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The Knee

An instrumented spatial linkage for measuring knee joint kinematics

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ABSTRACT

Background: In this study, the design and development of a highly accurate instrumented spatial linkage (ISL) for kinematic analysis of the ovine stifle joint is described. The ovine knee is a promising biomechanical model of the human knee joint.
Methods: The ISL consists of six digital rotational encoders providing six degrees of freedom (6-DOF) to its motion. The ISL makes use of the complete and parametrically continuous (CPC) kinematic modeling method to describe the kinematic relationship between encoder readings and the relative positions and orientation of its two ends. The CPC method is useful when calibrating the ISL, because a small change in parameters corresponds to a small change in calculated positions and orientations and thus a smaller optimization error, compared to other kinematic models. The ISL is attached rigidly to the femur and the tibia for motion capture, and the CPC kinematic model is then employed to transform the angle sensor readings to relative motion of the two ends of the linkage, and thereby, the stifle joint motion.
Results: The positional accuracy for ISL after calibration and optimization was 0.3 ± 0.2 mm (mean +/− standard deviation). The ISL was also evaluated dynamically to ensure that accurate results were maintained, and achieved an accuracy of 0.1 mm.
Conclusions: Compared to the traditional motion capture methods, this system provides increased accuracy, reduced processing time, and ease of use. Future work will be on the application of the ISL to the ovine gait and determination of *in vivo* joint motions and tissue loads.
Clinical relevance: Accurate measurement of knee joint kinematics is essential in understanding injury mechanisms and development of potential preventive or treatment strategies.

1. Introduction

Motion capture and analysis has proven to be a useful tool in examining kinematics during normal motion for biomechanical studies. These systems typically make use of optical or video camera based systems (surface skin markers) [1], electromagnetic sensors [2], accelerometers [3], or imaging tools such as magnetic resonance imaging (MRI) [4] and bi-plane fluoroscopy [5]. While each of these systems has the strength of being relatively non-invasive, there are drawbacks in terms of accuracy, volume of capture, data processing and motion specificity [6].

An instrumented spatial linkage (ISL) was the only measurement technique that could be developed to meet the requirements for both *in vivo* assessment of gait kinematics, and *ex vivo* feedback in motion reproduction with subsequent load determination [7,8]. An ISL is a series of instrumented joints (mainly rotational) constructed in such a way as to provide resistance-free motion while being able to report the relative motion of the two ends of the linkage [9,10]. To measure the complex 6-DOF motion of anatomical joints, six revolute ISLs (6R-ISLs) can be used, where the end fixtures are attached to the two bones of the joint of interest, hence allowing motion to be estimated from the linkage geometry and transducer readings [10]. However, due to tolerances of the linkage parameters, these systems may not be as accurate as desired [11]. In this study, the development of a highly accurate ISL for kinematic analysis of the ovine stifle joint is described.

The value of an ISL is related to the kinematic model employed to translate the angle sensor readings into the relative position and orientation of the two ends of the ISL [9,10]. For a kinematic model to be useful, it must be complete, and proportional or parametrically continuous [12]. Complete refers to the model containing a sufficient number of

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coefficients or parameters such that it is able to express any possible geometric shape of the structure. Eq. (1) details the necessary number of coefficients for a purely rotational joint linkage with six revolute joints [12].

$$\boldsymbol{C} = \boldsymbol{4R} + \boldsymbol{6} \tag{1}$$

where **C** is the total number of coefficients required, and **R** is the number of revolute joints. Thus, for the 6R-ISL presented here, 30 parameters are necessary. Proportionality or parameter continuity refers to a model that does not contain any singularities, *i.e.* small changes in geometry are reflected by small changes in model parameters [13]. This is critical for calibration purposes, to maintain numerical stability when solving for optimal parameters.

Various techniques have been used to model ISLs [10,11] and serial robots [14–17]. The use and geometry of ISLs have similarities to those of serial robots [13]. Some commonly used conventions in kinematic models, as summarized in Schroer et al. [16], are:

- A joint's coordinate system is aligned so that the z-axis is coincident with the joint's axis of motion, following the right hand rule for rotary joints
- The kinematic geometry is defined by a sequence of transformations from the base frame to the end or tool frame
- The homogeneous transformation matrix is most often used to describe the position and orientation of successive joint coordinate systems. The representation is as follows:

$$\boldsymbol{T}_b^c = \begin{bmatrix} \boldsymbol{n} & \boldsymbol{o} & \boldsymbol{a} & \boldsymbol{p} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

  where **n**, **o**, and **a** are the unit direction vectors of the **x**, **y**, and **z** axes of the c frame in the b frame, and **p** is the position vector of the c frame in the b frame.
- The elementary set of transformations is used for simple transforms: $\{T_x, T_y, T_z, R_x, R_y, R_z,\}$ where T_x represents a translation along the x-axis and R_y is a rotation about the y-axis.

