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Technical note

Validation of an alignment method using motion tracking system for *in-vitro* orientation of cadaveric hip joints with reduced set of anatomical landmarks

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ABSTRACT

Accurate *in-vitro* orientation of cadaveric hip joints is challenging due to limited available anatomical landmarks. Published hip joint *in-vitro* investigations commonly lack details on methods used to achieve reported orientations and the accuracy with which the desired orientation has been achieved. The aim of this study was to develop an accurate method for orienting hip joints with limited anatomical landmarks for in-vitro investigations, and to compare this method against orientation using guiding axes and by visual approximation. The proposed orientation method resulted in orientation angles achieved to within one degree (SD $\pm$ 0.58°). For most specimens, orientation using physical tools resulted in errors of $\pm$8° and $\pm$12° in at least one of three orientation angles used to place the femur and pelvis in neutral orientation, respectively. Precision was also worse, with SDs ranging from $\pm$1° to $\pm$5° for orientation angles of femoral specimens and SDs ranging from $\pm$1° to $\pm$8° for pelvic specimens. The error in the orientation angles was worse for orientation by visual approximation and the range of SDs were greater for both the femur and pelvis. Finite element modeling was used to assess the effects of observed orientation errors, on prediction of fracture load. In most cases, the largest error in fracture load among all trials exceeded 30%, relative to a femur oriented without any error in the orientation angles.

1. Introduction

In-vitro investigations have been crucial in the progression of our understanding of hip joint pathologies and biomechanics. Hip joint pathologies such as dysplasia and femoroacetabular impingement [1] as well as factors contributing to osteoporotic hip fracture risk are often investigated using cadaveric specimens [2–6]. *In-vitro* models are also used to investigate surgical procedures and techniques [7], soft tissues [8], implants and joint replacements [9]. The quality and reliability of the experimental data depends on both a relevant model of the *in-vivo* condition and the accurate realization of this model in the experiment. Experimental models of the hip joint aiming to simulate a variety of physiological conditions, including one leg stance, gait and falls, require orientation based on landmarks to accurately represent *in-vivo* loading.

Defining or measuring hip joint orientation often requires the use of anatomical landmarks from entire femoral and pelvic anatomy. In 2002, the Standardization and Terminology Committee of The International Society of Biomechanics proposed a general reporting standard for joint kinematics [10] based on the Joint Coordinate System first introduced by Grood and Suntay [11]. For the hip joint, their proposal defines landmarks accessible in humans from external palpation or by estimation and hence are difficult to apply to *in-vitro* investigations. Additionally, their proposal requires the entire femoral and pelvic anatomy to be available, which are not easily accessible *in-vitro*. A number of other previously reported methods also require landmarks from whole femoral and pelvic anatomy [12–15]. However, it is often unpractical to obtain and experiment on such large sections of anatomy. As a result, it is difficult to adapt these established hip joint orientation methods to *in-vitro* hip joint experiments, and may be part of the reason behind limited explanation on orientation methods used among different studies. For example, many hip fracture studies test only the proximal femur. These studies often lack any in-depth discussion on orienting the femur prior to testing [6,16,17]. Often authors report one target angle [17–20], typically the angle in the coronal plane between the shaft of the femur and the vertical axis. Unfortunately, without three angles, the femur cannot be defined in 3D space. Ambiguity in the orientation of the hip joint or femur alone causes uncertainty in the direction of applied

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load, though it remains unclear how this affects the measured outcomes.

Thus, the objective of this research was to develop and evaluate an experimental method for orientation of femoral and pelvic specimens when limited anatomy is available using a motion tracking system, and compare this to orientation using guiding axes and visual approximation. The study compares the accuracy and repeatability of specimen orientation using the three methods. It also explores some of the consequences of poor orientation by using finite element modeling (FEM) to compute fracture load of inaccurately oriented femoral specimens compared to the fracture load of a specimen oriented without any error.

2. Methods

2.1. Alignment method using motion tracking system for experimental orientation of cadaveric hip joints in-vitro

The primary objective of this study was to develop an alignment method using a motion tracking system for experimental orientation of cadaveric hip joints with limited anatomical landmarks for *in-vitro* investigations based on published averaged anatomical data. Using a motion tracking system (Optotrak, National Instruments) anatomical landmarks on the femur and pelvis were digitized and used to orient the specimens. Using First Principles software (Optotrak, Northern Digital Inc., Waterloo, Canada) and custom Matlab (Mathworks, MI, USA) scripts, orientation angles of the femur and pelvis were computed based on digitized points (Sections 2.1.1 and 2.1.2) and displayed in real time. The angles were measured with respect to a fixed global coordinate system defined *a-priori* which represented coronal, sagittal and transverse planes and were used to orient the hip joint in neutral position. The following sections provide more detailed descriptions of how this method was used for orientation of cadaveric specimens of the proximal femur (Section 2.1.1) and pelvis (Section 2.1.2).

