GENERATION OF A SUBJECT-SPECIFIC, DYNAMIC FOOT MODEL TO IMPROVE FOOT AND ANKLE SURGERY : A PROTOCOL

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ABSTRACT

In daily practice, common methods of assessment in patients suffering from foot and pathologies are observation, anamnesis, clinical assessment, medical imaging and in rare cases, gait analysis. Based on the results of this plethora of tests, orthopaedic (or foot and ankle) surgeons use a variety of treatments with respect to the latest evidence-based recommendations in conjunction with their clinical expertise to restore and maintain proper bony alignment and muscle balance. Despite the strict application of evidence-based interventions that emerge from science to clinical practice, our current treatment approach does not guarantee the complete resolution of our patient's symptoms. A growing body of evidence pointed out the existence of anatomical foot variations in terms of joint surfaces and geometries, muscle insertions, presence of accessory muscles or ligaments, ligament insertions and their potential impact on the mechanical behaviour of the foot and the lower limb. Therefore, rather than continue to apply a poorly founded treatment model of foot type whose basis is to make all feet criteria for the anatomical / radiological 'ideal' or 'normal' foot, clinicians should incorporate anatomical variation between feet and identify the patient's proper mechanics.

Therefore, Digital Orthopaedics has initiated the preliminary development of a subject-specific computational model of the human foot incorporating clinical reasoning and expertise in clinical decision making in the field of foot and ankle surgery. This platform integrates SIMULIA technologies (Simpack, Abaqus, Isight) deployed on the Dassault-Système's 3DEXPERIENCE platform providing orthopaedic surgeons efficient, outcome-driven and patient-specific diagnostic and treatment tools to deliver effective patient-care.

INTRODUCTION

It is well known that most of the current studies available to support clinical care in foot and ankle pathologies are low-level studies.(Zaidi et al., 2012) The nature of foot and ankle as a subspecialty offers a variety of reasons why this may be the case. First, in comparison to the other main joints of the lower limb, the foot and ankle is a highly complex structure composed of 26 bones, 34 synovial joints, hundreds of ligaments and muscles.(Nester, 2009) The foot further differs from the rest of the body as its plantar surface is uniquely responsible for transmitting forces from the ground to the body. Secondly, unlike many other musculoskeletal subdisciplines (or orthopaedic subdisciplines) there are numerous distinct individual pathologies affecting the foot and ankle. Lastly, the assessment of foot motor performance has been impeded for decades because of the simplified representation of foot as an unique functional entity.(Davis, 2004) The development of three-dimensional multi-segment foot models partially tackled this major shortcoming and showed their clinical value for the detection of intrinsic foot impairments.(Deschamps et al., 2011) However, these foot models are still a simplified representation of the foot where several bones are combined to a defined number of functional segments.

In daily practice, common methods of assessment in patients suffering from foot and pathologies are observation, anamnesis, clinical assessment, medical imaging and in rare cases on gait analysis. Based on the results of this plethora of tests, orthopaedic surgeons define a set of variety of treatments (surgical or conservative) with respect to the latest evidence-based recommendations in conjunction with their clinical expertise to restore and maintain proper bony alignment and muscle balance. Despite the strict application of evidence-based interventions that emerge from science to clinical practice, our current treatment approach does not guarantee the complete resolution of our patient's symptoms and functional limitations.(Canseco et al., 2012, 2011, 2009; Kernozek and Sterriker, 2002; Schuh et al., 2009; Wang et al., 2010) Inter-subject anatomical heterogeneity is one of the main reason why this may be the case and thus precludes one-type-treatment-suits-all approach to treat foot and lower limb diseases. A growing body of evidence pointed out the existence of anatomical foot variations in terms of joint surfaces and geometries, muscle insertions, presence of accessory muscles or ligaments, ligament insertions and their potential impact on the mechanical behaviour of the foot and the lower limb.(Alonso-Vázquez et al., 2009; Bonnel et al., 2013, 2011; Guiotto et al., 2013) This further supports the "one-type-treatment-suits-all" approach could potentially induce different contact pressure at the joints due to the large existence of inter-subject anatomical heterogeneity. Therefore, rather than continue to apply a poorly founded surgical / conservative model of foot type whose basis is to make all feet criteria for the anatomical / radiological 'ideal' or 'normal' foot, clinicians should incorporate anatomical variation between feet and identify patient's proper mechanical ideal. Significant inter-subject anatomical variation exists and question any surgical and/or conservative notion that is based on the concept of a single ideal anatomical / radiological foot type and alignment.

