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Globally optimal registration for describing joint kinematics

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Abstract

Investigation of joint kinematics contributes to a better understanding of musculoskeletal condition pathologies. However, the most commonly used optoelectronic motion analysis systems cannot determine the movements of underlying bone landmarks with high accuracy because of soft tissue artifact. We are developing a computer-aided tracking and motion analysis with ultrasound (CAT & MAUS) system to track the underlying bone anatomy in a 3D global coordinate frame for describing joint kinematics. To quantify the rotation and translation of joints, registration is an essential component in our computer-aided tracking pipeline. In this paper, we consider a globally optimal Iterative Closest Point (ICP) registration algorithm to quantify joint kinematics. We use a global branch-and-bound (BnB) scheme to speed up the search in the entire 3D motion space. A globally optimal result is guaranteed by iterating the BnB scheme and ICP registration. We collected phantom data for validation and *in-vivo* data from ten healthy volunteers. The globally optimal ICP registration results have been compared to the results from traditional ICP registration. The overall average rotation angle error is less than 1°. The registration result is then converted into local joint coordinate systems defined by the International Society of Biomechanics for joint kinematics description. The results from globally optimal registration defined a general hip joint kinematics model of healthy subjects during gait which can be compared as a reference to the results from subjects with hip joint conditions.

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1. Introduction

1.1. Computer-aided tracking and motion analysis with ultrasound system

The motion analysis with ultrasound system (MAUS) used in our work is composed of a 2D B-mode ultrasound (US) scanner and a motion analysis system to directly locate under-skin bony landmarks. It has been applied to track patella movements during daily movements previously¹. Based on the tracked positions of the ultrasound probe during a scan captured by the motion analysis system, 2D US frames can be transformed into 3D space and reconstructed as

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a 3D volume². However, the accuracy of the MAUS has been found to be highly dependent upon the sonographer's experience and knowledge of anatomy². Thus, we are developing a computer-aided solution to make the existing MAUS more automatic and accurate. Patch-based bony structure tracking³ and automatic bone segmentation⁴ in US series have been developed by Jia *et al.*, as a precursor to the registration problem addressed in this paper.

1.2. Three dimensional (3D) globally optimal registration

In order to investigate joint kinematics, a 3D bone surface-to-surface registration is considered to monitor the joint rotations between different body poses during daily activities. As the bony structures of interest are rigid bodies, we make use of the commonly used iterative closest point (ICP) registration algorithm to find the transformation between two 3D point clouds⁶. However, the cost function optimization of the traditional ICP algorithm can get trapped in local minima, which leads to an erroneous registration result⁵. Previous work used a smoothing kernel to enlarge the convergence basin, which improved the robustness of the general ICP algorithm⁶. However, the resulting algorithm still gets trapped in local minima⁵. Thus, a good initialization is required to obtain a correct registration result. Yang *et al.*, added a branch-and-bound (BnB) global search scheme to the traditional ICP registration algorithm to guarantee a global optimal result without the need for a well-defined initialization⁵. This is the first time this method has been applied and evaluated on medical imaging with *in-vivo* data, and its value has been demonstrated in our computer-aided tracking and motion analysis with ultrasound (CAT & MAUS) system for describing joint kinematics.

In the next section, we describe the methods including the data acquisition, globally optimal ICP algorithm and joint kinematics description defined by the International Society of Biomechanics (ISB). Results are presented in Section 3 and we conclude in Section 4.

2. Methods

2.1. Data acquisition

In this paper, we focus on describing hip joint kinematics during gait for human subjects. Ten healthy volunteers (5 males/females) aged 18-40 years were asked to perform four typical gait poses, i.e. heel strike, mid stance, toe off and mid swing⁷. A LOGIQ S7 ultrasound (US) scanner with a ML 6-15 transducer was used to scan their left greater trochanter (GT) at these four poses respectively. The GT was also scanned while the patient stood in an upright standing pose. Retro-reflective markers attached to the subject and transducer were captured by the motion analysis system (VICON opto-electronic motion capture system) to provide positional information in a global 3D coordinate system. The bone structure in the US image was automatically segmented using the approach in the work of Jia *et al.*,⁴. Then, referring to the transducer positions during the scanning, segments of the US video were transformed into a global 3D coordinate system and reconstructed as a 3D surface of the GT using the method of Jia *et al.*,².

