Modelling musculoskeletal mechanisms

Professor Dr Nico Verdonschot, Project Coordinator of the TLEMsafe project, discusses the innovative patient-specific surgical navigation system used for pre-operative planning and execution of complex musculoskeletal surgery.

The objective of TLEMsafe is to integrate this musculoskeletal model with the MRI of a patient to simulate the surgery and thus predict functional recovery. Similar technology can be used today to calculate anterior cruciate ligament reconstruction or a meniscus surgery. These are smaller interventions, but for cases involving substantial tumours or a prosthesis implant, the problem becomes much more severe. In these cases, it is difficult for the surgeon to accurately plan and estimate the surgery and recovery respectively.

For example, a patient may suffer from a tumour located in the knee and is advised the tumour be resected. Until now, surgeons have been unable to accurately determine how much of the surrounding muscle tissue and bone can be safely removed while maintaining the functionality of the leg, or even if the leg should be amputated. The surgeon will of course exhaust every avenue in an attempt to prevent amputation and will likely recommend an implant. Problems can arise, however, as the implants are very susceptible to infections or, as is sometimes the case, the leg becomes non-functional. TLEMsafe aims to avoid this and increase the chance of performing limb-salvage surgery by improving the safety and predictability of complex musculoskeletal surgery using a patient-specific navigation system.
REALISING SUCCESS

WE HAVE DEVELOPED a method to semi-automatically generate a personalised musculoskeletal model of an individual from an MRI scan – this in itself is a huge achievement. We have also generated a preplanning tool that allows a surgeon to perform a virtual surgery on a personalised model of the patient prior actually entering the operating theatre.

Personalising the model of the patient creates a much more realistic behavioural representation. We initially used simple scaling methods, but this method forced us to make breadth of general assumptions. Using this newly developed model we now have a better understanding of the muscular system.

Lastly, we have also developed a complex method to measure the muscle metabolism using volumetric glucose consumption. We modelled this by injecting the patient with 18F-fluorodeoxyglucose, asking the patient to perform a walking exercise, and using a PET scan to measure muscle energy consumption in terms of glucose metabolism. We are the first in the world to do this, and I am very proud. Due to 3D mapping, we can accurately determine which muscles consume energy, and exactly how much. This is our most significant achievement towards the validation of these musculoskeletal model predictions.

TLEMSafe provides a basis for further work in surgical navigation, as well as pushing surgery further towards the personalised approaches that the field must take in order to improve practice in this area. For example, the current procedure for muscle transfer calls for surgeons to use their experience in determining the best site for reattachment; no suitable model exists to help them. While this approach is perfectly adequate in the majority of cases, the musculoskeletal system is very complex, and patients in need of major surgical interventions are therefore put at risk by procedures which are uncertain in outcome and have a high complication rate. What is required to turn this situation around is an accurate musculoskeletal model that can predict how the patient will react and adapt to the surgery. To build such an accurate model, it must be personalised to reflect exactly the unique characteristics of the patient in question.

Thankfully, a prescient team of researchers based at the University of Twente in The Netherlands identified this need more than three years ago and has already gone a long way towards creating a revolutionary solution. With partners at the neighbouring Radboud University Medical Center, as well as international collaborators in Poland, Germany, Belgium and Denmark, the group is working towards creating a functional prototype of a new patient-specific modelling and surgical navigation system.

TLEMSafe combines the unique Twente Lower Extremity Model (TLEM) with an ICT-based system that will provide several functionalities to help surgeons. With its €3 million, four-year funding period coming to an end, the group is close to completing this fantastic prototype – though still a research based tool, it represents a peek into a new chapter of orthopaedic history, where musculoskeletal modelling and advanced medical information technologies guides the surgeon planning and carrying out the optimal surgery intervention.

FORM AND FUNCTION

A multinational consortium led by researchers at the University of Twente in The Netherlands is approaching completion of a revolutionary new surgical navigation system for orthopaedic operations.

ORTHOPAEDICS HAS ONE of the most varied and interesting histories of all medical fields; even its name, which is derived from the Greek words ‘orthos’ for ‘to straighten or correct’ and ‘paidion’ meaning ‘child’, seems enigmatic at first. The term was in fact coined by Nicholas Andry in his 1741 work The Art of Correcting Spinal Deformities in Children – although it would be almost 40 years before the first hospital to treat skeletal deformities in children was established. Interest in musculoskeletal deformity and its treatment first began to take hold during the late 17th Century, but other areas of medicine that we now consider orthopaedic had been under investigation for much longer. The treatment of wounds sustained in battle, for example, was one focus of Hippocrates – who observed that a shortened arm would make little difference to a soldier, whereas a shortened leg would leave him maimed.

