HOW MULTILEVEL BIOMECHANICAL MODELLING CAN HELP UNDERSTANDING SPORT MOVEMENT AND DESIGNING SPORT EQUIPMENT

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Analysing the complete influence of a sport equipment is highly difficult due to its multifactorial nature (covering physiology, biomechanics, motor control, and psychology). Indeed, changing the sport equipment can deeply modify the performance, in terms of absolute timing (lower running or cycling speed for example), by changing the way the musculoskeletal system is solicited or by favouring related-injuries. In this presentation, two points will be addressed. First, musculoskeletal modelling (EMG-Driven model) will be used to understand how wearing a running shoe can affect the muscle and tendon behaviours during the activity. Second, a finite elements model of the shod foot driven by experimentally-estimated muscle forces will be presented. This model can be used to numerically simulate modifications of the running shoe characteristics and assess their influences over the strain and stress of the different structures of the foot. These points will cover both fundamental and applied aspects in sport sciences.

KEY WORDS: Musculoskeletal modelling, Finite elements analysis, Running.

INTRODUCTION: Performing a sport activity (even fairly simple as running or cycling) is a very challenging task. Multidisciplinary analysis (covering mechanics, physiology, biomechanics, motor control, and psychology) are required to fully understand the implications of a specific sport equipment over the athlete. Combining already known and/or experienced methodological tools to strengthen the understanding of sport performance or enhance the development of sport equipment is now possible. This presentation will focus on two aspects of the running activity. First, a musculoskeletal model initially developed for clinical assessment will be applied to further understand the individual muscle forces as well as the inner functioning of muscle and tendon structures while running with different shoes. Muscle force represents a key variable that encompass all the kinematics, external forces, musculoskeletal anatomy, and muscle activations a single easily interpretable data, which can be a highly valuable addition to the experimental data. Indeed, the muscle force used to set a segment in motion or produce a force against an external support depends on muscle activation (usually measured using electromyography), fiber length and velocity (through the force-length-velocity relationship), and moment arm (Buchanan et al., 2004, Gerus et al., 2012). Second, finite elements analysis of the shoe-foot complex combined with the former musculoskeletal model will be presented in order to lead the development of running shoes. Indeed, the magnitude of the local tissue loading depends on several extrinsic and intrinsic factors, with the most important ones being the external force acting on the body segments, the geometry and mechanical properties of the anatomical structures, the intersegmental loads, and the forces produced by the muscles crossing the joints. From a computational point of view, taking into account all these factors as a whole is highly challenging because of their different natures. Indeed, muscle forces that set the body in motion are usually assessed using neuromusculoskeletal models of the body, whereas tissue loadings are estimated using Finite Elements Analysis of the concerned body structures (Besier et al., 2005).

METHODS: Eight subjects participated in the experiment that consisted in running with 2 different running shoes differing only in sole midsole height (0mm, 16mm), as well as barefoot (with no shoe). Lower limb kinematics, ground reaction forces, net joint torques, and

electromyographic data of 4 muscles surrounding the ankle joint (both gastrocnemii, Soleus, Tibialis Anterior – MG, LG, Sol, TA muscles) were acquired during the running trials. These data were further used as input of an EMG-Driven model to estimate the muscle forces and fibre length changes during the running cycles. These muscle forces and fibre length data were used to get an insight of the way the muscle-tendon complex acts during running.
The individual muscle forces were then used as input of a finite elements model of the foot-shoe complex aimed at estimating local loading of both foot and shoe structures (Figure 1). The data from a single participant were used. The 3D finite element model of the foot was developed based on medical imaging data of a single adult male subject (30 years, 1.80 m, 72 kg). MRI and CT scan data were obtained from this subject with the knee joint fully extended and the ankle joint in neutral position. For each acquisition, the ankle joint was kept in neutral position by using an anatomical cast of the lower limb. CT scans were further imported in Mimics© software to extract the geometries of the bones, tendons, ligaments, and plantar fascia. MRI data were used every time the CT scan data weren't sufficiently accurate to determine the paths of the tendons, ligaments, and fascia. The complete model results in 300000 nodes. Mechanical properties of tissues were, for a part of them, taken from the literature. These properties, are for a set of materials, direct expressions of mechanical models (for example Young's modulus or Poisson's ratio for linear models), or where extracted from stress-strain literature relationships, using established formulations of potentials, such as Ogden or polynomial representations. In order to drive the model using experimentally-derived muscle forces, 9 tendons were included in the FE foot model. These tendons consisted in linear elements. The boundary conditions of the EMG-Driven Finite Elements model were obtained experimentally and consisted in the initial foot velocity before ground contact, initial velocity of the centre of mass element, and the angle between the foot sole and the ground at contact. These conditions were obtained directly from the experimental data acquisition phase. Simulations were run for different types of shoes in order to assess their influence on the resulting foot tissue loading.