2.2. Globally optimal ICP registration

Having reconstructed GT surfaces, we treat the surface at upright standing pose as the reference (i.e. “model”) and other individual surfaces at the other four poses as the “data”. Iterative closest point (ICP) registration estimates the transformation including rotation and translation between the data and the model by minimizing the L_2 norm⁸. However, because of the risk of getting trapped in the local minima as mentioned above, ICP fails at some positions when it is not well-initialized. In order to tackle this problem, we use an ICP algorithm with an added branch and bound (BnB) scheme which allows efficient global optimization⁵. This method is briefly summarized in three steps.

Firstly, in order to get the globally optimal solution, the entire 3D Euclidean group, i.e. all feasible 3D transformations, is considered. Each member of the 3D Euclidean group is parametrized by six parameters (3 rotation angles and 3 translations). BnB search is used to search the 3D Euclidean group efficiently. The branch is deleted if its lower bound is higher than the other branch's upper bound. Detailed definition of the upper and lower bounds of each branch in the BnB search is presented in the work of Yang *et al.*,⁵. The globally optimal ICP starts with a random initialization in order to prove how sensitive an initialization is to the algorithm. Then, whenever a solution

with minimum cost is found, ICP registration is applied with the initialization starting at this solution to refine the cost function. Finally, the upper bound of BnB search is updated by the current ICP registration result until the L_2 norm converges. A diagram of the globally optimal ICP algorithm is shown in Fig.1.

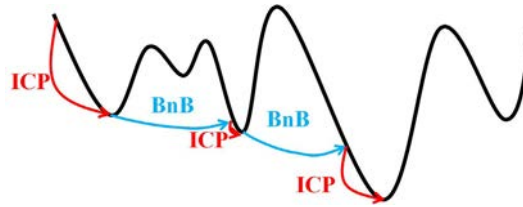


Fig. 1: BnB globally searched ICP registration.

A ball joint proximal femur phantom with a detailed femur's specification¹⁰ was used to validate the 3D surface-to-surface registration. We clamped the femur phantom in a water tank which has a plastic membrane window in the front surface shown in Fig.2. Degassed water was poured in to submerge the greater trochanter (GT). Five retro-reflective markers were attached on non-coplanar places of the rest of the exposed femur phantom. Then, the femur phantom was rotated to five different positions. The GT was scanned using the MAUS at those five rotated positions while the five markers were captured by the motion analysis system. We picked reconstructed surfaces at four different positions to register to the surface reconstructed at the fifth position with a random initialization. Finally we compared results from the globally optimal ICP algorithm to results from the traditional ICP algorithm and the ground truth captured by the motion analysis system.

The globally optimal ICP registration algorithm was implemented in MATLAB (MathWorks, R2014a, US) on a desktop computer (8-core Intel Core i704770 3.40GHz running a 64-bit Windows OS).

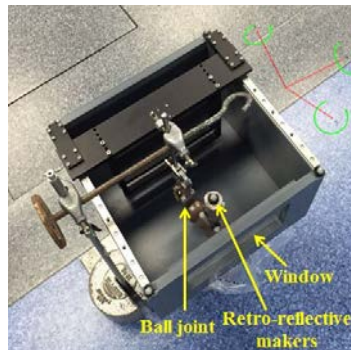


Fig. 2: Registration validation with a ball-joint proximal femur phantom.

2.3. Hip joint kinematics description

After registering the GT from one pose to another pose, we quantified the joint kinematics based on the transformed GT positions. The International Society of Biomechanics (ISB) has recommended a protocol to define local joint coordinate systems for joint kinematics description⁹. We followed the rules from ISB⁹ with a minor adaptation of the femoral coordinate system. The origin of the femoral coordinate system was redefined from the hip joint centre (HJC) which is coincident with the origin of the pelvis coordinate system to the GT as estimation of the HJC based on the static position of the pelvis markers or functional calibration introduce an error which we want to avoid. The bony landmarks used to define hip joint coordinate systems and the modality for data collection either motion analysis (MA) or MAUS are listed in Table.1 and shown in Fig.3.

