IMAGE-BASED MEASUREMENT AND BIOMECHANICAL ANALYSIS OF THE KNEE JOINT DURING FUNCTIONAL ACTIVITIES

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A new approach based on the integration of medical image-based measurement techniques, infrared stereophotogrammetry and finite element modelling (FEM) was developed for comprehensive subject-specific biomechanical analyses of the knee joint during weight-bearing functional activities including cycling. The medical image-based methods include digitally reconstructed radiograph (DRR) based 3D fluoroscopy methods, and a new slice-to-volume registration method using FLASH MRI for the real-time measurement of the 3D kinematics of the knee *in vivo*. With the new approach, the soft tissue artefacts associated with skin marker-based stereophotogrammetry and their effects on the calculated biomechanical variables were also investigated.

KEY WORDS: knee, kinematics, fluoroscopy, finite element modelling, MRI.

INTRODUCTION: The knee is one of the most commonly injured joints, making up about 55% of all sports injuries. Knowledge of the kinematic and force interactions between the force-bearing structures of the knee, including the articular surfaces, ligaments and muscles, during multi-joint functional activities is essential for a better understanding of the normal function of the joint and the mechanisms of injuries and diseases, as well as for the planning and evaluation of subsequent treatment. Skin maker-based stereophotogrammetry has been widely used in measuring inter-segmental motions and loads of human movement. However, such techniques are prone to soft tissue artefacts (STA) (Cappozzo et al., 1996; Tsai et al., 2009), which have significant effects on the calculated biomechanical variables (Tsai et al, 2011; Kuo et al., 2011). The detailed kinematics of the articular surfaces and the surrounding tissues cannot be measured simultaneously either. These limitations in measurements all contribute to the unsatisfactory predictions of the internal forces in the joint. Therefore, study of the force interactions within the knee *in vivo* remains a great challenge.

To bridge the gap, single-plane and bi-plane fluoroscopy-to-CT registration methods based on digitally reconstructed radiographs (DRR) and a similarity measure called Weighted Edge-Matching Score (WEMS) have been developed in our group for measuring 3D poses of the bone *in vivo* (Lu et al., 2008; Tsai et al., 2010). On the other hand, a new measurement technique for measuring 3D knee kinematics non-invasively and free from ionizing radiation will be helpful for future clinical applications (Lin et al., 2013).

The purposes of the current study was (1) to develop an approach based on the integration of the medical image-based techniques, infrared stereophotogrammetry and finite element modelling (FEM); (2) to measure non-invasively the 3D kinematics and arthrokinematics of the knee and ground reaction forces during functional activities including cycling; (3) to estimate the forces of the force-bearing structures of the knee during the tested activities; (3) to assess the STA and their effects on the calculated biomechanical variables; and (4) to develop a new slice-to-volume registration method using real-time MRI for non-invasive measurement of knee kinematics.

METHODS: A new measurement system was established by integrating a fluoroscope (Allura Xper FD20/20, Philips Medical Systems), 12 infrared cameras (Vicon Motion Systems Ltd, UK) and force plates/sensors (Advanced Mechanical Technology, Inc., USA). The integrated system was used to measure the movement of the knee and ground (or pedal) reaction forces in 13 young healthy subjects during isolated flexion/extension, sit-to-stand and stair-ascent and during cycling movements on an instrumented ergometer (Fig. 1a). Each subject was also CT and MR scanned to obtain the 3D volumetric data of the knee joint. The WEMS method was used to obtain the 3D poses of the femur and tibia which were used to derive the 3D kinematics of the knee joint (Fig. 1b). With the measured ground reaction forces, the forces and moments about the knee joint centre were calculated by considering the free bodies of the foot, shank and thigh using inverse dynamics analysis. Given the accurate kinematic data of the bones from the WEMS method and the 3D coordinates of the skin markers from VICON system, the STA of the markers (i.e., displacements of markers relative to the underlying bones) and its influence on the calculated biomechanical variables were also quantified.