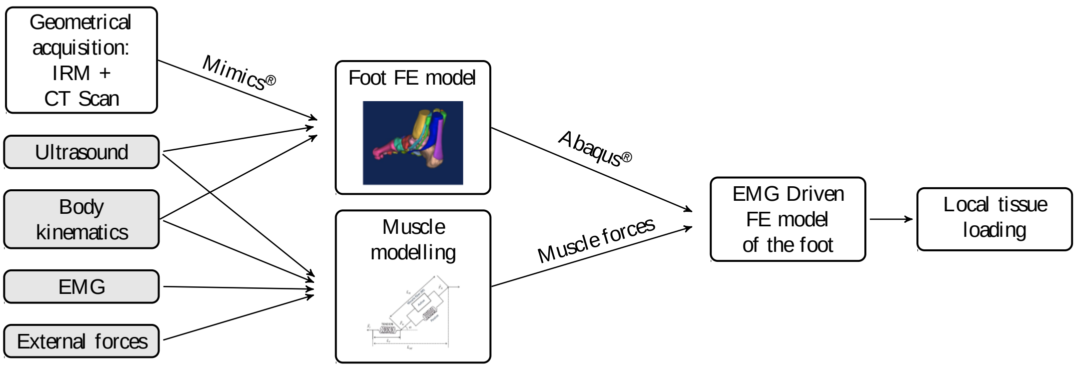

Figure 1: Complete process of model building, including the finite elements part and the tendon forces estimations.

RESULTS: No difference emerged on the net joint torques and muscular activations when comparing the running shoes. Kinematics differences were reported when comparing the barefoot condition with the two shod ones, with a flatter foot at impact and a higher ankle joint amplitude during the whole stance phase. While no difference were present on the individual muscle forces, the amplitude of fiber length of the MG and LG muscles during the stance phase showed a significant effect of the footwear factor. Indeed, lower amplitudes of fiber length were reported for the MG muscle in Bare condition (2.16±0.54cm) relative to the 00mm (2.83±0.29cm) and 16mm (2.72±0.54cm) conditions. Similarly, the LG muscle showed significantly reduced fiber length amplitude for Bare compared to 00mm and 16mm conditions (2.38±0.78cm, 2.92±0.31cm, and 2.83±0.31cm, respectively). Contrary to the MG and LG muscles, the Soleus muscle showed similar amplitudes for all the footwear conditions (2.04±0.94cm, 2.03±0.64cm, and 1.93±0.65cm respectively for 00mm, 16mm, and Bare conditions).

The output of the EMG-Driven finite elements model of the shod foot gave access to local tissue loading data that are almost impossible to measure experimentally (Figure 2). These data can further be used to enhance the running shoe features in order to prevent high contact pressure and/or localized elevated bone motion.

