Journal of Electromyography and Kinesiology 39 (2018) 149–155

Contents lists available at ScienceDirect

Journal of Electromyography and Kinesiology

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

Surface electromyography can quantify temporal and spatial patterns of activation of intrinsic human foot muscles

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ARTICLE INFO

Keywords:
Surface EMG
Intrinsic foot muscles
Topographical mapping
Sample entropy

ABSTRACT

Intrinsic foot muscles (IFM) are a crucial component within the human foot. Investigating their functioning can help understand healthy and pathological behaviour of foot and ankle, fundamental for everyday activities. Recording muscle activation from IFM has been attempted with invasive techniques, mainly investigating single muscles. Here we present a novel methodology, to investigate the feasibility of recording physiological surface EMG (sEMG) non-invasively and quantify patterns of activation across the whole plantar region of the foot. sEMG were recorded with a 13×5 array from the sole of the foot ($n = 25$) during two-foot stance, two-foot tiptoe and anterior/posterior sways. Physiological features of sEMG were analysed. During anterior/posterior epochs within the sway task, sEMG patterns were analysed in terms of signal amplitude (intensity) and structure (Sample Entropy) distribution, by evaluating the centre of gravity (CoG) of each topographical map. Results suggest signals are physiological and not affected by loading. Both amplitude and sample entropy CoG coordinates were grouped in one region and overlapped, suggesting that the region with highest amplitude corresponds with the most predictable signal. Therefore, both spatial and temporal features of IFM activation may be recorded non-invasively, providing opportunity for more detailed investigation of IFM function in healthy and patient populations.

1. Introduction

The human foot is critical for a wide range of activities of daily living. Foot pathologies and deformities, can have a major impact on a person's quality of life, with significant associated costs for healthcare providers. Issues associated with foot health can be structural (e.g. hallux valgus, pes cavus) and/or functional (e.g. hallux limitus and hallux rigidus) and can be associated with a range of chronic diseases such as diabetes mellitus where peripheral neuropathy and foot ulcerations are common. Understanding the features of good foot health and characteristics that underpin appropriate function is therefore important in a range of health-related fields.

The anatomy of the foot is complex, with different segments interacting to provide a flexible structure and facilitate motion (Kelly et al., 2014; Bates et al., 2013; McKeon et al., 2015). There are four layers of intrinsic muscles arranged within the narrow compartment of the plantar region (McKeon et al., 2015) (Fig. 1). Their anatomical positioning provides challenges to quantifying features of anatomy and activation during weight bearing tasks. Intrinsic foot muscle properties have been investigated using a number of techniques including electromyography (EMG), to investigate muscle activation patterns. The majority of EMG studies use invasive intramuscular techniques, focusing on a single or a small selection of muscles in the foot region (Kelly et al., 2012, 2014). Whilst providing useful insight, these approaches cannot be applied to problematic populations (e.g. diabetes patients) and cannot quantify activity across the whole foot region and so, interactions between or within regions of the intrinsic foot muscles cannot be probed, although such information is required for wider aspects of foot function to be evaluated in healthy and pathological populations.

One method of quantifying activation across a larger region is to use multi-channel electrode arrays. The use of a large number of electrodes within a grid, allows the processing of myoelectric signals as topographical maps quantifying both spatial and temporal features of signals (Rojas-Martínez et al., 2013; Holtermann et al., 2008). Due to heterogeneity either in the distribution of activated motor units or the strategy of recruitment, the spatial distribution of myoelectric intensity measures can change over time (Farina et al., 2008). Therefore, analysis of maps of sEMG intensities could quantify patterns of activation within and between muscles in a confined anatomical space. Such techniques

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https://doi.org/10.1016/j.jelekin.2018.02.009
Received 15 February 2018; Accepted 20 February 2018