The most commonly employed method for kinematic modeling is the Denavit–Hartenberg (DH) convention [15]. This system makes use of four parameters to construct a transformation, **T**.

$$\boldsymbol{T}(\boldsymbol{\theta}, \boldsymbol{d}, \boldsymbol{a}, \boldsymbol{\alpha}) = \boldsymbol{R}_z(\boldsymbol{\theta})\boldsymbol{T}_z(\boldsymbol{d})\boldsymbol{T}_x(\boldsymbol{a})\boldsymbol{R}_x(\boldsymbol{\alpha}) \tag{3}$$

where $\boldsymbol{\theta}$, $\boldsymbol{d}$, $\boldsymbol{a}$, and $\boldsymbol{\alpha}$ represent joint angle, link offset, link length, and link twist, respectively [15]. While this method is effective, the convention lacks the ability to model two joint axes being nearly parallel without a large change in parameters. The DH convention is also neither complete nor parametrically continuous [14,18]. The modified DH convention [19] attempts to overcome this problem by introducing an intermediate transform about the y-axis. The S-model was developed by adding two parameters to the DH convention, and is thus complete but still not continuous and requires more than the minimum number of coefficients. The complete and parametrically continuous (CPC) model was developed to avoid these shortcomings [17].

The CPC model makes use of Roberts' singularity free line convention [20]. In this model, a line in 3D space is represented by 4 terms (b_x, b_y, l_x, l_y). The direction unit vector of the line, $\mathbf{b} = (b_x, b_y, b_z)$ is defined using the convention that $b_z = +(1 - {b_x}^2 - {b_y}^2)^{1/2}$ enforcing that **b** always lies in the upper half-space of the reference frame. Note that a lowercase bold character here implies a vector and an uppercase bold denotes a plane. A plane **B** is defined as perpendicular to **b** and containing the origin of the reference frame. The coordinates of the intersection of the line and the **B** plane are l_x and l_y where l_x is along the projection of the reference frames **x** axis onto the **B** plane, likewise l_y is along the projection of the reference frames **y** axis onto the **B** plane [20].

In order to extend this definition of a line to a coordinate system transformation, Zhuang et al. [17] added two additional parameters: l_z *and* $\boldsymbol{\beta}$. l_z allows an arbitrary translation along the z axis. $\boldsymbol{\beta}$ is a rotation about the **z** axis which permits an arbitrary orientation of the **x** axis. These operations can be expressed by:

$$\boldsymbol{T}(\boldsymbol{i-1})(\boldsymbol{i}) = \mathbf{Rot}(\boldsymbol{z}, \boldsymbol{\theta}_i)\, \boldsymbol{R}_i\, \mathbf{Rot}(\boldsymbol{z}, \boldsymbol{\beta}_i)\, \boldsymbol{Trans}(\boldsymbol{l}_{i,x}, \boldsymbol{l}_{i,y}, \boldsymbol{l}_{i,z}) \tag{4}$$

$$R_i = \begin{cases} \boldsymbol{I}_{4x4} & \text{, if } z_i \text{ is not parallel to } z_{i-1} \\ \begin{bmatrix} 1-\dfrac{b_{i,x}^2}{1+b_{i,z}} & \dfrac{-b_{i,x}b_{i,y}}{1+b_{i,z}} & b_{i,x} & 0 \\ \dfrac{-b_{i,x}b_{i,y}}{1+b_{i,z}} & 1-\dfrac{b_{i,y}^2}{1+b_{i,z}} & b_{i,y} & 0 \\ -b_{i,x} & -b_{i,y} & b_{i,z} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} & \text{, if } z_i \text{ is parallel to } z_{i-1} \end{cases} \tag{5}$$

Thus, the total transformation is described by $(b_x, b_y, b_z, l_x, l_y, l_z, \beta)$ and the joint variable θ. As Roberts' line convention utilizes the minimum number of parameters, the additional parameters (l_z, β) are held constant in the parameter identification.

In this study, the CPC model was used to describe the ISL developed. The parameters were optimized using an objective function that was the simple sum of the root mean squared (RMS) error in position (mm) and rotation (deg) [21]. The ISL was also tested in a dynamic environment to examine its accuracy and functionality.

2. Materials and methods

2.1. ISL design specifications

As the ISL was to be used *in vivo*, there were several restrictions placed on the mechanical design. As the post/plate assembly of Tapper et al. [1] had proven to be an effective method of ensuring a rigid assembly to the tibia and femur, the ISL was designed to use these components

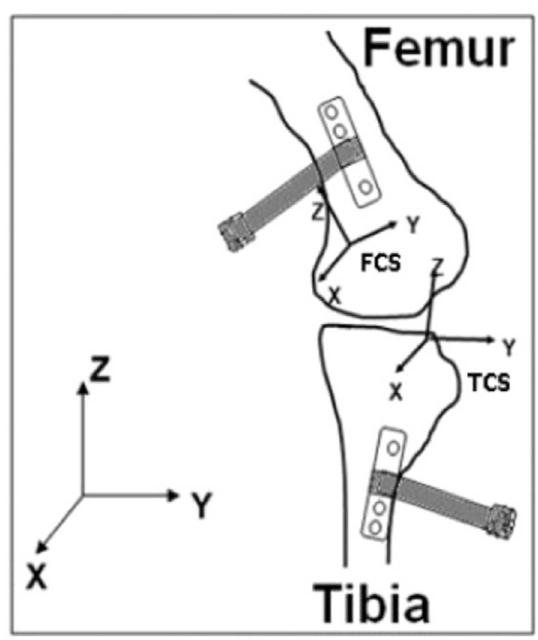

Fig. 1. The post-plate assembly of Tapper et al. Its use involves two procedures: The first is the implantation of the modified surgical fracture plates onto the lateral side of the two bones; the second procedure occurs just prior to data collection where an incision is made to expose the previously implanted plates. Once exposed, the posts are bolted onto the plates, creating a rigid connection.