motion has been reported to positively correlate to peak pressure at the hallux (Mootanah et al., 2013), and lateral-midfoot mobility to correlate to increased peak pressure under the midfoot (Bates et al., 2013). The latter studies provide some evidence to the causative link between foot joints kinematics and plantar load. In fact, association between limited joint mobility and increased plantar pressure has been extensively inferred in the diabetic foot (Fernando et al., 1991; Francia et al., 2015; Giacomozzi et al., 2008; Mueller et al., 1989; Veves et al., 1995; Zimny et al., 2004) and, in a previous effort by the present authors, temporal patterns of foot joints rotations were found to be significantly correlated to those of pressure in the corresponding plantar regions (Caravaggi et al., 2014; Giacomozzi et al., 2014). These results were obtained by the integration of kinematic and pressure measures, allowing to divide plantar pressure maps into regions-of-interest (ROIs), which can be uniquely associated to foot segments (Fig. 1). The anatomically-based ROI overcomes the previous geometry-based or operator-based pressure map subdivisions (Ellis et al., 2011), which can result in plantar regions only partially related to the foot anatomy and more prone to failure in case of morphological deviations from normality (Stebbins et al., 2005).

Although several foot morphological and functional parameters have been shown to affect plantar pressure, no exhaustive data exist on the relationship between dynamic motion of foot joints and plantar pressure distribution in the normal-arched asymptomatic foot. From a broader clinical perspective, the ultimate question may be the following: is mobility preferable over rigidity to limit the incidence and extent of foot ailments due to plantar overloading or excessive peak pressure? However, if neither a flexible foot nor a rigid foot is desirable, what is the “optimal” foot joint mobility allowing the most efficient force transfer at the foot/ground interface, while maintaining uniform plantar load distribution and minimizing areas with excessive pressure? From a purely energetic perspective, biological optimization may instead be oriented at maximizing the energy absorbed by the foot (Ker et al., 1987), or at minimizing the total expenditure of energy used by the body for locomotion (McNeill Alexander, 2002).

Regardless of the evolutionary criteria leading to the modern human foot compliance and biomechanics, the investigation of which is not an aim of this study, our hypothesis is that plantar load is correlated to foot joints mobility. If confirmed, this hypothesis may have profound implications on our understanding and interpretation of different foot pathologies, in relation to anatomical and morphological variations. Moreover, kinematics of foot joints could be partially derived from plantar load data, thus potentially extending the comprehension of foot function from pressure measurements. This is highly relevant to the clinical assessment of foot pathologies and deformities, where often only a limited set of instruments is available to clinicians.

In order to test our hypothesis, the integration between a validated multi-segment foot kinematic protocol (Leardini et al., 2007) and plantar pressure maps was used in a healthy feet population to determine the relationships between foot joints mobility and plantar load during barefoot walking.

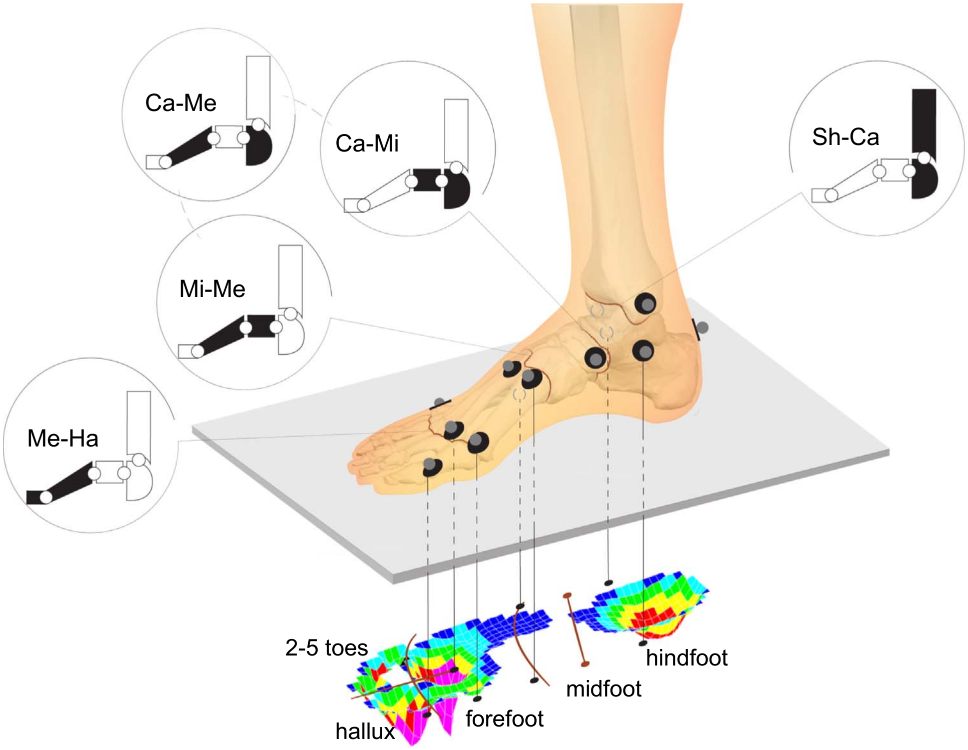

Fig. 1. The projection of the kinematic markers onto the pressure map during midstance allows for the division of the footprint in anatomically-based regions of interest (Giacomozzi et al., 2014). The round legends are pointing to the foot joints as in the Rizzoli Foot Model (Leardini et al., 2007), the motion of which has been used as predictor of plantar load in the multiple regression analysis.

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