The coordinate system (K_1 , K_2 , K_3) for describing hip joint kinematics followed the rules suggested by ISB⁹. We quantified the rotation angles around K_1 , K_2 , K_3 as flexion/extension, adduction/abduction and internal/external rotation respectively.

Table 1: Bony landmarks of the pelvis and the left thigh.

Bony landmarks	Description	Modality
LASIS	Left Anterior Superior Iliac Spine	MA
RASIS	Right Anterior Superior Iliac Spine	MA
LPSIS	Left Posterior Superior Iliac Spine	MA
MPSIS	Mid Posterior Superior Iliac Spine	MA
RPSIS	Right Posterior Superior Iliac Spine	MA
GT	Greater Trochanter	MAUS
LFE	Lateral Femoral Epicondyle	MA
MFE	Medial Femoral Epicondyle	MA

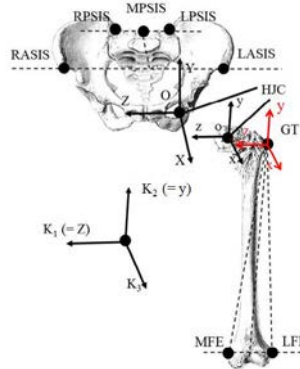


Fig. 3: Definition of the left hip joint kinematics with pelvic coordinate system (XYZ) and adapted left femoral coordinate system (red-xyz).

3. Results

In our femur phantom validation experiments, traditional ICP failed at many angle positions while globally optimal ICP registration performed well at any angle position because of the global search. One example is shown in Fig.4.

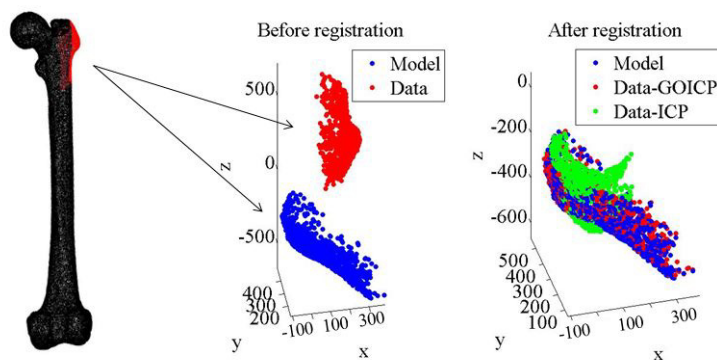


Fig. 4: Results comparison between globally optimal ICP registration and traditional ICP registration.

Compared to the ground truth, the globally optimal registration average errors were 0.52° , 0.55° and 0.071° with standard deviations of 0.90° , 1.15° and 1.13° about the x , y and z axes in Fig.4 respectively over 3 trials of the proximal

femur phantom at each positions. The elapsed time for a single registration was approximately 20s, which was slower than traditional ICP (0.23s) because of the extra time for global search.

