Gait & Posture 38 (2013) 56–61

Contents lists available at SciVerse ScienceDirect

Gait & Posture

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

In vitro analysis of muscle activity illustrates mediolateral decoupling of hind and mid foot bone motion

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ARTICLE INFO

Article history:
Received 29 November 2011
Received in revised form 16 October 2012
Accepted 22 October 2012

Keywords:
Foot and ankle
Cadaveric simulation
Kinematics
Gait simulation
Muscle pathology

ABSTRACT

Activity of the extrinsic ankle–foot muscles is typically described for the whole foot. This study determines if this muscle activity is also confirmed for individual foot segments defined in multi-segment foot models used for clinical gait analysis. Analysis of the individual bone motion can identify functional complexes within the foot and evaluates the influence of an altered foot position on muscle activity. A custom designed and built gait simulator incorporating pneumatic actuators is used to control the muscle force of six muscle groups in cadaveric feet. Measurements were performed in three static postures in which individual muscle force was incrementally changed. The motion of four bone embedded LED-clusters was measured using a Krypton motion capture system and resulting motion of calcaneus, talus, navicular and cuboid was calculated. Results indicate that primary muscle activity at bone level corresponds with that described for the whole foot. Secondary activity is not always coherent for bones within one segment: decoupling of the movement of medial and lateral foot bones is documented. Furthermore, secondary muscle activity can alter according to foot position. The observed medio-lateral decoupling of the foot bones dictates the need to extend some of the multi-segment foot models currently used in clinical gait analysis.

1. Introduction

Anatomical studies typically document muscle activity considering the foot as one rigid segment rotating around the ankle and subtalar joints in unloaded or loaded conditions [1–4]. These studies therefore provide only limited information on kinematics of individual foot joints. Biomechanical studies use multi-segment foot models to document kinematics of fore-, mid- and hind foot segments during gait. Several foot bones are combined in one segment and none or minimal motion between bones of each segment is assumed [5–7]. Using this approach, characteristic movement between foot segments has been described during gait, as well as changes in these patterns due to pathologic conditions [8–10]. However, medical imaging and in vitro studies clearly demonstrate motion between bones belonging to one foot segment [11–13]. Since it is known that in clinical conditions (e.g. flexible flatfoot), the mobility of individual foot bones is significantly altered, there is a need to document muscle activity at the level of individual segments and even individual bones. This will result in a better understanding on how muscle imbalance contributes to these conditions.

Non-invasive, in vivo measurements do not allow to study the role of muscle activity on individual bone kinematics as this would require the tracking of three skin-mounted markers on each individual bone. Furthermore, isolated muscle activation can seldom be induced [14]. In vitro studies allow assessment of individual foot bone motion using bone pins and allow controlled forces to be imposed on individual muscle actuators. Using this approach, previous research typically focused on specific clinical questions in static and dynamic conditions [15–19], but did not exhaustively document muscle activity on individual foot bone motion. Using a gait simulator that loads musculo-tendinous structures, a gait-like motion can be generated and foot bone kinematics can be measured [20–22]. Although technically feasible, only a limited number of in vitro studies explicitly explored the effect of individual muscle activity on bone motion [23–26]. Kim et al. described the unique role of the individual extrinsic foot muscles on center of pressure but did not report individual bone kinematics. Niki et al., Blackman et al. and Wülker et al. reported the effect of Tibialis posterior, Triceps surae and Tibialis anterior muscles on individual foot bone motion.

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http://dx.doi.org/10.1016/j.gaitpost.2012.10.014

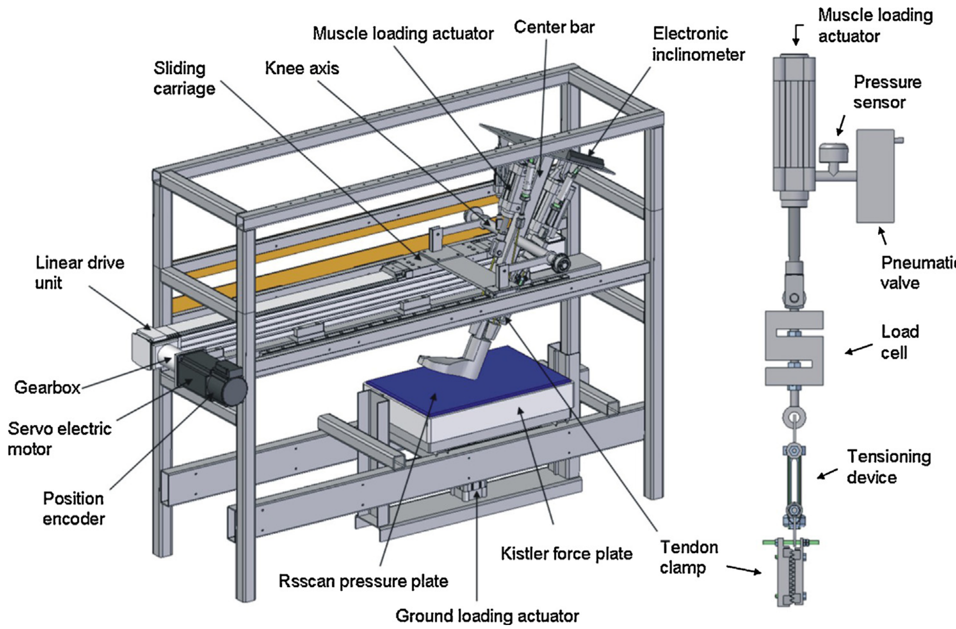

Fig. 1. Design of the in vitro dynamic gait simulator. The simulator consists of a general framework, carrying the actuator bearing frame. The actuators apply loads to a foot, mounted in the center of the actuator bearing frame. A sliding carriage, driven by a servo electric motor drives the foot through the stance phase of gait.