A subject-specific FEM procedure of the knee (Fig. 1c) was developed validated *in vitro*, and used for the analysis of the stresses, strains, and forces of the ligaments during the test activities. For each model, the geometry of the bones and ligaments were reconstructed from subject-specific CT and MRI data; parameters for the constitutive equations were customized to the subject via a combined experiment and optimization approach; and the kinematic and boundary conditions data were obtained via the 3D motion experiments.

A new MRI-based method for real-time, 3D kinematic measurement of the knee was also developed by integrating a novel, 2D real-time MRI sequence (i.e., refocused FLASH) and a 3D MRI data set. The 3D MRI at fully extended position was used to reconstruct volumetric bone models. The 2D real-time MRI was acquired during isolated flexion/extension. The 3D bone pose at each instance was determined when the reformed images interpolated from the volumetric bone model best matched the corresponding real-time image (Fig. 1d). An *in vivo* validation study was carried out to evaluate the performance of the method, giving the validity and repeatability of its measurements.

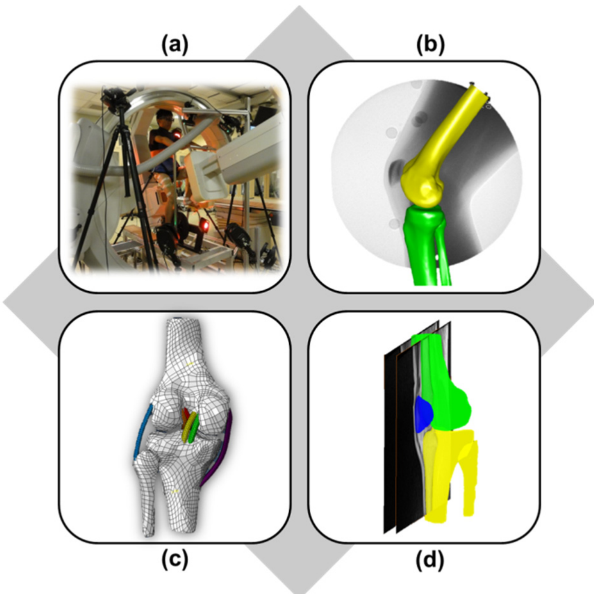

Figure 1: (a) *In vivo* measurement of knee kinematic and kinetic data during cycling using the integrated measurement system. (b) The fluoroscopy-to-CT registration method for the determination of 3D knee motion. (c) A subject-specific FEM model of the knee. (d) The new real-time MRI-based slice-to-volume registration method for non-invasive 3D knee kinematics.

RESULTS & DISCUSSION: The rigid-body kinematics (Fig. 2a) and arthrokinematics (Fig. 2b) of the knee during functional activities and cycling were measured for all subjects. The displacements of the skin markers relative to the underlying bones during all activities were also quantified and averaged across all subjects (Fig. 3a). The joint angles, shear forces and moments were underestimated and translations overestimated during cycling (Fig. 3b).

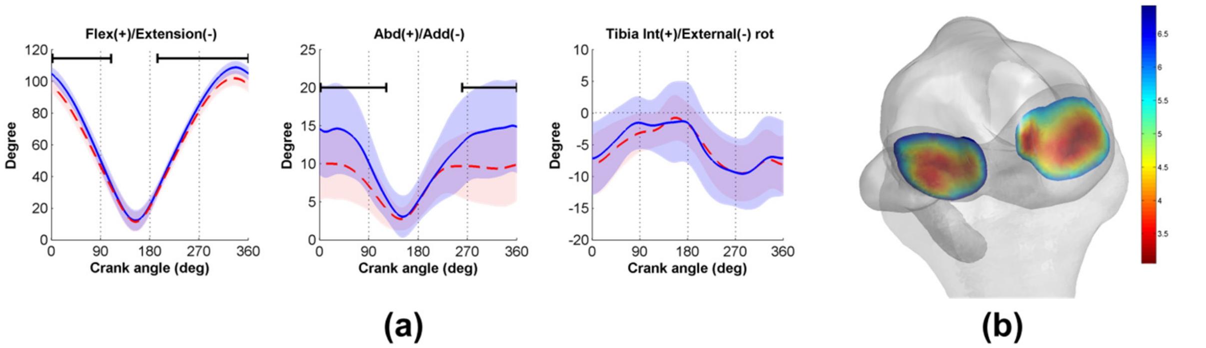

Figure 2: (a) The rotation angles of the knee during cycling using 3D fluoroscopy (blue lines) and motion capture system (red lines) (b) The colour map describing the relative distances between the femoral and tibial articular surfaces during cycling.

