In Silicon Study of 3D Elbow Kinematics

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Abstract. This study is to propose a novel technique to improve the accuracy of estimating bone kinematics. This technique will use the radiographic information of both soft tissue and hard tissue for the 2D-3D registration. Non-rigid registration technique and rigid-body registration will work seamlessly to guide the matching process to find the optimal bone pose. Such a technique could improve and accelerate the matching process.

Keywords: Elbow, Kinematics, Imaging.

1 Introduction

Musculoskeletal injuries are the most common healthcare problem in the United States. For example, it was reported that more than 57 million musculoskeletal injuries, which accounted for 60 percent of injuries of all types, were treated in healthcare setting in 2004 (AAOS 2009). The healthcare cost of treating these injures was estimated at $127 billion (AAOS 2008). Besides the direct cost, these injuries result in a lot more indirect cost since the injuries can lead to short term or long term disabilities. In fact, in 2004 musculoskeletal injuries resulted in the more than 72 million lost work days (AAOS 2008). These huge costs are expected to keep increasing due to the increasing prevalence of musculoskeletal injuries, especially in aging population (AAOS 2008).

Although musculoskeletal injury is a prevalent problem, current clinical diagnosis and evaluation methods for most mobility injuries have not been significantly advanced. Surgeons heavily rely on subjective evaluation, simple clinical tests, or at most radiographic images in unloaded or static scenarios to diagnose the injuries, evaluation surgical techniques, and determine treatment strategies. These simple techniques may not be able to detect the injury-induced critical kinematic changes, which are only observed in dynamical scenarios (Li, Tashman et al. 2011). Improving diagnostic techniques and treatment strategies may alleviate the economic burdens resulting from musculoskeletal injuries by reducing the long-term disability and returning the patients back to higher levels of functioning.

In the last decade of the 20th century, a surface marker-based motion capture technology was introduced into clinical studies to examine 3D in vivo joint functions, and thus enabled dynamic evaluation of surgical technique and rehabilitation strategy. However, the accuracy of surface marker-based systems in measuring underlying

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skeletal kinematics is compromised by the soft tissue artifacts (Tashman, Kopf et al. 2008). In fact, surface marker-based systems are even not able to track the gross movement of bones and joints, e.g. carpal bones of the hand. Thus, this type of system is not able to determine subtle but important changes in joint mechanics caused by musculoskeletal injuries and therefore not able to resolve the controversies surrounding the treatment management of many injuries.

Recently, a small number of research programs in the US start to develop bi-planar videofluoroscopy systems, which use two high-frequency cardiac cine-radiographic generators to measure 2D in vivo joint kinematics (Tashman, Kopf et al. 2008; Scarvell, Pickering et al. 2010). These systems utilize 2D-3D registration techniques (Fregly, Rahman et al. 2005; Lu, Tsai et al. 2008; Zheng and Zhang 2009; Acker, Li et al. 2010; Matsuki, Matsuki et al. 2010; Scarvell, Pickering et al. 2010; Tersi, Fantozzi et al. 2010) to match the digitally reconstructed radiographs based on 3D bone scans with the experimental measured fluoroscopic images, then estimate the 3D bone pose with high accuracy and resolution. Although these systems allow joint kinematics to be measured in vivo, a few drawbacks prevent widespread use of them in clinical studies: (1) high cost of building such a system, (2) relatively larger radiation expose compared to clinically available fluoroscopic device, (3) a very limited field of view, which does not allow capturing the entire movement of many functional activities (Matsuki, Matsuki et al. 2010), (4) significant setup and calibration time.

In clinical environment, commonly available is the single plane fluoroscopy system, such as the mobile C-arm. This type of system has relative larger field of view and generates less radiation expose but work at a lower sampling frequency. Although it has been demonstrated that such a system can be used for measuring in vivo 3D kinematics of upper and lower extremities (Matsuki, Matsuki et al. 2010; Tersi, Fantozzi et al. 2010), the out-of-plane accuracy is less optimal compared to the bi-planar X-ray system (Fregly, Rahman et al. 2005; Acker, Li et al. 2010). Therefore, research effort has been dedicated to develop new algorithms to improve the out-of-plane accuracy (Scarvell, Pickering et al. 2010). Although it is possible to identify the edge of soft tissue around the joint, such information has been ignored and never been utilized for helping identify the 3D bone pose. We now propose a novel technique to improve the accuracy of estimation out of plane kinematics. This technique will use the radiographic information of both soft tissue and hard tissue for the 2D-3D registration. Non-rigid registration technique and rigid-body registration will work seamlessly to guide the matching process to find the optimal bone pose. Such a technique could improve and accelerate the matching process.

2 Methods

One specimen will be used in this study. The specimen will be free of any other elbow injuries or medical conditions (musculoskeletal or otherwise) that would interfere with performing the requisite testing activities. High-resolution CT scanning of the intact elbow specimens will be obtained.

The elbow will be mounted onto a jig that holds the humerus in neutral rotation and perpendicular to the floor. Elbow ROM will be easily achieved in the gravity and antigravity orientation by rotating the jig 180 degrees. Active ROM will be achieved by running cables through a line-of-action approximating each muscle's centroid in both the elbow flexor and extensor muscle units. The muscle lines of action will be maintained using a tendon alignment unit.

Testing of the elbow is done in the supine overhead and upright positions before and after sectioning of the collateral ligaments. In total five severity levels of injury on each specimen will be created including the intact elbow, elbow with LCL torn, elbow with LCL and posterior band of MCL torn, elbow with LCL and entire MCL disrupted, distal humerus stripped of all soft tissues. For each level of severity of injury, 2 trials of movement (2 rehabilitation protocol) will be performed (10 trials total).

The single-plane radiographic imaging system consisting of a mobile C-arm fluoroscope, retrofitted with 30-cm image intensifiers and high-speed video cameras will be used for measuring accurate 3D skeletal kinematics. For this study, images will be acquired at 15 Hz. The following outcome variables will be obtained in order to determine elbow instability: 1) displacement of the proximal ulna relative to the distal humerus, 2) displacement of the radial head relative to the distal humerus and proximal ulna.

The recorded dynamic fluoroscopic radiographic data will go through a model-based tracking procedure to determine 3D elbow kinematics. CT scans of the elbows will be used to create specimen-specific 3D volumetric bone models. Then, a virtual x-ray system model proportionately identical to the true testing facility will be created. Digitally reconstructed radiographs (DRRs) can be computed using this simulation system for any bone orientation. A computer optimization algorithm will automatically determine the bone position/orientation at each instant in time that maximizes the correlation between the DRRs and the actual radiographs. The relative motions between the distal humerus, proximal ulna, and radial head bone will then be used to create a 3D model of skeletal movement. The joint rotations and translations will be determined. This model-based tracking, coordinate system determination, and kinematic analyses have been extensively used in our previous studies.

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