Due to the anatomic complexity of foot and the technical limitations of current external measurement systems used to understand the role of each internal structure of the foot during activities of the daily living, the foot and ankle with respect to the lower limb must be simulated to understand their function and how mechanical stresses are distributed in their bones and soft tissues. Several computational models of the foot and ankle were developed to provide foot and ankle specialists valuable information regarding mechanical pathogenesis of the lower limb and potential biomechanical predictions of their planned treatment (conservative or surgical). In contrast to current state-of-the-art instrumentation for measuring foot and lower limb biomechanics, these models can estimate the stress distribution in the bones and soft tissue and the contact pressure at the joints.(Wang et al., 2015) Once these models have been validated, they have the potential to explore different procedures (conservative and/or surgical) and predictably shed light predictively on post-treatment outcome.

Currently, there exists several computational simulations for predicting and evaluating the biomechanical behaviour of the foot during activities of the daily living.(Behforootan et al., 2017; Morales-Orcajo et al., 2016) However, the actual clinical contribution of computational foot modelling for the improvement of the therapeutic outcome of patients suffering from foot and ankle pathologies is relatively limited. Today's key challenges towards clinically applicable computational foot modelling are to implement clinically meaningful information, to accurately reconstruct the patient's foot and ankle in a non-labour intensive way, to minimise time-consuming computation procedure, to remove the barriers in the interpretation of complex biomechanical data and to tackle the poor verification and validation of current foot and ankle models with satisfactory levels of accuracy.

Therefore, in the search for better outcome measures and thereby improving patient care, Digital Orthopaedics has initiated the preliminary development and set up of a subject-specific computational model of the human foot incorporating clinical reasoning and expertise in clinical decision making in the field of foot and ankle surgery. This platform integrates Dassault-Systèmes SIMULIA technologies (Simpack, Abaqus, Isight) and clinically oriented data management providing orthopaedic surgeons efficient, outcome-driven and patient-specific diagnostic and treatment tools to deliver effective patient-care. The present paper describes a workflow that has been developed by Digital Orthopaedics to generate the biomechanical and anatomical data required to produce a subject-specific computational foot and ankle model.

METHODS AND DESIGN

Subject

One male healthy adult volunteer (age 34 years, height 1,70m, weight 75kg, BMI 25,95 kg/m2, shoe size 42) will be recruited. A participant will be considered healthy and included if he 1) is able to walk barefooted independently, without support, 2) has no history of major trauma and/ or surgery of the lower limb, or 3) presents no systemic or neurological disorder involving the musculoskeletal system directly.

Imaging studies :

Computed Tomography (CT)

A computed tomography (CT) scan of the right leg (shank and foot) of a healthy subject will be performed in an unloaded condition. The subject will be positioned with the right foot approximately 90° to the leg in a customized boot. The following parameters will be used to acquire the scan on a Siemens slice scanner (Siemens, Munich, Germany) at the Clinique du Parc Léopold (Brussels, Belgium): 130 kVp, 0,6mm effective slice thickness, 512x512 matrix.

Magnetic Resonance Imaging (MRI)

Due to the limitations of soft tissue information that can be provide from the CT-scan, the subject will also have a MRI taken from his right foot. This will take place on a different day to the rest of the testing. For the MRI, the foot will be placed in a suitable imaging foam padding placed around the foot and the leg to prevent movement during the scan. MRI images will be acquired using Optima MR450w (GE Medical Systems). Three scans (T1,T2 and DP FAT SAT) will be taken in total covering the full foot and ankle with the following scanning parameters : 0,8mm slice thickness and 512x512 matrix. MRI will be used for the identification of soft tissue insertion and via points.