The aim of this study was (1) to determine if muscle activity, as described for the whole foot, is confirmed for individual foot segments as used in clinical gait analysis, (2) to assess the influence of altered foot positions on muscle activity, and (3) to determine the need to differentiate muscle activity within foot segments and consider muscle activity on individual bones, therefore identifying functional complexes of the foot.

2. Materials and methods

2.1. Specimen preparation

Five fresh frozen cadaver specimens, voluntarily donated for scientific research, were tested in a custom designed and built gait simulator (Fig. 1). Following amputation, the feet were kept frozen and brought to room temperature in tepid water before handling and testing. The lower leg was transected at mid-tibial level and imbedded in a cylinder, fitting over the tibia, using polyester resin (Motip Dupli B.V.). This cylinder extends the tibia and allows mounting of the foot in the gait simulator. The tendons of nine extrinsic leg muscles were released, leaving retinaculae, capsules and ligaments intact to prevent interference with the muscles' natural trajectory. The following tendons were grouped in six functional equivalents according to Bogey et al. [27]: triceps surae, peroneal muscles (longus and brevis), pretibial muscles (extensor digitorum longus, extensor hallucis longus, tibialis anterior), tibialis posterior, flexor hallucis longus and flexor digitorum longus. To accommodate the attachment of LED clusters for 3D motion analysis, titanium intracortical pins (diameter: 4 mm, length: 50 mm, ICOS, New Deal, France) were inserted in the talus, calcaneus, navicular and cuboid and rigidly secured in the bone with a two component epoxy glue. A custom-designed stabilizing device provided extra stability and prevented axial rotation through three attachment points within the bone (Fig. 2). Anatomical integrity of the cadaveric feet and correct placement of the pins were evaluated by a 0.5 mm spiral CT (Aquillion 64, Toshiba Medical Systems B.V., Japan). These CT scans were also used to define the local anatomical reference frames for kinematic analysis.

2.2. Gait simulator

The gait simulator consists of a framework carrying pneumatic actuators that apply force to the tendons of the extrinsic foot–ankle muscles. The force magnitude was calculated based on kinematics and ground reaction forces, measured during a gait analysis trial in a control subject (female, 47.9 kg). Using a musculoskeletal model, inverse dynamics and a static optimization algorithm, the muscle force distribution problem was solved and individual muscle forces during stance were calculated for all relevant muscles [28]. To allow appropriate dimensioning of muscle forces to actuator capacity, forces were scaled to a body weight of 245N (25 kg). Nylon tendon clamps preventing tendon slippage but allowing application of high forces (1800N) connected the tendons to the actuators. Load cells in series with the actuators measured the actual force applied to the tendons.

The foot was mounted into the simulator by connecting the surrogate tibia to a bar in the center of the device. A force plate (Kistler Multicomponent Force Plate, Kistler Instruments GmbH) supported the foot and varied the force applied by a pneumatic actuator underneath the plate similar to the vertical GRF. All control software was programmed in Labview 8.2 (National Instruments, Austin, Texas, U.S.) and Matlab 7.1 (Mathworks, Natick, Massachusetts, U.S.). For a detailed description on technical specifications of the device, we refer to [29].

2.3. Measurement devices

Motion of the foot bones was tracked using a Krypton optoelectronic motion capture system (Krypton K600, Metris, accuracy: 90 micron, sampling frequency: 100 Hz) using five rigid bone-mounted clusters, each containing four active

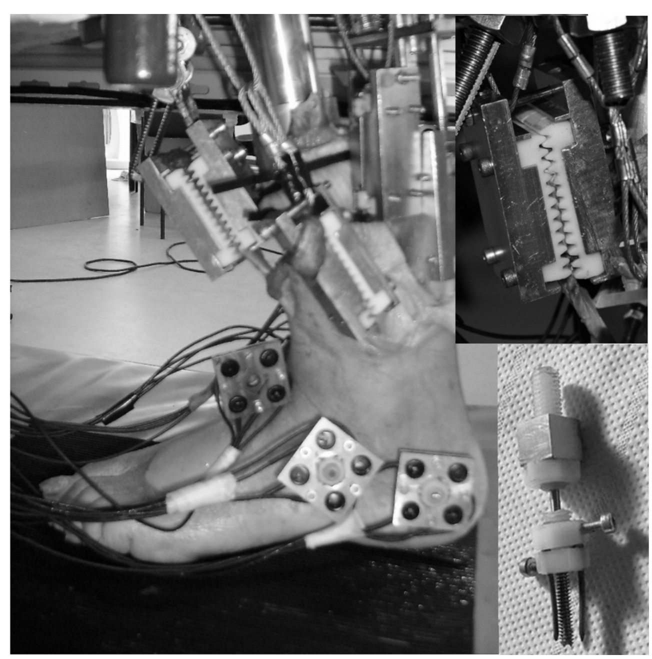

Fig. 2. Foot, mounted in the gait simulator. Custom built clamps are attached to the tendons of the six muscle groups. A detail of one clamp is shown in the top right of the image. The marker clusters, from which three are visible, are also present. A detail of an intracortical pin with a stabilizing device is shown in the bottom right corner.