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A METHOD FOR OBTAINING SUBJECT-SPECIFIC JOINT LAXITY INFORMATION FOR MUSCULOSKELETAL MODELING

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INTRODUCTION

The subject-specificity of musculoskeletal (MS) models has increased in recent years by incorporating bone geometry, muscle strength and attachment sites for ligaments and tendons. These improvements have advanced the applicability of MS models, allowing more accurate modeling.

Joint laxity is highly subject-specific and may have a large impact on modeling results [1]. However, current MS models rely on generic joint laxity information typically obtained from cadaver studies due to the inability to accurately measure 3D joint laxity in vivo [2]. Subject-specific joint laxity may in particular be relevant in modeling related to pre-operative planning and predictive modeling of pathological conditions.

We suggest a new method to obtain accurate subject-specific joint laxity in 3D that can be applied to optimise subject-specificity of MS models.

METHODS

A six degree-of-freedom (DOF) arthrometer was developed by combining a parallel manipulator (H-820.2D, Physik Instrumente, Germany) and a multi-axis force/moment sensor (Omega85 SI-1900-80, ATI Industrial Automation, USA).

The design of the arthrometer enables multi-directional forces and moments to be applied to the joint while the proximal segment is fixated and the distal segment is attached to a moveable platform. Thereby, loads can be applied to the joint to mimic clinical test conditions or targeting specific ligaments meanwhile forces and moments in any direction are controlled, allowing unconstrained motion.

The arthrometer is constructed to be used in conjunction with a low-dose biplanar x-ray system and 3D image data of the involved segments. This setup allows 3D tracking of joint kinematics under applied loads (Fig. 1).

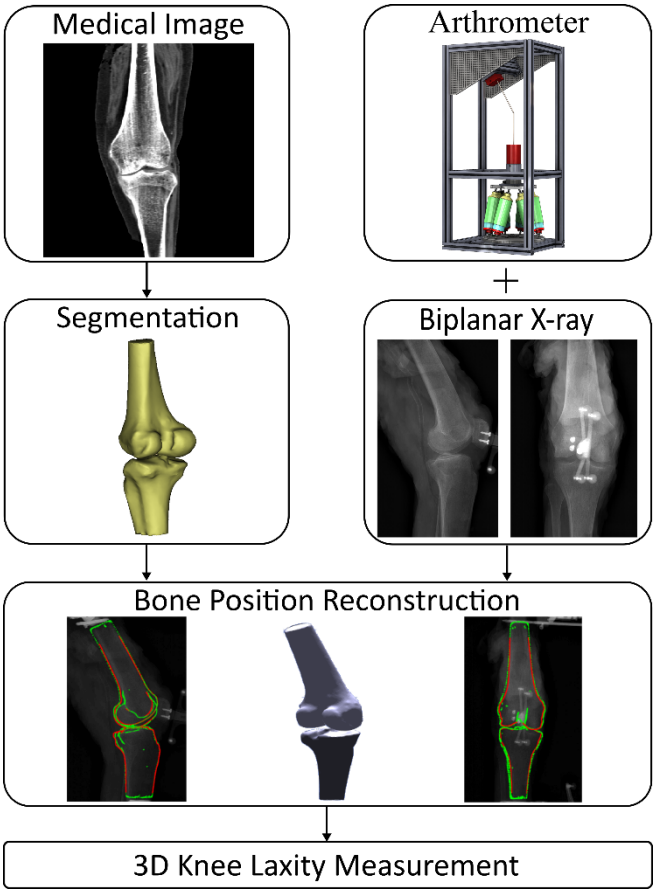

Fig 1: Flowchart representing the processes in the proposed method from acquiring image data to processed 3D knee joint laxity measurement.

As proof-of-concept, one cadaveric knee (female, age 73) was CT scanned (SOMATOM Definition Flash, Siemens) and subsequently mounted at 30 degrees of flexion in the device and placed inside a biplanar x-ray scanner (EOS, EOS imaging, France). Biplanar x-rays were obtained for eleven static load cases: anteroposterior loading (67 N, 134 N, -67 N and -134 N), mediolateral loading (12 N, 24 N, -12 N and -24 N) and internal-external moment (3 Nm, 6 Nm and -3 Nm).