Gait analysis

Gait analysis will be performed in the Laboratory for Clinical Motion Analysis of the Foot & Ankle Institute (Brussels, Belgium) using an advanced clinical examination platform. It is composed of a passive motion capture system, a plantar pressure platform and a force platform to obtain the simultaneous assessment of kinematics, kinetics, and plantar pressure measurements of each subject. This platform can provide further insight into the biomechanics of the foot and the lower limb.(Giacomozzi et al., 2014, 2000; MacWilliams et al., 2003; Sawacha et al., 2012)

The motion analysis system (MAS) (Qualysis, Sweden) is composed of 8 Miqus cameras in order to track the kinematic data (200Hz) of all participants while walking over a 10 meter walkway at a self-selected speed.(Caravaggi et al., 2010) Residual errors of < 1mm are deemed acceptable for the system.(Oosterwaal et al., 2011)

In the middle of the aforementioned walkway, a Footscan® pressure plate (dimensions 0.5m x 0.4m, 4096 sensors, 2.8 sensors per cm2, RSscan International, Paal, Belgium) is mounted on a custom made AMTI-force plate (dimensions 0.5 x 0.4m, Advanced Mechanical Technology, Inc., Watertown, MA, US). The current set-up allows the detection of specific gait events as well as for a continuous calibration of the pressure plate with the force plate using a Footscan® 3D interface box (RSscan International, Paal, Belgium). Data from the pressure and force platforms are measured at a sampling rate of 200Hz. The adequate integration and synchronization of the different hardware devices will be achieved by connecting all the hardware devices with the synchronisation unit (Qualysis, Sweden). Data from the pressure, force plate and MAS will be measured at a sampling rate of 200Hz.

Surface electromyographic signals (sEMG) will be collected from the tibialis anterior, peroneus longus, medial gastrocnemius and soleus muscles on both sides by means of a 16 channel wireless Zerowire system (Cometa, Italy) at a sample rate of 1500Hz.

Forty-two retro-reflective markers will be mounted over the described anatomical landmarks according to the 3D Multi-Segment Foot Model of Leardini et al. (2007)(A. Leardini et al., 2007) and of the 3D Lower Limb Model of Leardini et al. (2007).(Alberto Leardini et al., 2007) The skin markers will be attached over the anatomical landmarks using double-sided adhesive tape. After maker placement, two standing trials will be recorded in a relaxed standing position. After checking for a successful acquisition of all marker positions in static way, the participants will be asked to walk barefoot, walking at a self-selected speed until five valid trials are recorded.(Schwartz et al., 2004) A trial will be considered valid when the following criteria are met: walking speed within the outlined boundaries, no visual adjustment in gait pattern to contact the pressure plate and a clear pedobarograph contact with the foot.(Willems et al., 2006)

Data processing

Imaging data

CT-scan data will be segmented into the individual bones of the foot using ScanIP (Simpleware, Exeter, UK) image processing software. The same software will be used to create the surfaces and volume meshes of the bones. Based on the subject-specific imaging data and data from the literature,(Kelikian and Sarrafian, 2011) individual soft tissues of the foot will be segmented using ScanIP (Simpleware, Exeter, UK) image processing software. Soft-tissue segmentation is divided in two phases: first reconstruction of skin, muscle, heel pad and plantar pad volumes from literature(Kelikian and Sarrafian, 2011) and adapted to the current patient-specific model; a second reconstruction of ligaments and tendons insertion and reflection point coordinates from the MRI and from literature(Kelikian and Sarrafian, 2011) and adapted to the current patient-specific model. Fourteen anatomical landmarks on the patient's CT-scan will be placed by the clinician over the described anatomical landmarks according to the 3D Multi-Segment Foot Model of Leardini et al. (2007)(A. Leardini et al., 2007). Their respective coordinates will be used afterwards in the multi-body model.