2.1.1. Alignment method using motion tracking system for experimental orientation of the proximal femur

We propose orientation of the cadaveric femur based on measurements reported by Bergmann et al. [12], who reported the orientation of the neck and shaft axes of telemetric hip implants, when the subject stood in neutral anatomical position (Fig. 1). Based on these angles, they determined the orientation of the femur with respect to an anatomic coordinate system defined using landmarks on the bone (Fig. 1) [12]. AV angle was measured between the neck and the medial–lateral axis when viewed in the transverse plane; CCD angle was measured between the neck axis and the proximal–distal axis when viewed in the coronal plane; S angle was measured between the shaft axis and the proximal–distal axis when viewed in the sagittal plane (Fig. 1). Bergmann [21,22] reported average AV, CCD and S angles of $12° \pm 11.1°$, $135° \pm 0°$, and $8.7° \pm 1.5°$, respectively, measured from nine patients. These angles relate local femoral landmarks to a 'femoral coordinate system'. All forces in their studies were reported in this coordinate system, which was designed to approximate the global anatomic coordinate system when the patient stands in a neutral position. Assuming the neck and shaft of the implanted prosthesis were approximately parallel to the neck and proximal shaft of the intact femur, the angles reported by Bergmann et al. [21,22] can be used to orient cadaveric femurs without the condyles.

As mentioned above, we used an optical motion tracking system to track cadaveric specimen orientation in real time with respect to a fixed global coordinate system whose orientation is selected *a-priori* (Fig. 2a). This coordinate system is intended to approximate the anatomic coordinate system of the cadaveric specimen. This is accomplished only when the bone is oriented relative to this fixed coordinate system such that angles AV, CCD, and S (Fig. 1) are achieved. The local femoral neck and shaft axes were tracked by digitizing points on the head (15), the thinnest section of the neck (8) and two planes on the shaft (8 points per plane, approximately 2 mm and 50 mm below the lesser trochanter). These points were used to locate the centroids of the head, neck and shaft (Fig. 2b). These centroids were then used to construct the neck and shaft axes. Neck axis was approximated by a line connecting the center of the femoral head to the centroid of the neck, and shaft axis was approximated as the line connecting two centroids of the shaft defined in two locations (Fig. 2b). Locations of these points were approximated by a trained operator with at least 4 years of experience working with cadaveric hip bones; the operator was able to consistently reproduce the neck and shaft axis to within 2°. The camera continuously tracked the movement of the femur and the digitized landmarks as the femur was rotated. The position of the digitized landmarks with respect to the fixed global coordinate system (Fig. 2a) was continuously passed to a MATLAB script where neck and shaft axis were calculated. In the same MATLAB script these axes were then used to calculate AV, CCD and S orientation angles with respect to the fixed global coordinate system and were displayed on the screen in real-time. These angles were used by the operator to reorient each specimen until the target angles of 12°, 135°, and 9° for AV, CCD and S, respectively, were achieved.

2.1.2. Alignment method using motion tracking system for experimental orientation of the pelvis

We propose orientation of the cadaveric pelvis *in-vitro* using techniques developed by Lubovsky et al. [23] for reporting pelvic orientation by radiographic analysis. Using their method, the pelvic orientation is calculated with respect to the local coordinate system defined by the anterior pelvic plane (APP) created by the left anterior superior iliac spine (ASIS), right ASIS and symphysis pubis (Fig. 3a). The APP was set as the coronal plane as it would appear in a perfect anterior–posterior X-ray (Fig. 3b), and as such the sagittal and transverse planes are placed perpendicular to the APP. The line connecting the left and right ASIS is defined as the medial–lateral axis and a line perpendicular to this is the proximal–distal axis. The orientation of the pelvis is then reported in terms of anteversion (AV) and abduction (AB) angles calculated using the normal vector of the acetabular rim plane (Fig. 3a and b). The use of APP is important when measuring AV and AB from patient CT scans because it accounts for differences in patient positioning during the CT.

Though defining the APP is unlikely *in-vitro*, the AV and AB angles may be calculated from CT scans using APP, and these angles may be used to orient the cadaveric pelvis with respect to a fixed global coordinate system defined *a-priori* as well (Fig. 2a). By defining the rim plane, the pelvis can be aligned in the fixed global coordinate system by calculating AV and AB using the normal vector of the rim plane with respect to the medial–lateral and proximal–distal axes of the fixed global coordinate system.

To adopt this approach to *in-vitro* orientation of cadaveric pelvis, the same motion tracking system was used to digitize points outlining the acetabular rim. This allowed the acetabular rim to be tracked via the digitized points as the pelvis was rotated. The position of the digitized points with respect to a fixed global coordinate system defined *a-priori* (Fig 2a) were continuously passed to a MATLAB script to compute an acetabular rim plane by least-squares method and the normal vector of the plane. In the same MATLAB script, the normal vector was used to calculate AV and AB angles in the fixed global coordinate system and was displayed on the screen in real-time. AV was measured between the normal vector of the rim plane projected onto the transverse plane and the medial–lateral axis. AB was measured

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