Subsequently, the 3D bone geometries of femur and tibia were segmented from the CT image using Mimics (Materialise, Belgium).

Tab. 1: Translations and rotations of the knee joint in all six degrees of freedom in eleven different load cases relative to an unloaded condition. The primary motion for each load case are highlighted in bold.

Load cases	Superoinferior translation (mm)	Mediolateral translation (mm)	Anteroposterior translation (mm)	Flexion-extension angle (deg)	Varus-valgus rotation (deg)	Internal-external rotation (deg)
Internal rotational moment (3 Nm)	-0.6	0.9	1.5	0.9	0.6	**11.4**
Internal rotational moment (6 Nm)	0.6	-0.1	3.0	-0.3	1.0	**13.0**
External rotational moment (3 Nm)	0.3	-1.1	1.4	1.5	0.2	**-23.0**
Anterior translational load (67 N)	-0.5	-3.2	**3.8**	1.9	0.5	1.4
Anterior translational load (134 N)	2.0	-2.3	**5.2**	3.8	0.3	7.3
Posterior translational load (67 N)	0.3	1.4	**-5.2**	0.3	0.1	-9.9
Posterior translational load (134 N)	1.0	0.8	**-6.0**	0.3	0.1	-14.0
Lateral translational load (12 N)	1.6	**-2.7**	-0.2	2.0	1.1	-7.5
Lateral translational load (24 N)	-0.2	**-4.7**	0.6	2.8	2.1	-7.5
Medial translational load (12 N)	-0.2	**3.9**	-0.7	0.9	-0.2	-6.2
Medial translational load (24 N)	-0.3	**4.7**	-0.8	1.1	0.1	-6.0

Bone position and orientation for each load case were reconstruction by registering the 3D bone geometries onto the biplanar x-ray images using an iterative closest point (ICP) match between contours of the biplanar x-ray images and projected contours of the bones onto the image planes using Matlab (Mathworks, USA).

The relative translations and rotations between the reconstructed tibia and femur were computed in AnyBody Modeling System (AnyBody technology, Denmark) following ISB recommendations.

RESULTS AND DISCUSSION

Translation and rotation in all six DOF of the eleven load cases relative to an unloaded reference condition are presented in Table 1.

Anteroposterior loading of 67 N, 134 N, -67 N and -134 N resulted in an anteroposterior translation of 3.8 mm, 5.2 mm, -5.2 mm and -6.0 mm respectively. Mediolateral loading of 12 N, 24 N, -12 N and -24 N resulted in a mediolateral translation of 3.9 mm, 4.7 mm, -2.7 mm and -4.7 mm respectively. Internal-external moment of 3 Nm, 6 Nm and -3 Nm resulted in an internal-external rotation of 11.4°, 13.0° and -23.0°, respectively.

From the results, it can be seen that the method captured the coupled motion between anteroposterior translation and internal-external rotation. During mediolateral translational loading intern-external rotation was positioned at around -7±1 degrees compared to the unloaded condition. This suggest that there exists a passive band of internal-external rotation where multiple resting positions are possible.

Initial validation on three of the load cases comparing ICP using bone geometry and ICP using bone-pin markers displayed a RMSE of 0.7 mm and 0.7 degrees.

The preliminary results from this study displays that the method is capable of measuring knee joint laxity in 3D non-invasively. However, the method is still under development and several aspects can still be improved e.g. stability, efficiency and cost. Furthermore, the method needs to be thoroughly validated and tested in vivo.

Potentially, this method will allow estimation of ligament properties such as stiffness and slack length based on subject-specific information. This could be accomplished by solving an inverse identification problem based on the information provided by this method and a multi-body of the knee geometry.

CONCLUSIONS

We have presented a new method for obtaining 3D joint laxity non-invasively. The results presented indicates that the method is capable of obtaining subject-specific 3D joint laxity that could be useful in MS modeling. However, further validation and optimisation are warranted before the method becomes applicable and the specific measurement tool for in vivo measurements remain to be developed based on the ideas of the in vitro setup.

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