Motion capture data

The kinematic data, the kinetic data, surface EMG data will be processed by using Visual3D (C-Motion, Germantown, US) software and saved in the C3Dformat.

Three-dimensional rotation angles and planar angles and joint moments will be calculated according to the 3D Multi-Segment Foot Model of Leardini et al. (2007)(A. Leardini et al., 2007) and of the 3D Lower Limb Model of Leardini et al. (2007)(Alberto Leardini et al., 2007) using Visual 3D (C-Motion, Germantown, MD, US). Inter-segment 3D rotations will be calculated following ISB recommendations.(A. Leardini et al., 2007; Wu et al., 2002)

Plantar pressure data

The plantar pressure data will be processed by using Footscan 7.97 (RsScan International, Paal, Belgium) and saved in the ASCII-format. The semi-automatic total mapping procedure (SATM) will consist of determining ten anatomical pressure areas, called region of interest (RoI) on the peak-pressure footprint. These RoI are medial heel (HM), lateral heel (HL), midfoot (MF), metatarsal heads I to V (M1 to M5) and the hallux (T1). The RoI will be determined by using the free-mapping method of the total mapping technique. It involves the manual circumscription of RoI using graphical tools of the Footscan® 7.97 software (RSscan International, Olen, Belgium). The protocol for each SATM of each peak-pressure footprint will consist of (Kevin Deschamps et al., 2013): 1) positioning a pre-determined foot last, 2) delimitation of the complete forefoot and toe regions using the aforementioned graphical tools, 3) manual adjustment of the pre-established vertical oriented lines in order to determine the five metatarsals RoI, 4) manual adjustment at a sensor level to fine-tune the limits of the RoI.

Plantar pressure variables (e.g. peak pressure, average pressure, force-time related ratios, ground reaction forces and total contact area) for each RoI of the peak pressure footprint will be calculated within Python with the program made by the consortium of authors.

Gait events and subphases

The adequate integration and synchronization of the plantar pressure plate with the MAS and the force platform will allow the detection of subject specific gait events.(De Cock et al., 2005; K Deschamps et al., 2013)

The stance phase will be divided in three sub-phases:

- Forefoot Contact Phase (FCP) starts with the First Foot Contact (FFC) and ends when all the metatarsal heads are in contact with the ground.
- Foot Flat Phase (FFP) is the time between the Forefoot flat (FFF) and Heel Off (HO).
- Forefoot Push Off Phase (FFPOP) is defined as the duration between Heel Off and Last Foot Contact (LFC).

The division of the stance phase into the sub-phases described in the current study is based on studies of De Cock et al. (2005)(De Cock et al., 2005) and Deschamps et al. (2013)(K Deschamps et al., 2013) and referred to the evolution of the plantar pressure distribution during roll-over. The time between the gait events First Foot Contact and Last Foot Contact will be used to define the stance phase, whereas the duration between the gait events Last Foot Contact and the Second Heel Strike (collected with the motion capture system) will be used to define the swing phase. The complete gait cycle will be defined as the duration between the First Foot Contact and the Second Heel Strike.

Model creation (Finite element and Multi-body)

Multi-body model (MBS)