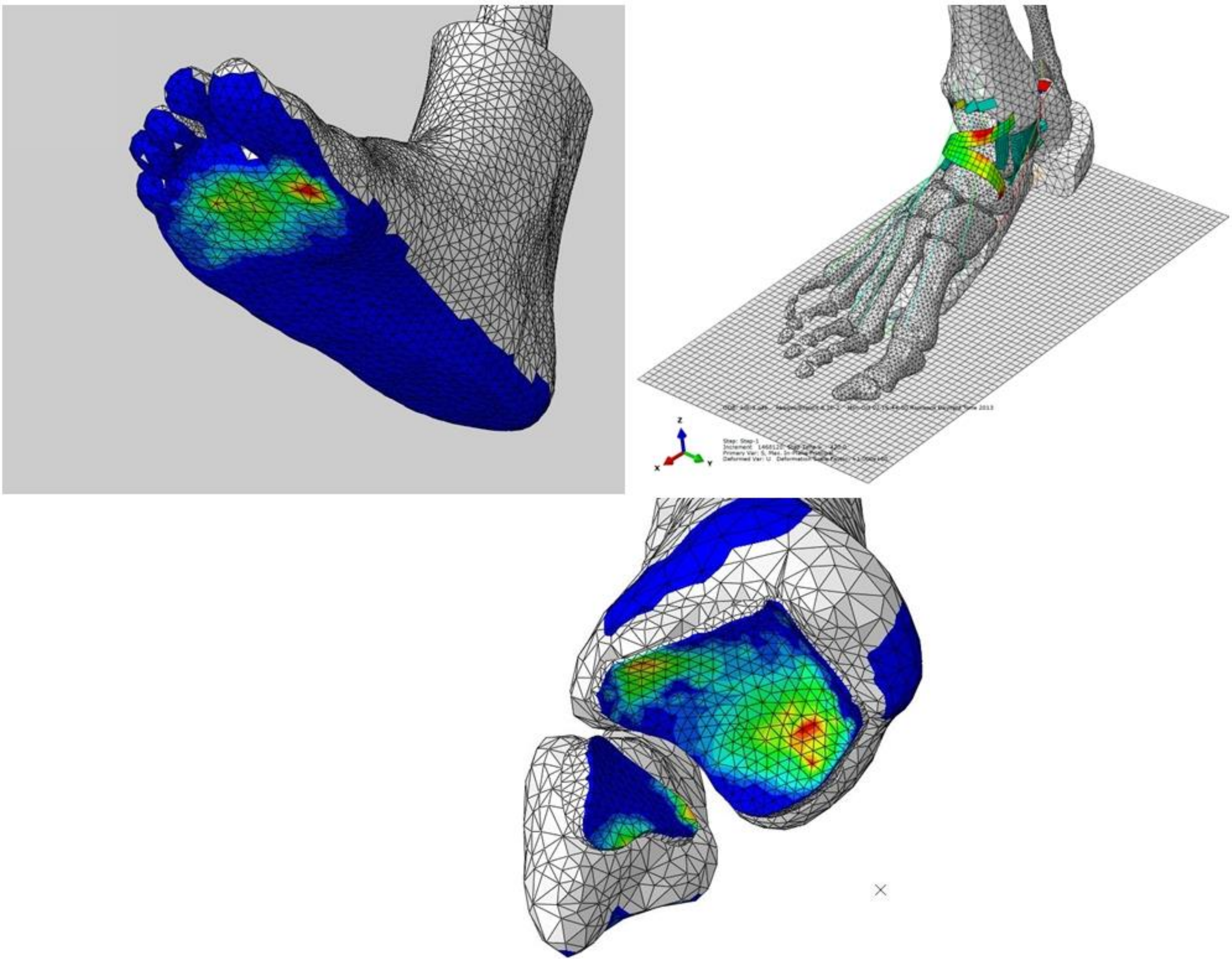

Figure 2: Examples of field data that can be extracted from the model, during a running cycle, foot contact pressure (top left, blue = 0 MPa, red = 0.5 MPa), in plane principal stress on the ligaments (top right, blue = 0 MPa, red = 60 MPa), tibia cartilage contact pressure (bottom, blue = 0 MPa, red = 13 MPa).

DISCUSSION: Interestingly, while few difference emerged on the classical motion analysis related variables (kinematics, ground reaction forces, EMG), the outputs from the EMG-Driven musculoskeletal model showed that the muscle fibre behaviour was affected by the height of the running shoe midsole. Indeed while running barefoot, the tendinous structures of the biarticular calf muscles (Medial and Lateral Gastrocnemius) were more stretched as revealed by an increased range of motion at the ankle joint and a decreased fiber length

amplitude. Hence, wearing a shoe can deeply modify the way the different anatomical structures interact. These data could only have been revealed by using such types of musculo-skeletal models that combine as much experimental data available as possible.
The second part of the presentation will focus on the outputs of the EMG-Driven finite elements model of the shod foot in order to improve the running shoes features while keeping the human body as safe as possible without deteriorating the running performance.

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