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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.

Keywords: Registration, Ultrasound, Motion analysis, Joint kinematics.

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 previously [1]. 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 volume[2]. However, the accuracy of the MAUS has been found to be highly dependent upon the sonographer's experience and knowledge of anatomy[2]. Thus, we are developing a computer-aided solution to make the existing MAUS more automatic and accurate. Patch-based bony structure tracking[3] and automatic bone segmentation[4] 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 clouds[6]. However, the cost function optimization of the traditional ICP algorithm can get trapped in local minima, which leads to an erroneous registration result[5]. Previous work used a smoothing kernel to enlarge the convergence basin, which improved the robustness of the general ICP algorithm[6]. However, the resulting algorithm still gets trapped in local minima[5]. 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 initialization[5]. 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 swing[7]. 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 norm[8]. 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 optimization[5]. 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