The main purpose of the multibody model is to reconstruct the patient-specific muscular activation scheme which will serve as input for the finite element model. Using all the information previously described, a multi-body model will be automatically generated using an in-house Python script. A 23 degrees of freedom 3D multi-body model (MBS) will be created in Simpack (Dassault Systèmes, France) based on the CT-scan and the MRI of the subject. MBS model includes all intrinsic foot joints, nine extrinsic foot muscles ((Tibialis Anterior, Tibialis Posterior, Peroneus Brevis, Peroneus Longus, Achilles tendon, Extensor Hallucis Longus, Extensor Digitorum Longus, Flexor Hallucis Longus, Flexor Digitorum Longus) and all foot ligaments. The joints or kinematic links between the bones of the foot and the ankle will be simulated using a combination of revolute (one rotation allowed), universal (two rotations allowed) and spherical (three rotations allowed) joints. The number of rotations allowed per joint will be based on previous kinematic 3D multi-segment foot models and results of bone pine studies.(a Leardini et al., 2007; Lundgren et al., 2008; Nester et al., 2007, 2014; Westblad et al., 2002) The interaction between the ground and the skin will be simulated using independent discrete contact elements attached to each element of a triangular mesh of the foot surface. The contact elements will be modeled as spring-damper system.(Aerts et al., 2017) Muscles and ligaments will be represented using connectors between the origin, via points (for the muscles) and insertion. Material properties will be assigned for each element from the literature.(Athanasiou et al., 1995; Behforootan et al., 2017; Lemmon et al., 1996; Morales-Orcajo et al., 2016; Pai and Ledoux, 2012; Siegler et al., 1988) A forward dynamic gait simulation will be generated by combining Simpack and Isight (Dassault Systèmes, France) based on 3D motion capture data (markers and ground reaction forces) and used to reconstruct the patient-specific muscular activation scheme. The orientation of the foot from the pro-active phase just before heel strike obtained from experimental data will be used as initial condition of the model.

Finite element model (FE)

Using all the information previously described, a finite element model will be automatically generated using an in-house Python script. Material properties will be assigned for each element from the literature.(Athanasiou et al., 1995; Behforootan et al., 2017; Lemmon et al., 1996; Morales-Orcajo et al., 2016; Pai and Ledoux, 2012; Siegler et al., 1988) Muscle insertions will be identified using the subject-specific MRI and data from the literature.(Kelikian and Sarrafian, 2011) Muscles and ligaments will be represented using connectors between the origin, via points and insertion. The same nine extrinsic muscles as described in the MBS model will be implemented in the FE model. The patient-specific muscular activation scheme identified in the MBS simulation will be used as input for the FE model. The plantar fascia will be represented by multiple connectors to evenly spread the loads.

Validation

Initial validation of the multibody model will be carried out by comparing predicted and measured (via surface EMG) muscle timings. Formal validation of both models will be carried out by comparing plantar pressure measurements (e.g. peak pressure, average pressure, force-time related ratios, ground reaction forces and total contact area) taken during the stance phase to those predicted by the model. Comparison of the plantar pressure data between the experimental and the simulation will be performed for each region of interest of the peak pressure footprint.

CONCLUSION

An innovative aspect of this project is the preliminary development and set up of a subject-specific computational model of the human foot incorporating clinical reasoning and expertise in clinical decision making to improve the insight in foot and ankle pathologies and the functional impact of their surgical treatments. Even though recently developed advanced clinical examination platforms integrating 3D multi-segment foot kinematics, kinetics and plantar pressure measurement showed their clinical value for the detection of intrinsic foot mobility impairments,(Deschamps et al., 2011) these platforms are unable to perform direct measurements of detailed internal foot loading conditions such as stress distributions within bones and soft tissues or the contact pressures at the foot joints.(Behforootan et al., 2017; Morales-Orcajo et al., 2016) Therefore, it is believed that proposed approach has the potential to provide a broader and more meaningful picture of the functional health of patients treated surgically for foot and ankle pathologies, which can then be used for decision-making purposes and consequently result in an improved evidence-based clinical practice. It is well known that most of the current studies available to support clinical care in orthopaedic foot and ankle surgery are low-level studies.(Zaidi et al., 2012) The nature of foot and ankle as a subspecialty offers a variety of reasons why this may be the case. First, unlike many other disciplines there are numerous distinct individual pathologies affecting the foot and ankle. Secondly, the gathering of information from the patient is performed with non-validated outcome measures to analyse foot and lower limb function.(Madeley et al., 2012) These factors result in a large number of low level of evidence studies which limits our ability to generate a high-grade treatment recommendation for foot and ankle disorders.(Zaidi et al., 2012) Therefore, the current project tackles these challenges by developing subject-specific computational model of the human foot incorporating clinical reasoning and expertise in clinical decision making. Such a platform could provide a novel, valid, reliable and responsive tool which has the potential to make significant advancements in evidence-based medicine, and thus leading to better clinical decision making and more predictable patient care.

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