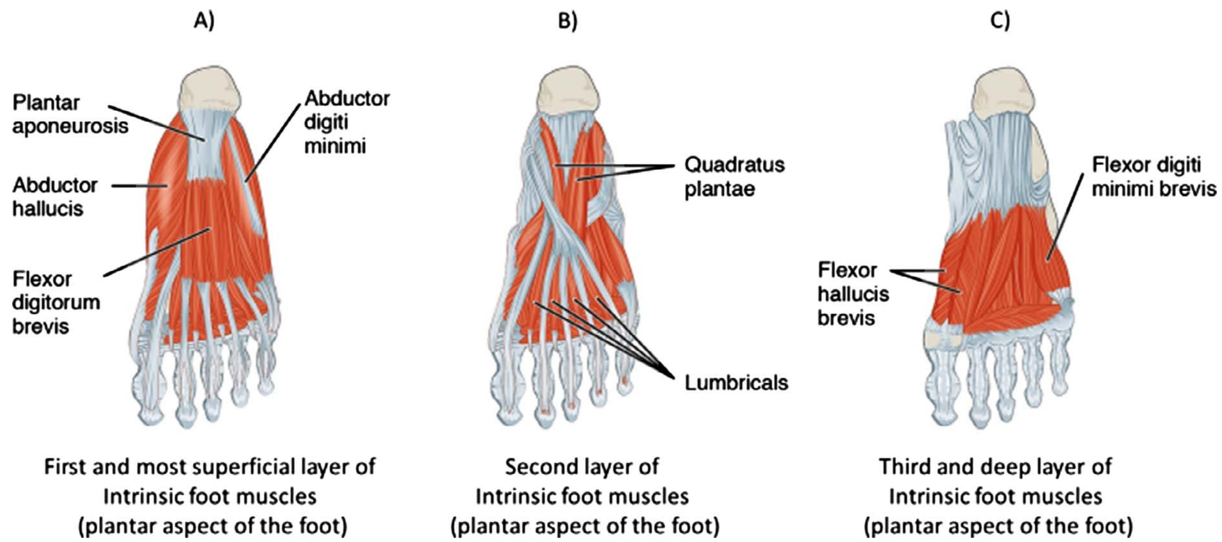

Fig. 1. Representation of the first three layers of the intrinsic foot muscles. Panel (A) shows the most superficial muscles, Panel (B) shows the second layer and Panel (C) the third and deep layer. The image has been amended from OpenStax (2016) down loaded from: https://commons.wikimedia.org/wiki/File:1124_Intrinsic_Muscles_of_the_Foot.jpg.

have been applied to different regions of the body (Falla and Farina, 2008; Gallina and Botter, 2013; Tucker et al., 2009; Rodriguez-Falces et al., 2013). However, to date, there have been no attempts to investigate the features of intrinsic foot muscle activation through the plantar surface of the foot using multi-channel systems.

In addition to traditional measures of sEMG intensities, changes in the complexity of motor patterns have recently been related to changes in motor strategies and muscle firing patterns (Rathleff et al., 2011), quantified with the use of Sample Entropy (SampEn). SampEn is defined as the negative natural logarithm of the conditional probability that two sequences are similar to m points and remain similar at the next point, $m + 1$ (Richman and Moorman, 2000). Greater SampEn values indicate a more complex signal structure and lower predictability of the time series (Richman and Moorman, 2000). To our knowledge, such analysis approaches have not previously been applied to explore variations in signal characteristics across a muscle region nor to study characteristics of intrinsic foot muscle activity.

Commercially available electrode arrays are flat and flexible and can be applied to the contours of the plantar region of the foot. However, these arrays have not been used previously on the foot region, as one concern is that loading due to body weight could influence signal characteristics. As such, signal amplitude changes could represent the movement of electrodes toward/away from the intrinsic foot muscles, rather than the physiological neuromuscular activation. Therefore, the aim of this work was to use a commercially available multi-channel array in a novel application to intrinsic foot muscles and to investigate whether it is possible to non-invasively quantify physiologically relevant temporal and spatial activation patterns from the plantar foot surface to provide new information about the human foot in health and disease.

2. Methods

2.1. Participants

Twenty-five healthy participants (twenty-two males and three females, age: 41 ± 15 years, weight: 73 ± 16 kg, height: 1.7 ± 0.1 m) voluntarily took part in the study having provided informed, written consent to do so. All procedures were approved by the local ethics committee in the Faculty of Science and Engineering at Manchester Metropolitan University. Exclusion criteria for participants included foot pain or lower limb pain during the last six months.

2.2. Data acquisition

Monopolar sEMGs were collected from the intrinsic foot muscles with a high-density grid of 64 channels (ELSCH model, OT Bioelettronica, Turin, Italy), consisting of 13 rows and five columns, with one missing electrode (2 mm diameter, 8 mm inter-electrode distance in both directions). Prior to attaching the grid of electrodes, the skin of the plantar region of the right foot was lightly abraded with abrasive paste and cleaned to remove any debris. To determine the array location, the adipose pads at the heel and toes were palpated and the grid positioned between these regions with the columns along the longitudinal axis of the foot (Fig. 2). A conductive cream (Spesmedica, Italy) was inserted into each cavity of the grid to assure proper electrode skin interface. The reference electrode was positioned around the right ankle.

Three-dimensional motion data were recorded using a 9-camera motion-capture system (Vicon Motion Systems, Oxford, UK) positioned around a force plate (Advanced Mechanical Technology, Inc., AMTI, Watertown, Massachusetts, USA) with an accuracy of ± 0.4 mm, which was covered with a 50 mm thick Styrofoam layer to reduce electrical noise from the ground. Fifty-four reflective markers were position on anatomical landmarks to track whole body movement. The Plug-in Gait marker set was utilised for anatomical landmarks on the shoulder to knee epicondyle and, from the tibial tuberosity to the foot, a modified Heidelberg foot marker set (Simon et al., 2006) was applied, with an additional marker on the shank to reduce problems associated with marker occlusion.

Each participant stood in the test area and was instructed to perform three motor tasks: (i) two-foot quiet standing (self-selected stance width); (ii) deliberate anterior/posterior sways (following a metronome beating at 2 Hz) and (iii) two foot continuous standing on tiptoe. These conditions were selected as they provided a range of quasi-static and motion-based conditions, and also provided one condition where there was no contact between the ground and the electrode grid meaning EMGs would be free from external loading. Each trial lasted 30 s. Synchronisation between force plate, motion capture data and EMG signals was achieved with the use of an external trigger.

2.3. Data analysis

Recorded sEMGs were visually inspected and channels showing noise due to poor skin-electrode interface contact or line interference were reconstructed based on the interpolation of the signals from