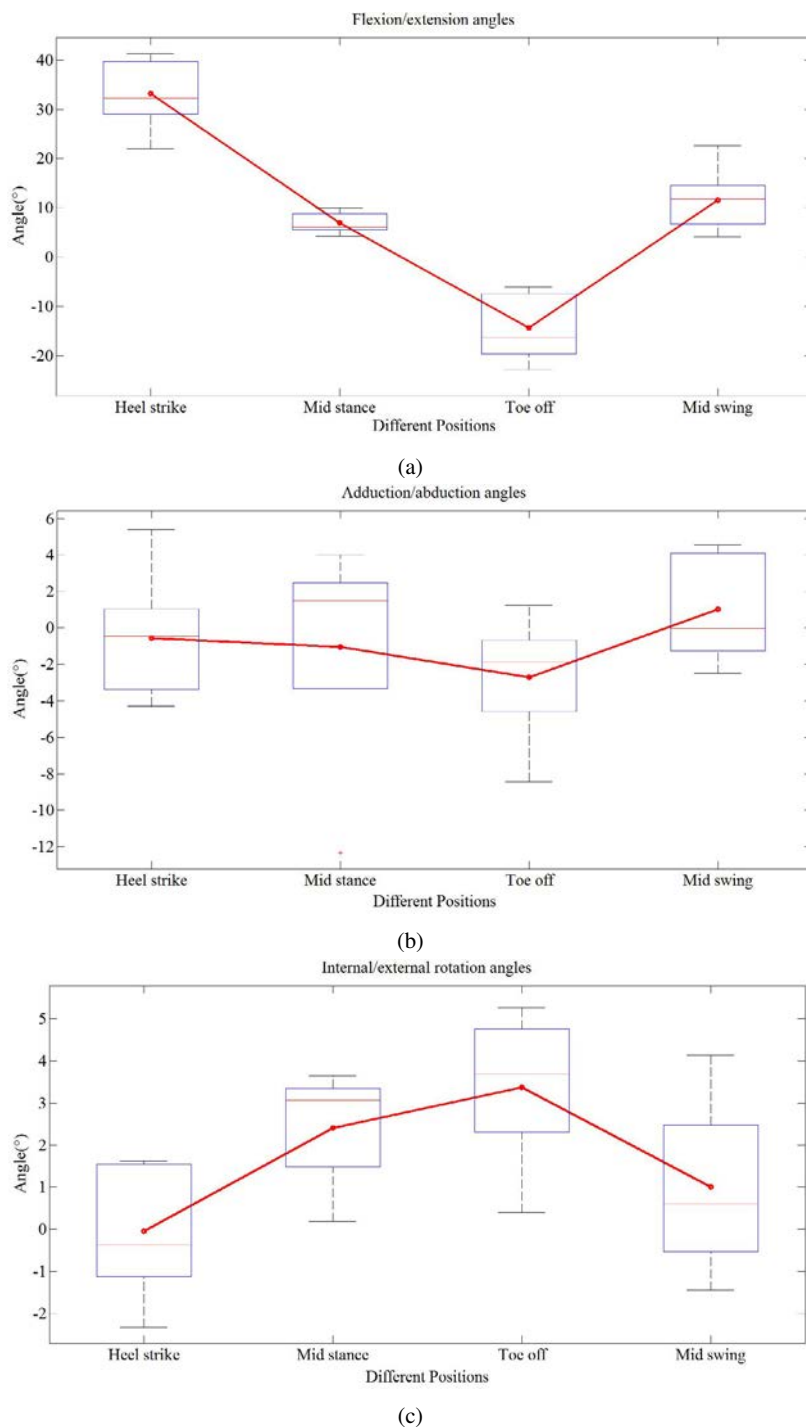


Fig. 5: Hip joint rotation angles, a) flexion/extension, b) adduction/abduction and c) internal/external rotation.

For the *in-vivo* tests, the results of flexion/extension, adduction/abduction and internal/external rotation angles at four typical gait positions over ten volunteers are plotted in Fig.5. Due to the difference between individual step strides, the flexion/extension angles vary from -14.34° to 33.22° with a standard deviation of 5.97° , the adduction/abduction angles vary from -2.73° to 1.02° with a standard deviation of 4.23° and the internal/external rotation angles vary from -0.05° to 3.38° with a standard deviation of 1.77° .

All the volunteers recruited to our study had no hip joint injuries or operations. Thus, rotations in Fig.5 defined a general hip joint rotation model of healthy subjects during gait. Interestingly, the rotation trends in Fig.5 resemble the trends presented in the work of Ramakrishnan *et al.*,¹¹. Moreover, the hip joint rotations calculated using the globally optimal ICP algorithm are similar to the results modeled by a Euler model reported by Ramakrishnan *et al.*,¹¹. Because the individual step stride varies, the maximum difference of the rotations between the results from globally optimal ICP registration and the results from the Euler model is 4° .

4. Conclusion

We presented a globally optimal ICP registration as one part of our computer-aided tracking and motion analysis with ultrasound (CAT & MAUS) system to describe hip joint kinematics. It is guaranteed to find the global optimal solution without the need for a good initialization like the traditional ICP algorithm. We have also shown that CAT & MAUS can model hip joint kinematics of healthy subjects which can be used as a reference to potentially diagnose other diseases, like the trochanter bursitis. Moreover, since our system describes the movements of real under-skin bony landmarks which significantly reduces the error caused by the soft tissue artifact, the results can be used as the ground truth for other similar research of joint kinematics modelling.

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