Today, orthopaedics has begun a new and no less fascinating chapter in its history; as improved access to higher quality medical treatment increases life expectancy all over the world, so our population ages, placing greater importance on orthopaedic treatment. The musculoskeletal system is a mechanical one, and like all mechanisms, it has a certain lifespan built into it – a lifespan that we are, in some cases, beginning to exceed. The excessive wearing of cartilage, wasting of muscles and weakening of bones associated with ageing all call for orthopaedic attention and often demand surgical operations, such as joint replacement, fracture repair and spinal surgery. As a result, the demand for this type of surgery is increasing as quickly as the average life expectancy.

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Based on this record demand, there is a pressing need to address the shortcomings of surgical
INNOVATION INTERNATIONAL

or prosthesis implants. Subsequently, in order to suggest optimal sites for muscle reattachment of different surgical options, and the ability to predictive utility detailing the functional effects virtual operations on the patient model, a TLEM safe to mechanical operation. Based on this insight, the opportunity to accurately link morphology system provides surgeons for the first time with the functional capabilities of the patient, the By matching the musculoskeletal map with various speeds, ascending and descending stairs simulating daily activities such as walking at a patient-specific model capable of accurately scanning bone contours, joint geometry, muscle volumes and muscle attachment sites. As a third step, all these data are integrated to create a patient-specific model capable of accurately simulating daily activities such as walking at various speeds; ascending and descending stairs or sitting down.

By matching the musculoskeletal map with the functional capabilities of the patient, the system provides surgeons for the first time with the opportunity to accurately link morphology to mechanical operation. Based on this insight, TLEMsafe offers medics the facility to conduct virtual operations on the patient model, a predictive utility detailing the functional effects of different surgical options, and the ability to suggest optimal sites for muscle reattachment or prosthesis implants. Subsequently, in order to provide the surgeon with maximum continuity between planning and operation, TLEMsafe includes an integrated surgical navigation system for use during the final surgery, so that the planned intervention is exactly reproduced and finally the optimal functional result for the patient is reached.

A STRONG START

The TLEMsafe team has not yet completed work on its functional prototype, which will need to be clinically validated before it can be made available. But in the three years that the researchers have worked on the project, they have made some impressive headway. The first year of the project began with pilot MRI scans of three healthy subjects and one orthopaedic patient, to be used as test targets for the development by Belgian partner Materialise of software capable of extracting personalised parameters from MRI. This information was then coupled with the modelling system provided by Danish collaborator, AnyBody Technology, in order to build personalised musculoskeletal models. Once this had been achieved, the research group at the University of Twente performed an extensive sensitivity analysis to assess which musculoskeletal parameters are key to the process of walking – and when these parameters had been identified, it was possible to define an optimal strategy for obtaining personalised models in a fast and reliable way. Finally, in collaboration with the Warsaw University of Technology, Poland, the team generated a virtual toolbox for the pre-planning component of the system, allowing the surgeon to operate on a virtual patient; this toolbox then had to be made compatible with the patient-specific model and its output coupled with the computer navigation system provided by German partner, Brainlab.

Year two was equally busy for the team. The complete measurements of 10 healthy subjects – which included MRI and PET/CT scans according to developed protocol, functional analysis and strength measurements – were finalised at the Radboud University Medical Center, and development of software to automatically determine muscle volumes and attachment sites from MRI data was pursued. Once completed, these algorithms were then validated using measurements from specific cadaver segmentations. It was only then that the team began to see the fruits of their labour for the first time, as initial results began to show how a patient-specific approach could improve predictive capacity of the TLEM model. It was also during this year that the researchers began to involve the end-users – surgeons – in their process, designing special pre-planning software and output formats to make the biomechanical analyses provided by the system clinically relevant and comprehensive from a surgical viewpoint.