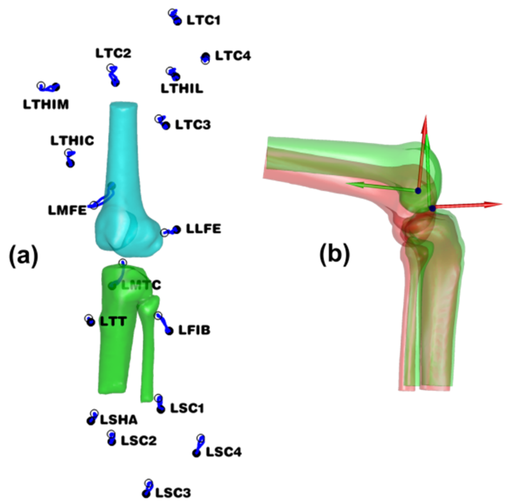

Figure 3: (a) The 3D displacements of the markers relative to the underlying bones. (b) The poses of femur and tibia obtained from the skin markers (red) and the true poses (green).

Finite element analysis of the knee joint and its surrounding soft tissues were performed. The resultant forces, stresses and strains of the cruciate and collateral ligaments during activities were obtained (Fig. 4). The PCL was found to transmit greater loads than the ACL during cycling, indicating a risk in PCL rehabilitation using cycling. Muscle activities played a crucial role in modulating the stresses and strains in the ligaments.

The new MRI-based slice-to-volume registration technique for 3D knee kinematics was shown to have sub-millimetre and sub-degree bias (means of errors) and precision (standard deviations of errors) for 3D poses of the femur and tibia, suggesting very good validity and reliability.

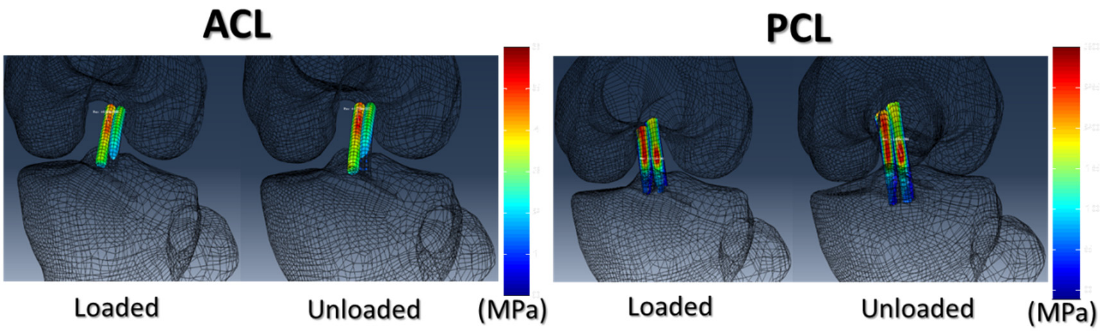

Figure 4: The principle stress patterns of the ACL (left) and PCL (right) at maximum knee flexion during cycling with and without external resistance.

CONCLUSION: A new integrated approach incorporating fluoroscopy-to-CT 3D measurement techniques, multi-camera motion capture system and finite element modelling techniques was developed and shown to be useful in the study of *in vivo* mechanical interactions between the force-bearing structures of the knee joint. The new approach provides a more comprehensive subject-specific biomechanical analysis of the knee during weight-bearing functional activities and exercises (e.g., cycling). The STA of the skin markers and their effects on the calculated biomechanical variables were quantified, which will be helpful for further improvement of modelling of the lower extremities in the field of 3D motion analysis. The new slice-to-volume registration method using the FLASH MRI for the real-time measurement of the 3D kinematics of the knee *in vivo* has been shown to be promising in future clinical applications and merits for further developments.

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