A RECORD YEAR

In the last year, TLEMsafe has come into its own. An updated version of TLEM was developed, which represents the first consistent lower extremity model including accurate musculoskeletal geometry and medical imaging data, and the new version was successfully incorporated into the TLEMsafe workflow. The Functional Outcome and Evaluation Tool (FOET) – an all-important component that quantifies the effects of surgery on the virtual patient and provides comparison between post-operative, pre-operative and healthy subject states – was further developed with the help of experienced surgeons, who ensured the vast technical output of the model is translated into useful information for the surgeon, both clinically relevant and user-friendly.

Another aspect that met with great approval from surgeons was the prototype surgeon-model virtual reality system, Surgery Planning Environment 3D.
TLEMsafe aims to create a patient-specific surgical navigation system based on innovative ICT tools, for training, pre-operative planning and execution of complex musculo-skeletal surgery. It is intended to help the surgeon safely reach the optimal functional result for the patient and will serve as user-friendly training for surgeons.

KEY COLLABORATORS

Vincenzo Carbone, Project Manager

PARTNERS

University of Twente, The Netherlands
Radboud University Medical Centre, The Netherlands
Warsaw University of Technology, Poland
Materialise NV, Belgium
AnyBody Technology A/S, Denmark
Brainlab AG, Germany

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CONTACT

Professor Dr Ir Nico Verdonschot
Project Coordinator
Laboratory of Biomechanical Engineering
Faculty of Engineering Technology
MIRA Institute
University of Twente
PO Box 217
7500 AE Enschede
The Netherlands
T +31 53 489 4362
E n.verdonschot@utwente.nl

www.tlemsafe.eu

NICO VERDONSCHOT received a MSc in (Bio-)Mechanical Engineering from the University of Twente, and obtained his PhD degree at the Orthopaedic Research Lab of the Radboud University Medical Center, where he was involved in a number of projects focusing on the testing of orthopaedic implants. He is currently the coordinator of the EC FP7 TLEMsafe project, and in December 2012 obtained a five year ERC Advance Grant enabling the expansion of the project’s work on the personalised modelling of the lower extremity.

INTERNATIONAL LINKS

The TLEMsafe project has been very successful in meeting its goals over a relatively short timespan, but the team at the University of Twente and Radboud University Medical Center could not have come so far on their own. Their wide-ranging collaborations with project partners outside The Netherlands have been part of the secret to their success.

Warsaw University of Technology, Poland – over the last year of operations, collaborators at the Warsaw University of Technology have been responsible for developing knowledge and software for 4D imaging of the human body for use in the data collection process, as well as developing the virtual reality interface, Surgery Planning Environment 3D (SPE3D) to be used in TLEMsafe

Materialise NV, Belgium – Materialise NV is a company concerned with 3D printing, and computer-aided design and medical image processing software. Their expertise made them the ideal candidate to develop software tools to extract the maximum information from 3D medical image data, using segmentation and morphing tools to determine patient-specific muscle volumes and attachment points

AnyBody Technology A/S, Denmark – AnyBody Technology A/S has been active in the field of orthopaedics for a long time and is responsible for the development of one of the leading software systems for simulating the mechanics of the live human body – a great asset to the project

Brainlab AG, Germany – Brainlab AG specialises in the development, manufacture and marketing of medical technology. In the TLEMsafe project they were responsible for the surgical navigation portion of the system

(SPE3D). SPE3D was subsequently interfaced with the surgical navigation system. The crowning achievement, however, has been the fact that this year all the different steps of the TLEMsafe patient workflow were connected to each other and validated in concert – which means that it is now possible, using an MRI scan of a patient, to generate a musculoskeletal model specific to that patient, perform a series of virtual surgeries and predict functional effects; resulting in an optimal procedural plan, which can be exactly reproduced at the operating table.

REAPING THE REWARDS

The TLEMsafe project has come together very neatly in a relatively short space of time. Of course, there is still a year to go until the prototype is slated for completion – and delays early in the project have meant that an increased duration of around six months may be necessary. However, this is still a brief timeframe for a project set to reap such remarkable rewards.

And these rewards do not lie simply in an improved quality of life for patients, fewer surgical complications and a reduced burden of healthcare to society – there are impacts for the practice of surgery too. TLEMsafe provides a basis for further work in surgical navigation, as well as pushing surgery further towards the personalised approaches that the field must take in order to improve. The additional patient information provided by the system will also allow for the use of more advanced robotic tools during operations, and open up routes to less invasive, more precise surgery. It may even inspire altogether new practices in medicine.